

Energy Technology Perspectives 2017

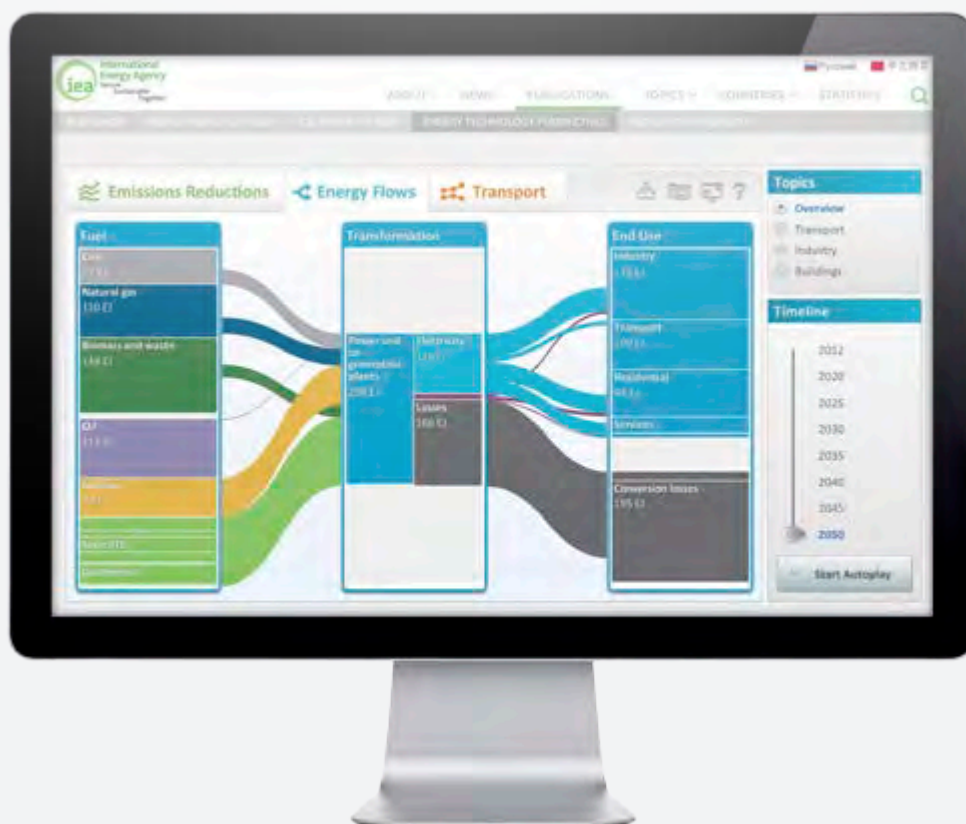
Catalysing Energy Technology Transformations



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Energy Technology Perspectives 2017

Catalysing Energy Technology Transformations



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- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
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Catalysing energy technology transformations

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Foreword

The energy sector has always been profoundly shaped by technological innovation, building on new discoveries to facilitate everyday life and provide access to new services. Since its establishment in 1974, the International Energy Agency (IEA) and its members have understood the fundamental role of technology in ensuring access to affordable and secure energy, in stimulating economic growth, and in addressing environmental challenges. Today, countries around the world agree that a proper understanding of the opportunities that technology can offer is undoubtedly an essential element of energy policy making that supports the shared goals of energy security, economic development and environmental sustainability. But, to foster energy technology development and innovation, governments must provide the right policy signals and framework.

From its inception, the IEA has been a supporter of energy technology collaboration. For over 40 years, the newly rebranded IEA Technology Collaboration Programmes, or TCPs, have been bringing together 6 000 experts from 53 countries, key companies and top research institutions to accelerate energy technology innovation. The IEA also continues to act as a hub for the analysis of energy technologies and policies. Since 2006, the Energy Technology Perspectives (ETP) project and this annual *ETP* report have been providing strategic guidance on energy technology and policy through an integrated approach, keeping IEA stakeholders informed about technological trends, advances and opportunities, while presenting various scenarios for technology deployment that can efficiently meet policy objectives.

New policy objectives are emerging as the energy sector sits on the verge of a historic transformation, driven by technological progress and evolving political, economic and environmental issues. Solar photovoltaics, onshore and offshore wind energy, energy storage systems, unconventional oil and gas resources, and electric vehicles are now realities that are changing the nature of the energy sector. Energy security issues and the measures to address them as well as expectations of societies towards energy systems are also changing. The Paris Agreement on climate change, signed by over 190 countries, demonstrates the new expectations from societies for the energy sector. This international agreement's ambitious climate mitigation target implies drastic alterations to the way the energy sector needs to consider its own development.

The unique value of IEA analysis is that in all its research, the organisation never loses sight of energy security imperatives, with a focus on solutions that can also improve affordability and sustainability. *ETP 2017* analyses various energy sector development paths to 2060, each with different implications for the development and deployment of energy technologies and for energy policy. As in previous years, the aim of these scenarios is to demonstrate what types of measures and what level of commitment would be required to attain specific policy goals. The nature of our analysis continues to focus on understanding how a portfolio of technologies can be nurtured to effectively address multiple energy policy objectives. The root challenge remains how to adopt a systems integration approach that can optimise the synergies between energy supply and demand for services.

ETP 2017 also features the annual *Tracking Clean Energy Progress* report, which provides an overall sense of the state of global progress for each energy technology. I remain confident that this analysis, with its related scenarios and performance monitoring, will provide useful insights to governments, companies and other stakeholders, and will enable them to successfully navigate the changing energy landscape.

Dr Fatih Birol
Executive Director
International Energy Agency

Executive summary

The energy system is evolving, but policy signals are needed to accelerate and steer its transformation

A number of trends indicate that the global energy system is changing. The energy mix is being redefined; in the power sector, renewables and nuclear capacity additions supply the majority of demand growth. On the demand side, innovative transportation technologies are gaining momentum and are projected to increase electricity demand. Rising living standards mean more people will buy appliances, electronic devices and other goods powered by electricity, also driving up electrical needs.

Energy technology innovation can bring more benefits and facilitate transformation, but strong policy signals are needed. *Energy Technology Perspectives 2017 (ETP 2017)* highlights how energy innovation, i.e. scaled-up deployment of available technologies and further development of technologies in the innovation pipeline, can support multiple policy objectives while ensuring secure, reliable and affordable energy.

The annual *Tracking Clean Energy Progress (TCEP)* report, included in *ETP 2017*, examines how various technologies are moving in comparison with global climate targets. The results show that transformation towards a clean energy system is not in line with stated international policy goals. Many technology areas suffer from a lack of policy support, and this impedes their scaled-up deployment. Energy efficiency, bioenergy and carbon capture and storage (CCS) are notable examples of where significant potential for technology progress remains, but strong policy signals will be required to trigger the appropriate investments.

Overall, only a few surveyed energy technologies are on track to achieve sustainability goals. *TCEP* demonstrates, however, that where policies have provided clear signals on the value of technology innovation, such as in solar photovoltaics (PV), onshore wind, electric vehicles (EVs), and energy storage, progress has been substantial.

An integrated approach is essential for a sustainable energy future

Energy technologies interact and thus must be developed and deployed together. Affordable, secure and sustainable energy systems will feature more diverse energy sources and rely more heavily on distributed generation. Therefore, they will need to be better integrated and managed from a systems perspective. This can increase efficiency and decrease system costs, and it will require a broader range of technologies and fuels. However, success depends not only on individual technologies but also on how the overall energy system functions. The most important challenge for energy policy makers will be to move away from a siloed, supply-driven perspective towards one that enables systems integration. Effective planning tools, supportive regulatory frameworks, and increased policy dialogue are essential.

Integrated and connected electricity systems are key to the transformation of the energy sector. Increasing electrification provides opportunities to enhance the flexibility, efficiency and environmental performance of electricity systems. Systems integration technologies, such as energy storage, are being driven by decreasing costs, increasingly favourable regulatory treatment, and an improved understanding of their value. In 2016, deployment of

new storage capacity, mostly battery technologies, grew by more than 50%. The widespread application of digital technologies can help accelerate this transformation.

Energy system integration and enhanced demand response will bring new opportunities for optimisation and increased efficiency in delivering services. Smart energy systems can enable demand–response measures. Technologies such as advanced metering infrastructure, smart appliances, or bidirectional smart meters allow demand management and provide incentives for consumers to play an active role in energy systems. These approaches can stimulate more efficient energy use and contribute to load management and system flexibility.

Long–term co–ordinated planning for stronger and smarter infrastructure investment is needed to ensure continued system efficiency and reliability. An efficient and low–carbon energy system will need sustained investment in multiple infrastructure areas. Already, there are bottlenecks in electricity transmission capacity in large markets (such as, for example, Germany and the People’s Republic of China) that threaten to limit the future expansion of electrification and variable renewables. The deployment of carbon dioxide (CO₂) transport and storage infrastructure is another example: for most individual applications, the quantities of CO₂ will mean that project–specific transport and storage infrastructure are unlikely to be economical. Effective co–ordination and planning, from the local to the regional level, could help alleviate these barriers.

Technology progress needs strong co–ordinated policy support. While economic competitiveness of new technologies is improving, policy drivers do not always have sufficient market impact to steer technology choices in an optimal direction. Energy security and sustainability benefits need adequate market signals and regulations to encourage investments directed at long–term impacts. Market forces alone will not deliver the needed impetus. Strong and consistent policies co–ordinated across various energy sectors should account for energy policy objectives throughout the many facets of government and business decision–making, including taxation, international trade, urban planning, and innovation.

Higher ambitions for a sustainable energy system are not being translated into action

Today’s critical challenge is to ensure the momentum of the energy sector transformation and speed its progress. The ratification of the Paris Agreement and calls to implement the United Nations Sustainable Development Goals show strong global support to address climate change and other environmental concerns. Rapid and clear signals aligned with long–term objectives will be needed to steer the energy sector towards sustainability.

The current trajectory falls short. *ETP 2017* presents three pathways for energy sector development to 2060. The Reference Technology Scenario (RTS) provides a baseline scenario that takes into account existing energy– and climate–related commitments by countries, including Nationally Determined Contributions pledged under the Paris Agreement. The RTS — reflecting the world’s current ambitions — is not consistent with achieving global climate mitigation objectives, but would still represent a significant shift from a historical “business as usual” approach.

More ambitious decarbonisation requires increased effort and sustained political commitment. The 2°C Scenario (2DS) and the Beyond 2°C Scenario (B2DS) each sets out a rapid decarbonisation pathway in line with international policy goals. The 2DS has been the main climate scenario in the *ETP* series for many years, and it has been widely used by policy makers and business stakeholders to assess their climate strategies. For the first time, the B2DS looks at how far known clean energy technologies could go if pushed to their practical limits, in line with countries’ more ambitious aspirations in the Paris Agreement.

Technologies currently in the innovation pipeline need strong policy support to meet global climate ambitions. In the B2DS, the energy sector reaches carbon neutrality by 2060 to limit future temperature increases to 1.75°C by 2100, the midpoint of the Paris Agreement’s ambition range. This pathway implies that all available policy levers are activated throughout

the outlook period in every sector worldwide. This would require unprecedented policy action as well as effort and engagement from all stakeholders.

Co-ordinated action and a mix of technologies are needed for cost-effective solutions

Actions across all sectors will be needed to leverage the most cost-effective solutions.

Technological opportunities abound in both the supply and demand sides of the energy system. A portfolio of technologies is needed to deliver secure and affordable energy services while also reducing emissions.

End-use electrification is expanding, but decarbonising power systems while increasing electricity in end-uses brings new challenges and opportunities.

Current trends would increase the share of electricity in final energy demand across all end-use sectors from 18% today to 26% in the RTS by 2060, the largest relative increase of all energy carriers.

End-use electrification can also enable a shift from direct reliance on fossil fuels to decarbonised power. In the 2DS and the B2DS, electricity becomes the largest final energy carrier, slightly ahead of oil. The shift is particularly notable in transport, where electricity becomes the primary fuel for land-based transport in the B2DS.

Decarbonised power is a backbone of the clean energy transformation. The global power sector can reach net-zero CO₂ emissions by 2060 under the 2DS scenario. This would require a scaled up deployment of a portfolio of technologies, including 74% of generation from renewables (including 2% of sustainable bioenergy with CCS [BECCS]), 15% from nuclear, 7% from fossil fuelled power plants with CCS, and the remainder from natural gas-fired generation.

More efficient buildings support the whole energy system transformation. Rapid deployment of high-efficiency lighting, cooling, and appliances could save 50 EJ or the equivalent of nearly three-quarters of today's global electricity demand between now and 2030. Those savings would allow greater shifts to electricity without additional burden to the power sector.

Technology and policy can steer transport towards increased sustainability. Electrification emerges as the major low-carbon pathway for the transportation sector. This trend is already partly underway, with the electric car stock projected to increase 28 times by 2030 in the RTS from today's two million vehicles. The 2DS scales up this ambition to 160 million electric cars, while the B2DS would require 200 million electric cars on the road in the same time frame, leading to 90% of all cars on the road being electric by 2060. Fast tracking electro-mobility will require major technological developments and infrastructure investments based on strong policy support. Policies and technologies that reduce the need for individual transportation — such as better urban planning or increased use of collective transportation — can make deployment of new technologies more manageable and significantly reduce the required investment.

Energy-intensive industries are essential actors in any sustainable transformation strategy.

Energy demand in industry is the highest of the end-use sectors, and it is projected to increase by about two-thirds by 2060 in the RTS. Opportunities exist to improve manufacturing efficiency, maximise the use of locally available resources, and optimise materials use. Technologies that are not yet commercial play an important role in industrial process decarbonisation, contributing to an 18% reduction in cumulative direct CO₂ emissions in 2DS and 36% in the B2DS. This demonstrates the need to support innovation in economically strategic sectors such as iron and steel, cement and chemicals.

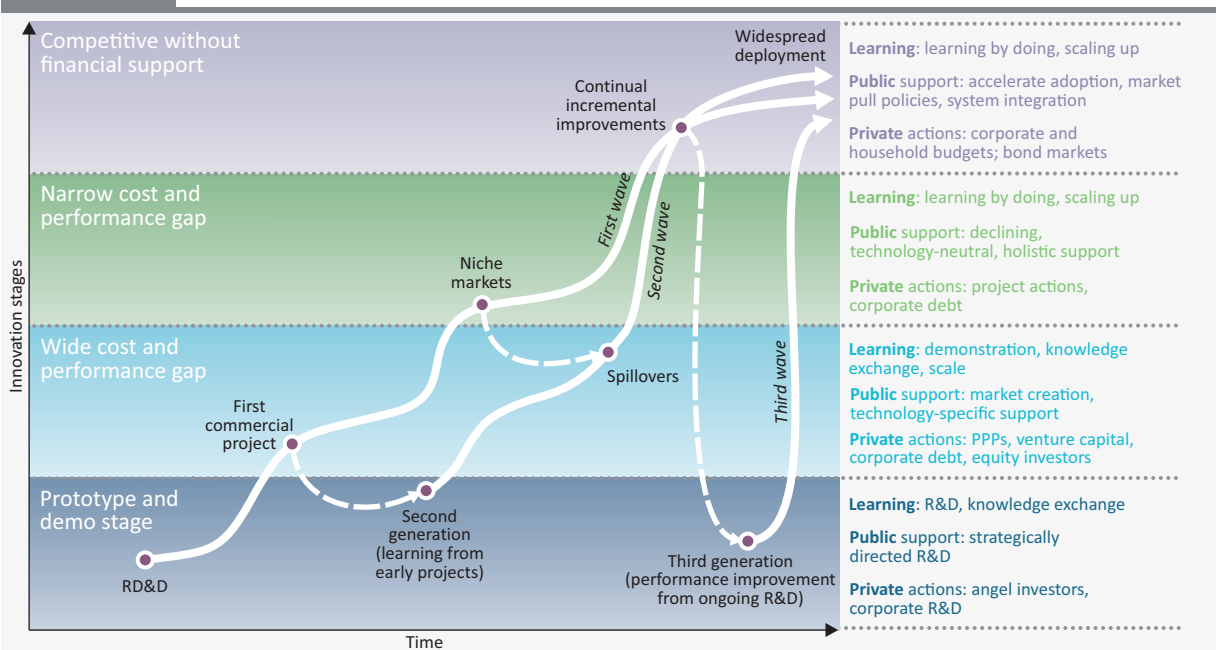
There is a considerable potential for energy savings in heating and cooling that remains largely untapped.

Today, heating and cooling in buildings and industry account for approximately 40% of final energy consumption — which is a larger share than transportation (27%). Additionally, nearly 65% of this demand relies on fossil fuel sources. Energy efficiency and switching to clean final energy carriers (including decarbonised electricity and district energy) could cut fossil fuel consumption for heating and cooling in half by 2060 compared with today.

Negative emissions, notably in power generation and fuel transformation, become critical as low-carbon ambitions rise. In the B2DS, BECCS delivers almost 5 gigatonnes of “negative emissions” in 2060. These negative emissions are key to the energy sector becoming emissions-neutral by 2060. While BECCS technologies face substantial challenges, they compensate for residual emissions elsewhere in the energy system that are even more technically difficult or costly to abate directly. This will require massive technological learning and scale-up in both sustainable bioenergy and CCS, which have been lagging behind so far.

Innovation must be supported at all stages, from early research to full demonstration and deployment. Both incremental and radical innovations are needed to transition to a new energy system. Governments have an important role in ensuring predictable, long-term support in all stages of innovation – i.e. from basic and applied research through to development, demonstration and deployment phases. Allocation of resources to various technologies must consider both short- and long-term opportunities and challenges for innovation, as well as reflect the level of technology maturity (Figure 1.1).

Figure 1.1. Energy technology innovation process



Notes: PPP = public-private partnerships. RD&D = research, development and demonstration. R&D = research and development.

Key point *Energy technologies require support across all innovation stages.*

International co-operation between various levels of governments and with the private sector is essential. Multilateral collaboration can improve the cost-effectiveness of energy technology innovation and build confidence that progress is being achieved at a worldwide scale. Globalisation is sparking more open innovation frameworks that help pool resources to accelerate research and development (R&D), underwrite demonstration, and stimulate faster deployment of proven technologies. Increasing local innovation capacity is essential to the successful deployment of innovative technologies that can help meet local policy and environmental objectives and contribute to global sustainability goals. Existing initiatives, such as the IEA Technology Collaboration Programmes, the Clean Energy Ministerial and Mission Innovation should be properly anchored in all policy decision-making processes.

Key recommendations for policy makers

- **Governments should develop a vision for a sustainable energy future that addresses multiple energy policy challenges and tracks progress towards stated objectives.** Defining pathways and ensuring progress towards a long-term energy transformation that satisfies energy security, climate change and air quality objectives will be critical for the energy sector to respond optimally to multiple challenges and attain policy goals.
- **International collaboration needs to be enhanced to achieve global objectives.** Joint innovation programmes create market opportunities that benefit both manufactures and users of technologies while contributing to the most cost-effective transformation of global energy systems. Collaboration with local stakeholders to build capacity and share best practices can support local action adapted to local circumstances.
- **Policy support for technology should be accelerated at all stages of the innovation cycle.** Public support should be measurable and target all phases of innovation (including research, development, demonstration and deployment) to facilitate both incremental and radical innovation, as well as deployment measures for specific technologies. Initiatives such as the IEA Technology Collaboration Programmes, the Clean Energy Ministerial and Mission Innovation are key platforms to co-ordinate and accelerate global efforts.
- **Policy, finance and market mechanisms must be adapted to support new business models enabled by the changing technology landscape.** Market designs and regulations should leverage the opportunity brought by increased access to energy information to enable new energy transaction models. More efficient institutional dialogue and co-ordination should be established between national, regional and local governments as well as with other energy stakeholders to accelerate the energy sector transformation and to discover novel solutions.
- **Policy makers should develop a better understanding of opportunities and challenges that arise from increasing digitalization in the energy sector.** Digitalization and the energy sector are increasingly converging, bringing new prospects as well as risks. Better data and more rigorous analysis are needed to ensure that digitalization and the changing energy landscape work together in the most sensible and cost-effective manner.

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Setting the scene

Energy systems worldwide are evolving. Improvements in energy technologies are bringing new opportunities and changing the outlook for the energy sector, with resulting implications for energy security and sustainability. In Part 1 of *Energy Technology Perspectives (ETP) 2017* we take a look at global trends in the energy sector and analyse how these trends, as well as possible technological advances, can shape the energy sector and drive its transformations.

The global outlook is presented in detail in Chapter 1. Three scenarios are employed to assess how technologies can make a decisive difference in achieving global climate goals while enhancing economic development and energy security. For the first time, the technology-rich modelling expands the time horizon to 2060 and reveals a possible although very challenging pathway to net-zero carbon emissions across the energy sector. Chapter 2 features the annual IEA *Tracking Clean Energy Progress* report, which evaluates the current progress in clean energy technology development and deployment.

The transformation of the energy sector is already underway; energy-related CO₂ emission levels have been stable for three consecutive years, and the energy intensity of the global economy has been improving at a notable rate. This suggests a decoupling of economic growth, energy demand, and related CO₂ emissions. This chapter provides detailed insights into how clean energy technologies can be harnessed and their deployment accelerated to deliver energy security and environmental sustainability benefits in the decades ahead. It highlights that, despite impressive progress in recent years, the pace of decarbonisation and efficiency improvements needs to be vastly accelerated if countries are to achieve their stated policy goals. With aggressive deployment of a portfolio of available technologies and those in the innovation pipeline supported by unprecedented policy actions, the energy sector could become CO₂ emissions-neutral by 2060 and follow a pathway consistent with limiting future global temperature rises to 1.75°C. Let there be no doubt, however, that achieving this would require an exponential increase in the speed, depth, and scope of the clean energy technology and effective policy response worldwide.

This annual stock-taking exercise notes advances in a number of clean energy technology areas. Yet, only 3 out of the 26 technologies that are monitored are on track to meet ambitions for a low-carbon energy sector transformation.

Chapter 1



The global outlook

Accelerated deployment of clean energy technologies will be critical for a manageable and sustainable transformation of the energy sector. The aggressive and comprehensive uptake of available technologies could accelerate the low-carbon transition beyond an already very challenging 2°C pathway, with potential for energy sector carbon dioxide (CO₂) emissions to be reduced to net zero by 2060. However, this is a formidable challenge that would rely on a fundamental and immediate shift in the current level of energy and climate policy action.

Key findings

- **The global energy system is evolving at a rapid rate.** Energy security, access to modern energy services, air quality, climate change and economic competitiveness are driving substantial shifts in energy sector trends. However, these shifts are not yet occurring at the scale or pace needed to meet future energy sector challenges.
- **Technologies are transforming the global energy landscape, and strong policy signals are important to guide these developments and address emerging challenges.** Technology breakthroughs and innovations have delivered increasingly competitive options for low- or zero-emission power generation, supported greater integration of energy systems, and radically shifted the dynamics of traditional energy markets in the case of unconventional oil and natural gas. Decisive policy action will be required to harness these technology developments to support the accelerated modernisation of the global energy system.
- **Today's energy and climate commitments represent a substantial shift from a historical "business as usual" approach but fall short of achieving long-term goals.** In the Reference Technology Scenario (RTS), which takes into account current and announced policies and commitments, energy sector CO₂ emissions do not peak until around 2050 and are 16% higher in 2060 compared with 2014. The average global temperature would increase to 2.7°C by 2100, at which point it is unlikely to have stabilised and would continue to rise.
- **Rapid and aggressive deployment of a portfolio of clean energy technologies could put the world on a pathway to a carbon-neutral energy system by 2060.** *Energy Technology Perspectives 2017 (ETP 2017)* looks at the potential to shift the energy sector transformation beyond the already challenging 2°C Scenario (2DS). The accelerated "technology push" approach of the Beyond 2°C Scenario (B2DS) avoids the long-term lock-in of emissions-intensive infrastructure with rapid deployment of low-emission technologies and energy efficiency measures. The analysis suggests that limiting global average temperature increases to 1.75°C from pre-industrial levels by 2100, the midpoint of the Paris Agreement's ambition range, is technically feasible. However, the gap between this pathway and current efforts is immense and unlikely to be bridged without an unprecedented acceleration of action on a global level.

- **The shift from a 2°C pathway to a 1.75°C pathway would require faster and deeper CO₂ emissions reductions across both energy supply and demand sectors.** The power sector is virtually decarbonised by 2060 in the 2DS but this decarbonisation would need to be drastically accelerated in the B2DS. In parallel, much deeper emissions reductions across the industry, transport and buildings sectors would be critical, with emissions from these end-use sectors becoming significantly more challenging to mitigate in the 2DS to B2DS shift.
- **An optimised, cost-effective pathway to 2°C or below requires investment in technology innovation across a portfolio of clean energy technologies and energy efficiency.** Energy efficiency contributes 38% and renewable energy sources contribute 30% of the cumulative CO₂ emissions reductions needed to 2060 in the B2DS relative to the RTS. The importance of carbon capture and storage (CCS) technologies increases over time and with more ambitious temperature targets. CCS accounts for 14% of the emissions reductions in the 2DS relative to the RTS and 32% of the additional emissions reductions needed to achieve the B2DS. Technologies modelled in all *ETP* scenarios are currently available or in the innovation pipeline, but policy support for continued technology innovation and improvement is essential to enable this portfolio to displace CO₂-intensive incumbents.
- **Reliance on fossil fuels is halved in absolute terms in the 2DS and falls by almost two-thirds in the B2DS.** By 2060, the primary energy mix changes substantially in both the 2DS and the B2DS. The proportion of primary energy supplied by low-carbon sources rises from 18% today to 65% in the 2DS and to 74% in the B2DS. Coal use experiences the most significant decline, falling by 72% in the 2DS and 78% in the B2DS compared with today's levels. In the 2DS, all coal-fired power generation and more than half of gas-fired generation comes from plants equipped with CCS in 2060.
- **The availability of sustainable bioenergy is a critical factor for achieving climate targets.** The use of biomass more than doubles from today's levels in the 2DS and B2DS, growing to around 145 exajoules (EJ) in 2060 in both scenarios. Recognising its constrained availability and importance across all energy sectors, the development of integrated systems to support highly efficient production and use of biomass will be essential.
- **Widespread electrification supports emissions reductions across end-use sectors in parallel with the rapid decarbonisation of the power sector.** Electrification is a key lever for CO₂ emissions reductions, with the share of electricity in final energy demand across all end-use sectors more than doubling in the 2DS. The CO₂ intensity of electricity generation falls from around 520 grammes of CO₂ per kilowatt hour (gCO₂/kWh) today to close to zero by 2060 in the 2DS. In the B2DS, it moves past zero to -10 gCO₂/kWh, with significant negative emissions stemming from the use of bioenergy equipped with CCS (BECCS).
- **Carbon neutrality in the energy sector is achieved with negative emissions from BECCS.** BECCS delivers almost 5 Gt of negative CO₂ emissions in 2060 in the B2DS, primarily from fuel transformation and the power sector. These negative emissions are key to the energy sector becoming CO₂ emissions-neutral in 2060 as they compensate for residual emissions elsewhere in the energy system that are too difficult or costly to abate directly. However, the capacity to deliver BECCS at this scale and within this timeframe would be dependent upon substantial support for CO₂ transport and storage infrastructure investment.
- **A significantly strengthened and accelerated policy response is required to achieve a low-carbon energy future.** Early action to reduce emissions and avoid lock-in of emissions-intensive infrastructure will be essential if future temperature increases are to be kept to 2°C or below. The scale of effort needed to achieve carbon neutrality by 2060 in the B2DS highlights that there would be almost no room for delay; all available policy levers would need to be pulled, and soon.

Opportunities for policy action

- **Rapid introduction of measures to avoid the lock-in of emissions-intensive infrastructure can help to close the gap between current effort and ambition.** Achieving a 2°C target would require cumulative energy sector CO₂ emissions to be around 40% lower (approximately 760 Gt) in the period to 2060 compared with the RTS, which already accounts for current efforts and commitments. Moving beyond a 2°C target requires even deeper greenhouse gas (GHG) emissions reductions, but with most of the low-hanging fruit having already been harvested, these emissions are considerably more challenging to mitigate. Rapid and comprehensive implementation of policy measures to avoid the lock-in of emissions will be a key to achieving climate ambitions while minimising the cost of the energy sector transformation.
- **Improved alignment of near-term action with longer-term technology needs and policy objectives will support a managed and sustainable transformation of the energy sector.** Long-term policy planning is essential to ensure that the technologies and institutions needed to deliver deep emissions reductions in the future are available. The 2030 timeframe for action under Nationally Determined Contributions (NDCs) should be aligned with mid-century climate and energy strategies. The United Nations Framework Convention on Climate Change (UNFCCC) facilitative dialogue in 2018 could also provide a critical near-term signal to boost ambition before the formal start of the Agreement in 2020.
- **Increased investment in energy technology innovation is critical for a 2°C or below pathway.** Enhanced policy support for technology innovation is essential in the *ETP* scenarios. Intervention at all stages of the innovation life cycle will be needed, from early-stage research, development and demonstration (RD&D) through to pre-commercial deployment. The period to 2030 is a critical window for promoting RD&D that can support the innovations and improvements in technology performance needed to underpin the deep GHG emissions reductions targeted in the post-2030 period. Initiatives such as Mission Innovation, the Clean Energy Ministerial and the IEA Technology Collaboration Programmes should be harnessed as key platforms to co-ordinate and accelerate global efforts on nascent technology development.

Introduction

The global energy system is going through a period of historic change. Concerns about energy security, energy poverty, air quality, climate change and economic competitiveness are all drivers of a substantial shift in energy sector trends. In 2016, renewables supplied half of global electricity demand growth and overtook coal as the largest source of power-generating capacity globally, while nuclear net capacity reached its highest level since 1993 (IEA, 2016a). Global energy intensity also fell by 2.1% in 2016 (IEA, 2016b), and efforts to reform fossil fuel subsidies have been gaining ground (IEA, 2016c). Growing attention to energy-related air pollution linked to 6.5 million premature deaths per year, together with increased investment in low-carbon technologies, has put aggregate global emissions of the main pollutants on a slowing trend (IEA, 2016d).

This change is influencing the private sector. Businesses are increasingly incorporating environmental risks in their plans and responding to policy measures, such as energy performance standards and carbon prices. This has led to an increase in the share of energy investments motivated by regulatory and policy measures, resulting in observable shifts in energy system investment towards renewables, electricity networks and energy efficiency (IEA, 2016e).

Energy technology innovation has played, and will continue to play, a key role in driving many of these trends. Cost reductions and improvements in renewables-based power generation have seen their competitiveness increase compared to traditional fossil fuel

sources, and this is underpinning new business models and regulatory responses. Similarly, developments in unconventional oil and gas technologies and processes have transformed global market dynamics, recently offsetting the expected price impact of agreements by major producing countries to limit conventional oil output.

Technology innovation has also been opening new doors on the demand side, with effects that permeate the entire energy system. For instance, almost all major carmakers now offer electric vehicles (EVs), reflecting advances in increased energy density of batteries, declining battery costs and economies of scale in battery manufacturing. Support for the development and deployment of technologies such as light-emitting diode (LED) lighting and highly efficient appliances are driving enhanced performance and deep cost reductions. Digitalization and information and communication technology (ICT) are also increasingly facilitating the development of smarter and more integrated energy systems worldwide.

For the last ten years, the *ETP* series has focused on the role of energy technologies in achieving multiple societal objectives, including delivering cost-effective mitigation options for meeting global climate ambitions. Recent *ETP* editions have explored the role of technologies in delivering integrated electricity systems (IEA, 2014), achieving climate ambitions through innovation (IEA, 2015a), and transitioning to sustainable urban energy systems (IEA, 2016f). These publications have enabled a deeper understanding of energy technology trends and future technology pathways, while also providing actionable policy recommendations to support modern, secure and low-emissions energy systems.

ETP 2017 expands this focus to also consider the potential policy and technology implications for the energy sector of more ambitious climate goals. Implementing the Paris Agreement's ambition of "well below 2°C" requires a fundamental and accelerated shift in how energy is produced and used, impacting all parts of the global energy system. Technology innovation will be critical to ensuring that this shift is consistent with sustained economic and social prosperity for future generations as well as providing modern energy to the 1.2 billion people who lack access today.

Energy system transition scenarios

In *ETP 2017*, three scenarios are presented that identify different energy technology and policy pathways for a low-carbon energy system in the period to 2060 (Box 1.1).

The RTS provides a baseline scenario that takes into account energy- and climate-related commitments by countries, including NDCs pledged under the Paris Agreement. Under this scenario, global final energy demand continues to grow by 50% in the period to 2060, with cumulative energy sector CO₂ emissions increasing by over 1 750 Gt. The RTS is not consistent with achieving global climate objectives, but would still represent a significant shift from a historical "business as usual" approach.

The 2DS has been the main climate scenario in the *ETP* series for many years, reflecting the 2009 Copenhagen Accord's acceptance of "the scientific view that the increase in global temperature should be below 2°C". The 2DS is consistent with a 50% chance of limiting future global average temperature increases to 2°C by 2100 and represents an inherently challenging and ambitious transformation of the energy sector.

In the 2DS, energy sector CO₂ emissions fall to around one-quarter of today's levels in 2060 while still supporting growing demand for energy. Reliance on fossil fuels declines substantially, from around 82% of primary energy demand in 2014 to 35% in 2060. The power sector approaches carbon neutrality at the end of the scenario period, with the share of electricity generation from low-carbon technologies rising to 96% by 2060. Around 1 500 gigawatts (GW) of global coal-fired capacity needs to be retired before the end of its technical lifetime, while the remaining coal-fired generation fleet must be fitted or retrofitted with CCS technologies. Achieving an energy sector transformation at this scale requires a significantly strengthened policy response and targeted support for technology research, development, demonstration and deployment.

Box

1.1. *ETP 2017* scenarios

The *ETP* model comprises four interlinked technology-rich models that cover the energy supply, buildings, industry and transport sectors. Depending on the sector, the modelling framework includes 28 to 39 world regions or countries. *ETP 2017* covers the period to 2060, expanding the analysis beyond the 2050 timeframe of previous *ETP* publications.

The *ETP* scenarios are constructed using a combination of forecasting to reflect known trends in the near term and “backcasting” to develop plausible pathways to a desired long-term outcome. The scenarios should not be considered as predictions, but as analyses of the impacts and trade-offs of different technology choices and policy targets, thereby providing a quantitative approach to support decision making in the energy sector. The *ETP* scenarios are complementary to those explored in the International Energy Agency (IEA) *World Energy Outlook (WEO)*.*

The **Reference Technology Scenario (RTS)** takes into account today’s commitments by countries to limit emissions and improve energy efficiency, including the NDCs pledged under the Paris Agreement. By factoring in these commitments and recent trends, the RTS already represents a major shift from a historical “business as usual” approach with no meaningful climate policy response. The RTS requires significant changes in policy and technologies in the period to 2060 as well as substantial additional cuts in emissions thereafter. These efforts would result in an average temperature increase of 2.7°C by 2100, at which point temperatures are unlikely to have stabilised and would continue to rise.

The **2°C Scenario (2DS)** lays out an energy system pathway and a CO₂ emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. Annual energy sector CO₂ emissions are reduced by 70% from today’s levels by 2060, with cumulative emissions of around 1 170 gigatonnes of CO₂ (GtCO₂) between 2015 and 2100 (including industrial process emissions). To stay within this range, CO₂ emissions from fuel combustion and industrial processes must continue their decline after 2060, and carbon neutrality in the energy system must be reached by 2100. The 2DS continues to be the *ETP*’s central climate mitigation scenario, recognising that it represents a highly ambitious and challenging transformation of the global energy sector that relies on a substantially strengthened response compared with today’s efforts.

The **Beyond 2°C Scenario (B2DS)** explores how far deployment of technologies that are already available or in the innovation pipeline could take us beyond the 2DS. Technology improvements and deployment are pushed to their maximum practicable limits across the energy system in order to achieve net-zero emissions by 2060 and to stay net zero or below thereafter, without requiring unforeseen technology breakthroughs or limiting economic growth. This “technology push” approach results in cumulative emissions from the energy sector of around 750 GtCO₂ between 2015 and 2100, which is consistent with a 50% chance of limiting average future temperature increases to 1.75°C. Energy sector emissions reach net zero around 2060, supported by negative emissions through deployment of bioenergy with CCS. The B2DS falls within the Paris Agreement range of ambition, but does not purport to define a specific temperature target for “well below 2°C”.

* The *ETP* RTS is broadly aligned with the *WEO* New Policies Scenario (NPS) and the *ETP* 2DS with the *WEO* 450 Scenario.

Note: an extended summary can be found in Annex A, including details of modelling and scenario changes from *ETP 2016*. Full descriptions of the scenarios and extensive additional global and regional scenario results can be found online at www.iea.org/etp.

For the first time, *ETP 2017* looks beyond the 2°C pathway to explore the feasibility of accelerating clean energy technology deployment in pursuit of more ambitious climate goals. The B2DS assesses how far today's clean energy technologies could take the sector towards a well-below 2°C objective. The analysis was informed by a high-level workshop with participation from climate scientists and technology experts at the IEA in 2016.¹ In the B2DS, the deployment of clean energy technologies, inclusive of those currently available and in the innovation pipeline, is pushed to its maximum practical limits across all key sectors.² The B2DS approach has the potential to achieve carbon neutrality of the energy system by 2060 and limit temperature increases to 1.75°C by 2100.

While technically feasible, the B2DS describes a future that is a long way from today's energy reality. The NDCs pledged in the lead-up to the UNFCCC's 21st Conference of the Parties (COP21) would lead to an average temperature increase of around 2.7°C by 2100, but with temperatures likely to continue rising beyond this point (IEA, 2015b). To close the gap between where current efforts are heading and a 1.75°C pathway, the B2DS requires cumulative CO₂ emissions reductions of around 1 000 Gt across the energy sector in the period to 2060 relative to the RTS. This is equivalent to more than 30 years of the current level of annual energy-related emissions,³ or around half of total anthropogenic CO₂ emissions released since the Industrial Revolution. The B2DS highlights that an unprecedented increase in near-term action and ambition are required if the Paris goals are to be more than aspirational.

The outcome of the B2DS technology push approach is to limit cumulative energy sector CO₂ emissions to around 750 Gt in the period 2015 to 2060 and to achieve carbon neutrality of the energy system by 2060.⁴ This is consistent with a 50% chance of limiting future temperature increases to 1.75°C, or the midpoint of the temperature range implicit in the Paris Agreement. In comparison, the 2DS has cumulative emissions of 1 000 GtCO₂ for the period 2015 to 2060 and the RTS around 1 800 GtCO₂. Net-zero emissions are reached around 2100 in the 2DS (Figure 1.1).

The 2DS and B2DS both follow a rapid decarbonisation pathway that does not result in an "overshoot" of the energy sector carbon budget in the near term that must be counterbalanced with significant deployment of negative emissions technologies in the latter part of the century. This is not to suggest that negative emissions do not have an important role. In fact, in the B2DS, deployment of BECCS is central to ensuring that the energy sector stays within its carbon budget and reaches net-zero emissions in 2060. The negative emissions from BECCS compensate for the remaining emissions in industry and transport that are very difficult technically or very costly to abate. Looking beyond 2060, the B2DS anticipates that prevailing trends across the buildings, industry, transport and power sectors would be sufficient to maintain energy sector emissions at or below net zero through to 2100.

In terms of the technology mix, the *ETP* scenarios do not depend on the appearance of unforeseen breakthroughs in the 2060 time horizon. All technology options introduced are already commercially available or in the innovation pipeline; that is, at a stage of development that makes commercial-scale deployment possible within the scenario period. Increased support for technology innovation is fundamental to advance the technologies currently at laboratory scale to the demonstration phase, to boost technology performance, to reduce technology costs, and to facilitate market access and systems integration.

1. Details on this workshop are available at www.iea.org/workshops/re-defining-climate-ambition-to-well-below-2c-.html.

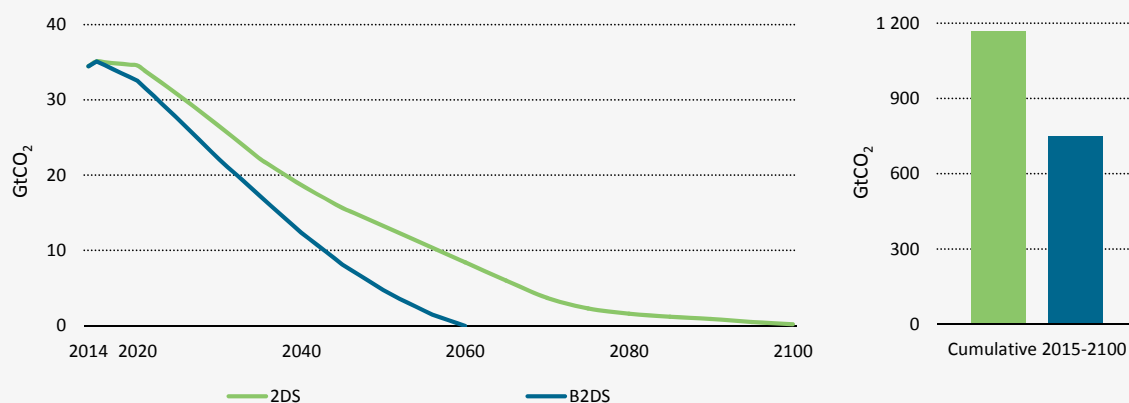
2. Technologies available and in the innovation pipeline include those that are commercially available, or at the stage of development that makes commercial-scale deployment possible within the scenario period. A detailed description of these technologies is provided in Annex A.

3. Energy-related CO₂ emissions, excluding industrial process emissions, were 32.1 Gt in 2016 (IEA, 2017).

4. Unless otherwise specified, references to energy sector CO₂ emissions in the *ETP 2017* include industrial process emissions.

Figure

1.1. Cumulative energy sector CO₂ emissions budgets in the 2DS and B2DS



Key point

The B2DS requires a 36% reduction in cumulative CO₂ emissions compared with the 2DS by 2100, and net-zero CO₂ emissions by 2060.

Another central feature of the *ETP* scenarios is the inclusion of policies and measures aimed at changing consumer behaviour to further enable the clean energy technology transition. For example, in the transport sector, “avoid and shift” policies, such as smart urban planning, investment in public transit, shared transportation and road pricing policies, can reduce demand for personal mobility and shift remaining demand to more efficient transport modes. Increased pre- and post-consumer recycling can help decarbonise the industry sector by shifting materials production to more energy-efficient process pathways. In the buildings sector, shifting purchases to best available efficient equipment and appliances through labelling and energy performance standards can significantly and rapidly reduce the sector’s energy use. Some of these strategies play a particularly important role in the B2DS, which recognises that the envisioned technology push must also be enabled through important, policy-driven changes in consumption of major energy services across the end-use sectors.

Uncertainty in targeting well below 2°C

The Paris Agreement sets a globally agreed target of limiting future temperature increases to “well below 2°C” above pre-industrial levels and “pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels”. Consistent with this objective, countries aim to peak global emissions “as soon as possible”, with rapid reductions thereafter to “achieve a balance between anthropogenic emissions by sources and removals by sinks” in the second half of this century.

It is notable that the Agreement did not define a specific temperature target nor a particular date (or decade) for when net-zero emissions would need to be achieved. There is no commonly agreed definition of what would constitute a well-below 2°C outcome. While discussions on this continue, the target has been interpreted to fall within the range of a reasonable chance of keeping global average temperatures below 2°C and a reasonable chance of achieving a 1.5°C target. For example, the IEA *WEO 2016* considered a 66% probability of achieving a 2°C target, which is equivalent to a 50% probability of 1.84°C (IEA, 2016c).

The 1.5°C to 2°C temperature range is immense in terms of the implications for the scale and pace of the transformation of the energy sector and the remaining CO₂ emissions

budget.⁵ For a 50% chance of achieving a 1.5°C target, the Intergovernmental Panel on Climate Change (IPCC) has indicated that a total CO₂ budget of 400–450 Gt remains (IPCC, 2014). Recent studies with higher probabilities of remaining below or at 1.5°C have suggested that the budget could actually be as low as 50–250 Gt (Rogelj et al., 2015). Within this 1.5°C to 2°C temperature range, attaching different probabilities to achieving specific temperature targets also has a significant impact on remaining CO₂ budgets (Box 1.2).

Understanding the implications of the Paris Agreement’s well-below 2°C target in practice will therefore involve analysis of a range of possible scenarios. It is not clear if the Parties to the Agreement will seek to further define “well below 2°C”, and the IEA is not attempting to define or propose a particular temperature target. Rather, the *ETP 2017* analysis aims to contribute to broader understanding of pathways that could be consistent with these climate objectives, and particularly the implications for the transformation of the energy sector.

Box

1.2. Calculating the energy sector CO₂ emissions budget

The energy sector accounts for two-thirds of global GHG emissions and accordingly will need to play a commensurately large role in mitigation efforts. For the purposes of the *ETP* scenarios, the energy sector carbon budget is calculated from an estimate of the total CO₂ emissions budget for a given temperature target over a particular timeframe, less the anticipated contribution from non-energy sector CO₂ emissions.

Total CO₂ emissions budget

According to climate studies, the average global surface temperature rise is almost linearly proportional to cumulative emissions of CO₂ (IPCC, 2014). This relationship can be used to determine the remaining CO₂ budget that can be emitted over a given timeframe, in order to achieve a particular temperature target with a given probability. Alternatively, it can be used to estimate possible future temperature rises for an anticipated emissions trajectory.

This CO₂ budget is very sensitive to apparently small changes in the probability attached to a given temperature target. For example, moving from a 50% chance of limiting temperature increases to 2°C by 2100 to a 66% chance reduces the total CO₂ budget by around 250 Gt, or approximately 25%. Moving to an 80% probability reduces the CO₂ budget by 650 Gt, or more than 60% (IEA, 2016c).

The total CO₂ budget is derived with consideration of the expected contribution of non-CO₂ emissions. These emissions, such as methane, nitrous oxide and aerosols, predominately originate from non-energy sectors, in particular agriculture and waste. Variations in the projections from these sectors affect the necessary rates of transformation of the energy sector. The IPCC *Fifth Assessment Report (AR5)* scenario database contains projections of non-CO₂ emissions over the 21st century across a number of scenarios. Using these IPCC projections of non-CO₂ emissions to 2100, it is possible to determine the residual CO₂-only budgets for particular temperature targets.

Non-energy sector CO₂ emissions

Non-energy sector emissions predominately arise through land use, land-use change and forestry (LULUCF) and were around 3 GtCO₂ in 2015. Future projections of LULUCF emissions are inherently uncertain. The estimate used in *ETP 2017* is based on data from the United Nations Food and Agriculture Organisation, national analysis and NDC pledges. This estimate assumes significant effort to reduce CO₂ emissions across this sector, consistent with the IPCC long-term scenario analysis. LULUCF emissions are close to zero by around 2045 and turn negative thereafter. The net emissions from LULUCF between 2015 and 2100 are estimated at –30 GtCO₂.

5. The cumulative amount of CO₂ emitted over a given timeframe.

Energy sector CO₂ emissions budget

The energy sector CO₂ budget in *ETP 2017* includes CO₂ emissions from industrial processes as well as fuel combustion. In 2014, industrial process emissions were around 2 GtCO₂ (70% of which were from cement production) while emissions from fuel combustion were around 32.2 GtCO₂. The assumptions used to calculate the carbon budget for the energy sector (including process emissions) for the two decarbonisation scenarios are shown in Table 1.1.

1.1. Table: CO₂ budget assumptions in the 2DS and B2DS (GtCO₂)

Scenario	Total CO ₂ budget 2015–2100	LULUCF 2015–2100	Energy sector CO ₂ budget (2015–2100)*	Energy sector CO ₂ budget (2015–60)*
2DS	1 140	–30	1 170	1 000
B2DS	720	–30	750	750

* Includes emissions from industrial processes and fuel combustion.

Global modelling results

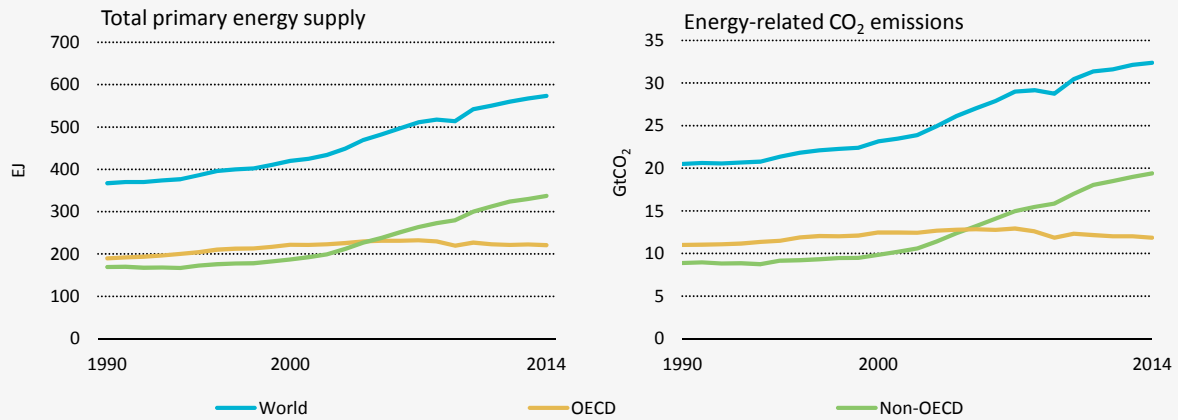
The *ETP 2017* scenarios present different pathways for the future transformation of the global energy sector. They differ in their level of ambition towards stated climate targets, but all represent a significant departure from a historical business-as-usual approach.

Central to all *ETP 2017* scenarios is the need to accelerate the decoupling of CO₂ emissions from economic growth (measured by gross domestic product [GDP]). This involves two related objectives: first, improve energy efficiency measures to weaken the historical relationship between economic growth and primary energy demand; and second, reduce the CO₂ intensity of primary energy supply to extricate its link with CO₂ emissions (Figure 1.2). The objectives are particularly important in non-member economies of the Organisation for Economic Co-operation and Development (OECD), where rapid growth in population and economic development is driving increases in primary energy demand and CO₂ emissions. In this context, improved energy efficiency can mean the ability to provide greatly improved access to energy services.

In the 2DS, growth in total primary energy demand (TPED) must be decoupled from economic growth over the period to 2060, while the energy intensity of GDP falls by almost 70% compared with today (Figure 1.3). To facilitate the decarbonisation of primary energy demand, the CO₂ intensity of the primary energy mix in the 2DS must be reduced by 78% by 2060. To meet the increased climate ambition of the B2DS, the primary energy mix must be fully decarbonised by 2060.

There are promising signs that the once seemingly intractable link between energy-sector CO₂ emissions and global economic growth is weakening. Global energy-related CO₂ emissions were flat for a third straight year in 2016, despite continued global economic growth. This was primarily the result of growing renewable power generation, switches from coal to natural gas, improvements in energy efficiency, and structural changes in the global economy (IEA, 2017).

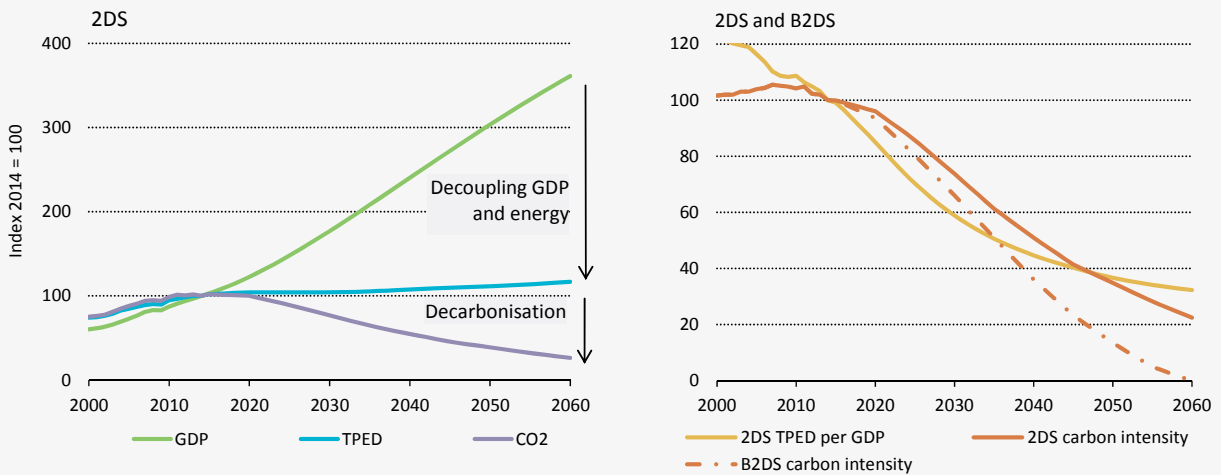
Figure 1.2. Total primary energy supply and CO₂ emissions



Source: IEA (2016h), *World Energy Statistics and Balances*; IEA (2016i), *CO₂ Emissions from Fuel Combustion*.

Key point *Recent global trends in primary energy supply and energy-related CO₂ emissions have been driven by growth in non-OECD economies.*

Figure 1.3. Global GDP, primary energy demand and CO₂ emissions



Note: Carbon intensities expressed as CO₂ emissions per unit of GDP.

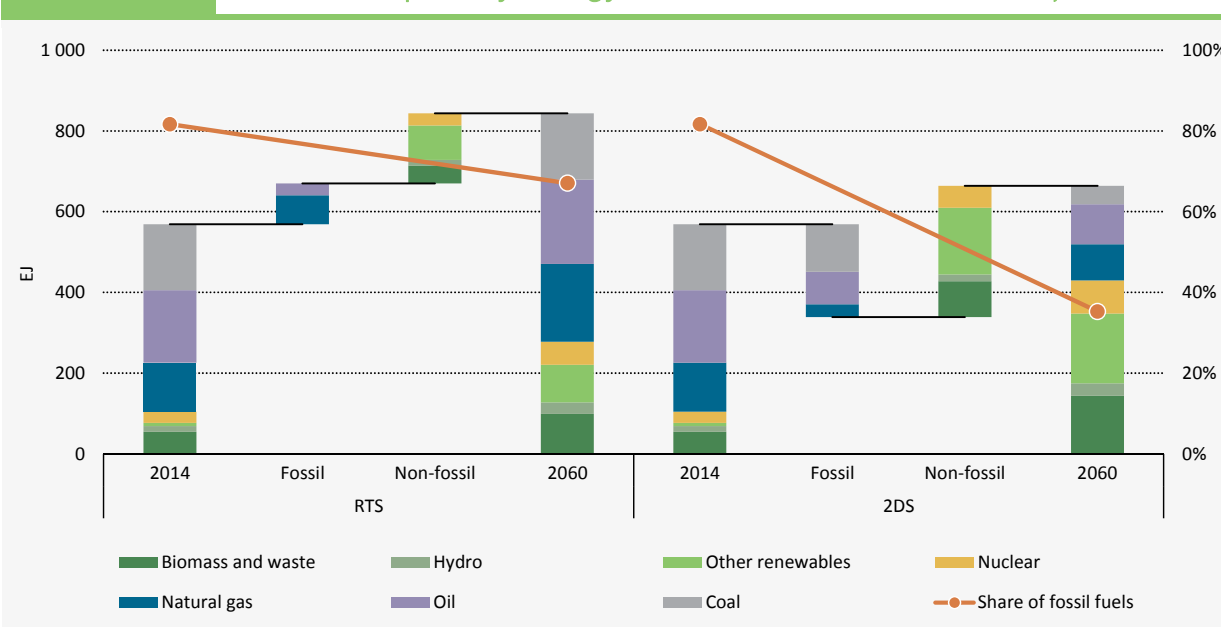
Source: IEA (2016h), *World Energy Statistics and Balances*; IEA (2016i), *CO₂ Emissions from Fuel Combustion*; IEA (2016c), *World Energy Outlook*; IMF (2016), *World Economic Outlook*.

Key point *Achieving the 2DS will require a significant decoupling between energy use and economic growth, with decarbonisation of the energy mix occurring in parallel.*

Primary energy demand

In 2014, global primary energy demand was 570 EJ, up by 22% since 2004 or an average of 2% a year over the past decade.⁶ The mix was oil (32%), coal (29%), natural gas (21%), biomass and waste (10%), nuclear (5%) and other renewables (3%)⁷ (Figure 1.4).⁸ While the share of fossil fuels (82%) has remained stable since 2004, absolute levels of primary fossil energy demand rose by about 100 EJ, or 25%, between 2004 and 2014.

Figure 1.4. Global primary energy demand in the RTS and 2DS, 2014–60



Key point *More than half of primary energy demand is from renewables in the 2DS.*

In the RTS, primary energy demand increases by 48% from 2014 levels to reach 843 EJ in 2060 at an average annual growth rate of 0.9%. Fossil fuels continue to dominate primary energy supply, although the share of coal, oil and gas falls from 82% in 2014 to 67% in 2060. This represents an absolute increase in fossil fuel consumption of around 100 EJ, or 22%, compared with 2014 levels. All of the growth in fossil fuel demand is for oil and natural gas, while coal use remains steady. The remaining share of the primary energy mix in 2060 is biomass and waste (12%), other renewables (11%), nuclear (7%) and hydro (3%).

In the 2DS, growth in primary energy demand is limited to 17% (about 95 EJ) in 2060 compared with 2014 levels and is around 20% (180 EJ) lower than in the RTS. The average annual growth in primary energy demand between 2014 and 2060 is 0.3%. The role of fossil fuels declines substantially to just 35% of the mix in 2060, with an absolute decline in consumption of around 230 EJ, or 50% lower than the 2014 consumption level. Coal use falls by 72%, oil by 45% and natural gas by 26% compared with 2014. Renewables overtake fossil fuels to dominate the primary energy mix, with the share of renewables reaching 52% (348 EJ) in 2060. This is an addition of 271 EJ between 2014 and 2060, an

6 Unless otherwise specified, all annual growth rate values in this section are expressed as compound average annual growth rates (CAAGRs).

7. Other renewables includes geothermal, wind, solar and tidal energy resources.

8. If not stated otherwise, TPED includes bioenergy conversion losses for liquid and gaseous biofuel production for future years, though these losses are not included in primary energy numbers from the IEA *World Energy Statistics and Balances* for historic years. The ETP results tables (www.iea.org/etp2017) show both primary bioenergy demand indicators, including and excluding biofuel conversion losses, for future years.

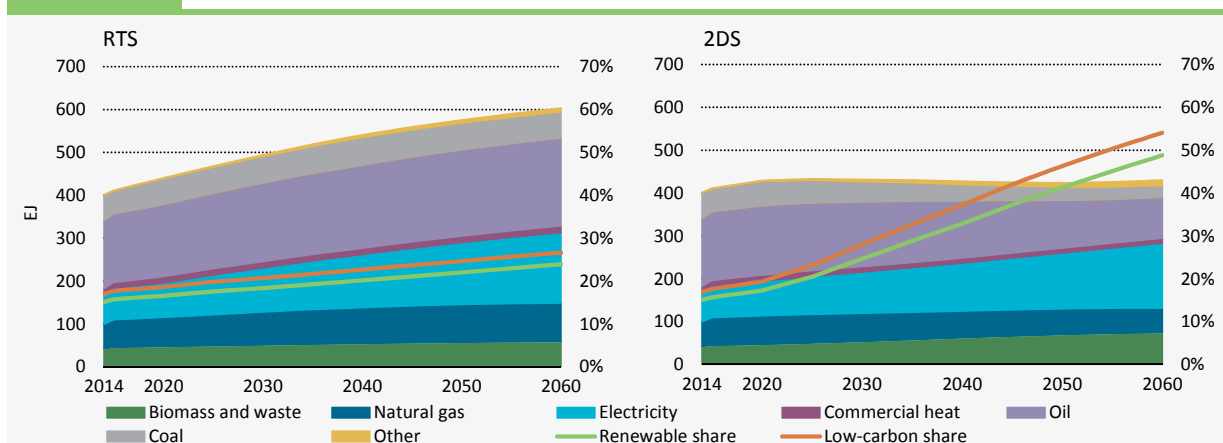
increase that is equivalent to half of today's total primary energy demand. The share of biomass and waste doubles by 2060 to reach 22% (144 EJ) of the energy mix, representing around a 160% increase in biomass and waste consumption from current levels. The remainder of the primary energy mix in 2060 in the 2DS is nuclear (12%) and hydro (5%).

Final energy demand

Final energy demand is the total energy consumed by the main end-use sectors (transport, buildings, industry and agriculture) (Figure 1.5). In 2014, final energy demand totalled 402 EJ, with oil accounting for about 39%, electricity 18%, coal 15%, natural gas 14%, biomass and waste 10%, and commercial heat 3%. The share of renewables was 15% and low-carbon energy 17%.⁹

Figure

1.5. Final energy demand in the RTS and 2DS, 2014–60



Key point

Growth in final energy demand in the 2DS is substantially lower than the RTS, and more than half of it is met by low-carbon sources by 2060 in the 2DS.

In the RTS, final energy demand reaches 604 EJ in 2060, an increase of almost 50% from 2014 levels. The average annual growth in the period 2014 to 2025 is 0.9%. The share of low-carbon energy rises from 17% in 2014 to 27% in 2060. Oil remains the dominant fuel in 2060 with a 34% share, with absolute oil consumption increasing by 30% compared with 2014 levels. Electricity shows the largest relative increase, with its share growing from 18% to 27%, representing a doubling of absolute consumption with an additional 94 EJ between 2014 and 2060. The share of natural gas remains stable at around 15%, while coal falls to 10% in 2060.

In the 2DS, final energy demand experiences only limited growth, due to strong energy efficiency measures, with 2060 levels only 7% higher than in 2014 (around 29 EJ). The average annual growth in the decade from 2014 to 2060 is 0.1%. Final energy use peaks in the 2020s, and the composition of final energy use changes significantly compared with the RTS, with low-carbon energy accounting for more than half of the mix. Oil consumption declines to a 22% share, coal falls to 6% and the share of natural gas declines only very slightly to 13%.

9. Low-carbon energy sources include electricity and heat generated from renewables and nuclear.

CO₂ emissions

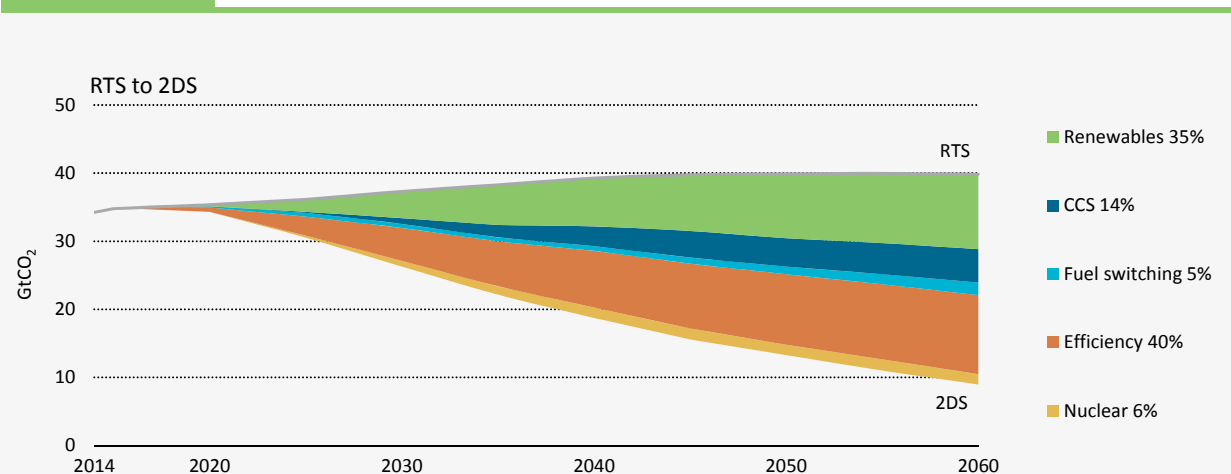
Global energy-related CO₂ emissions were around 32.2 Gt in the scenario base year of 2014, with total energy sector CO₂ emissions rising to around 34.3 Gt when industrial process emissions are also included. While there are signs that energy-related emissions have been flat since 2014, global energy sector emissions still have risen by almost 25% over the past decade. In 2014, energy sector CO₂ emissions were mainly from four sectors: power (40%), industry (24%), transport (22%) and buildings (8%).

A substantial effort is required to permanently arrest historical growth in CO₂ emissions and ensure that recent signs of stabilisation become the basis from which emissions begin to decline. In the RTS, the growth in CO₂ emissions continues to slow through 2060, when emissions would be 16% higher than 2014 levels, reaching almost 40 GtCO₂. In this scenario, energy sector CO₂ emissions do not peak until around 2050.

In contrast, the 2DS requires CO₂ emissions to peak before 2020 and to fall to around one-quarter of 2014 levels by 2060. The cumulative carbon budget over the period to 2060 is about 40% lower in the 2DS compared with the RTS, requiring abatement of an additional 760 GtCO₂ over this period. A portfolio of technologies is needed to deliver these cumulative emissions reductions, with the major contributors being efficiency and renewables, which account for a 40% and 35% share, respectively. CCS and innovative processes have their contribution ramp up towards the later part of the outlook period, cumulatively contributing 14%, while fuel switching contributes 5% and nuclear 6% (Figure 1.6).

Figure

1.6. Global CO₂ emissions reductions by technology area: RTS to 2DS

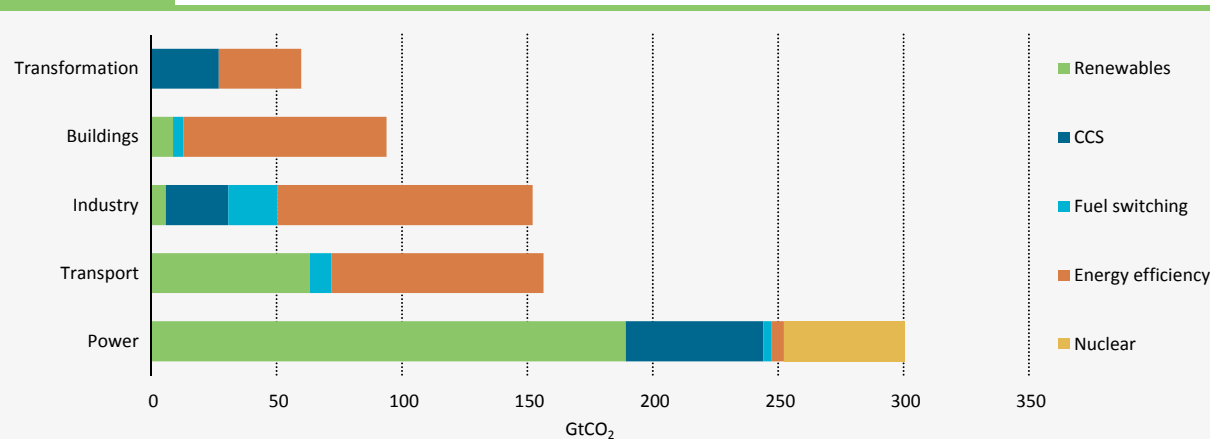


Key point

Achieving the 2DS requires contributions from a diversified technology mix across all sectors.

All end-use and supply sectors contribute to these emissions reductions. Energy-efficient technologies dominate the cumulative CO₂ emissions reductions achieved in the industry, buildings and transport sectors, reinforcing the importance of efficiency as the “first fuel” for achieving the 2DS vision. CCS plays an important role in reducing CO₂ emissions in the industry, transformation and power sectors (Figure 1.7). Renewable energy technologies are deployed most aggressively in the power sector, driven by the need for rapid decarbonisation in the 2DS, with further applications in the transport (biofuels), buildings (renewables-based heating) and industry (renewable feedstocks) sectors.

Figure

1.7. Cumulative CO₂ emissions reductions by sector and technology: RTS to 2DS

Note: CO₂ emissions include both energy-related CO₂ emissions and emissions from industrial processes.

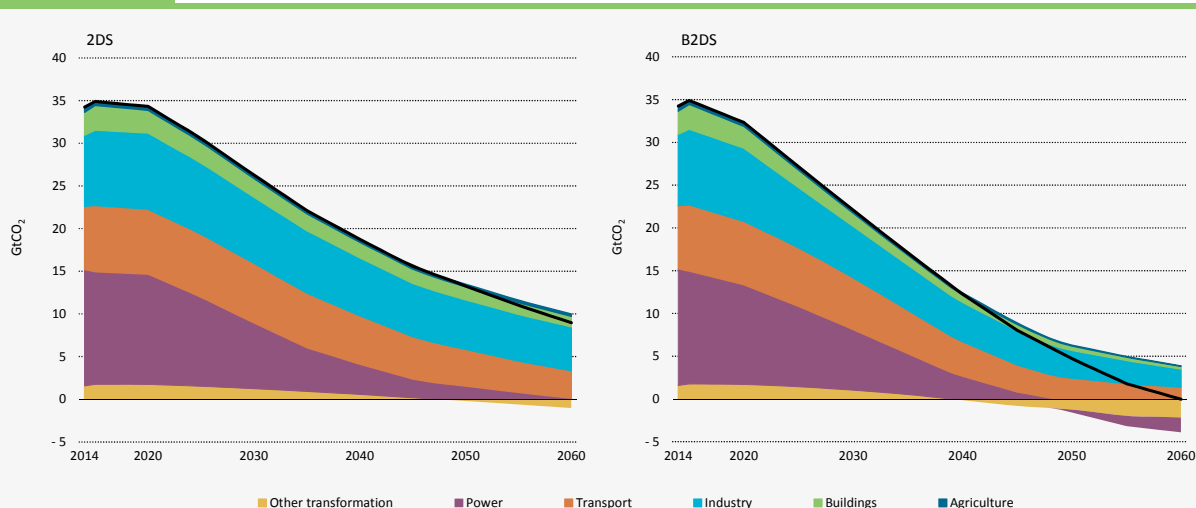
Key point

Actions need to be pursued by stakeholders in all sectors to achieve an optimal technology transition strategy.

Pushing the limits: The B2DS

Given that the 2DS represents a significant emissions reduction effort from current levels, pursuing even deeper reductions will be very challenging. In the B2DS, a renewed emphasis on end-use sectors would be required: by 2060, the power sector is already virtually decarbonised in the 2DS, while the industry and transport sectors become the largest source of CO₂ emissions at the end of the 2DS scenario period, accounting for 57% (industry) and 36% (transport) of net emissions. Over the period to 2060, the greatest cumulative emissions in the 2DS are from industry (32%), power (27%) and transport (27%) (Figure 1.8).

Figure

1.8. Remaining CO₂ emissions in the 2DS and B2DS

Note: Solid lines represent net energy sector CO₂ emissions for each scenario.

Key point

The remaining CO₂ emissions from industry and transport in the 2DS must be targeted in the B2DS, with negative emissions necessary to achieve net-zero energy sector emissions by 2060.

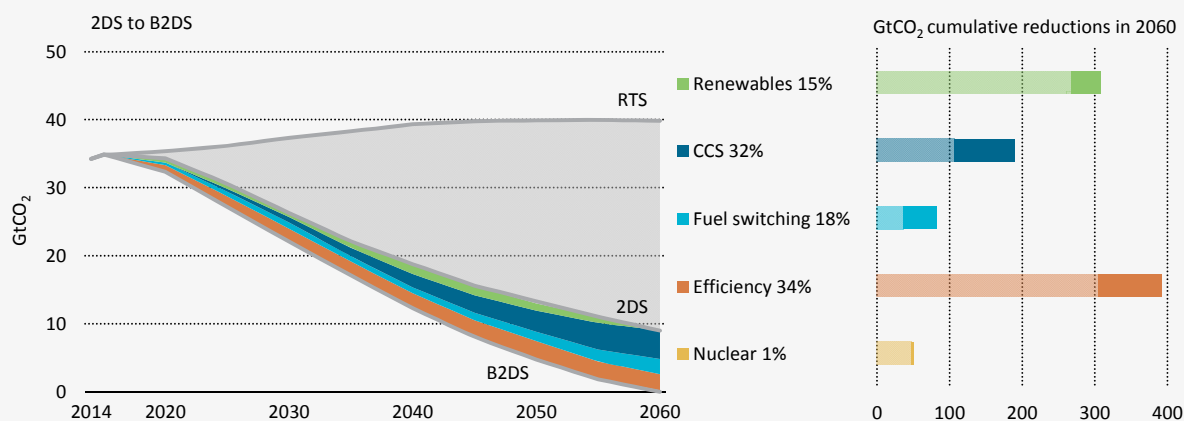
These remaining emissions represent an increasingly difficult and complex abatement task for the B2DS pathway. The relative contribution of technologies needed to address these emissions and support the shift to the B2DS changes compared to the shift from RTS to 2DS, including a greater reliance on BECCS as a negative emissions technology in the post-2040 period.

In the B2DS, CO₂ emissions peak immediately and rapidly decline in order to reach net-zero emissions in 2060. Electrification plays a major role in reducing emissions in the buildings and transport sectors, with the power sector absorbing this increased demand in parallel with a much faster decarbonisation compared with the 2DS pathway. The power and fuel transformation sectors become a source of negative emissions, with this being critical in balancing remaining emissions in the end-use sectors.

The importance of these negative emissions is reflected in CCS technologies making one of the largest contributions to emissions reductions in the shift from the 2DS to B2DS, at 32%. CCS is also widely deployed in industry in the B2DS to achieve deeper CO₂ emissions reductions. Energy efficiency again plays a leading role in the 2DS to B2DS shift at 34%, while fuel switching (18%), renewables (15%) and nuclear (1%) provide the remainder of the emissions reductions in the push beyond a 2°C pathway (Figure 1.9).

Figure

1.9. Global CO₂ emissions reductions by technology area and scenario



Note: Light areas in the right graph represent cumulative emissions reductions in the 2DS, while dark areas represent additional cumulative emissions reductions needed to achieve the B2DS.

Key point

Pushing energy technology beyond the 2DS could deliver net-zero CO₂ emissions by 2060.

Of the end-use sectors, the industry sector leads the way in reducing emissions in the shift from the 2DS to the B2DS, providing around 90 GtCO₂ of additional cumulative abatement, or more than one-third of the additional emissions reductions. Around 60% of this contribution is delivered through increased use of CCS. The transport sector provides over 50 GtCO₂ of additional emissions reductions compared with the 2DS, primarily through energy efficiency (57%), fuel switching (28%) and renewables (15%). Fuel switching, including from natural gas to electricity and biogas, supports around half of the additional direct emissions reductions needed in the buildings sector in the shift from the 2DS to B2DS.

Increased electrification of end-use sectors sees the power sector absorb increased demand in the B2DS compared with the 2DS, while delivering around 40 GtCO₂ of additional abatement. This additional abatement from the power sector is equivalent to around 15% of the total additional emissions reductions needed for the B2DS pathway. Renewable energy plays the predominant role in the additional emissions reductions from

power in the B2DS, comprising around two-thirds of these reductions, followed by CCS (including BECCS), which contributes around one-quarter.

Notwithstanding the immense scale of the effort to reduce energy sector emissions in the B2DS, almost 4 GtCO₂ of direct emissions remain in 2060, predominately from the industry and transport sectors. These emissions are offset with negative emissions produced from BECCS.

In the B2DS, growth in primary energy demand is limited to only 10% (or 55 EJ) in the period to 2060, underpinned by strong energy efficiency measures. The fuel mix in the B2DS is substantially different from the current mix, with the share of fossil fuels falling to 26% and total renewables increasing from 13% to 60%. Fossil fuels see an absolute decline of 300 EJ (65%) compared with 2014 consumption levels, with coal use falling by 78%, oil by 64% and natural gas by 47%. In part, this reflects the important role of renewables in decarbonising the electricity mix, with far-reaching electrification of the transport and building sectors central to achieving the B2DS pathway. Biomass experiences only limited growth compared with the 2DS, reaching 24% of the energy mix in 2060, reflecting constraints on the availability of sustainably sourced biomass. The share of nuclear grows to 14% by 2060 in the B2DS, and hydro remains at similar levels to the 2DS, at 5% of the primary energy mix.

Final energy demand in the B2DS reflects the significant role of electrification of end-use sectors (particularly ground transport and buildings) in order to achieve this ambitious pathway. The final energy demand in the B2DS is around 45 EJ (10%) lower than the 2DS in 2060 and marginally lower (4%) than 2014 levels. However, the fuel mix looks vastly different to that in 2014, with the share of low-carbon energy growing to 67%. Oil experiences the greatest decline in its share, from almost 40% in 2014 to 16%, an absolute decline of 96 EJ, reflecting the shift away from petrol- and diesel-fuelled vehicles. Most of the decline in fossil fuels is counteracted by growth in electricity demand, which expands from 18% to 41% of the mix in 2060, more than doubling from 2014 levels in absolute terms.

Technologies for energy transformations

The sustainable transformation of the energy sector can be achieved only with accelerated investment in a portfolio of clean energy technologies and energy efficiency. The magnitude of the emissions reductions needed to achieve a 2°C goal – and beyond – will require targeted efforts across both energy supply and demand sectors. Energy efficiency remains at the forefront of reducing demand from end-use sectors while renewables are central to the decarbonisation of the power sector in the 2DS. Better systems integration, smart electricity grids and improved load management can play an important role in supporting high penetration of variable and distributed renewable energy sources (Box 1.3).

Box

1.3. Digitalization: New opportunities and challenges for the energy sector

The growing use of digital information and communications technology (ICT) is permeating nearly all aspects of modern life, influencing how people live, work and play. Rapid advances in data collection and storage, connectivity, and analytics are driving digitalization across the economy, and the energy sector is no exception.

From power generation to upstream oil and gas, from personal transport and industry, virtually all aspects of the energy system are being influenced by digital technologies. For instance, smart grids can help to support the integration of variable and distributed energy sources in electricity markets while enabling better load management, including through demand-side response measures. Sensors and remote analysis can enable predictive maintenance to extend the life of power generation, transmission and distribution assets. Big

data and improved analytics in seismic mapping can significantly increase recoverable resources in oil and gas. Smart charging for EVs and intelligent road traffic management can support more efficient and low-emission use of energy in transport. Advanced energy controls and optimisation algorithms are leading to more energy-efficient homes, commercial buildings and industrial plants.

While the scale of the impact of digitalization on today's energy system is difficult to fully quantify, the challenge is even greater when considering the future impacts of emerging technologies such as autonomous vehicles and additive manufacturing. Given the rapid pace of technological change, it is almost impossible to credibly forecast the range of potential impacts that digitalization may have on the energy sector over the next two, three or four decades. However, it is clear that the digital world and global energy system will increasingly converge, giving rise to both opportunities and challenges for the energy sector in achieving energy security, energy access, economic growth and environmental sustainability goals.

Building on past efforts, the IEA is undertaking enhanced efforts in 2017 to analyse and characterise the potential drivers and trends of digitalization across the global energy system. This cross-cutting analysis will bring together expertise from across the IEA, industry, government, and research communities, in an effort to provide policy makers and other key stakeholders with credible analysis and tools to help navigate this complex and dynamic trend. This analysis will be published in October 2017. More information is available at: www.iea.org/newsroom/news/2017/april/iea-examines-critical-interplay-between-digital-and-energy-systems.html

Early action on energy efficiency

Energy efficiency is crucial to the energy sector transformation. It has played an important role in the recent slowing of global CO₂ emissions growth and is expected to lead the way in achieving a 2°C target, with a 40% contribution to the cumulative emissions reductions needed in the shift from the RTS to the 2DS. Energy efficiency is equally essential in the B2DS, where it accounts for around 34% of the additional emissions reductions needed compared with the 2DS.

The scale of the energy efficiency contribution depends on early action: accelerated measures to avoid the long-term lock-in of inefficient energy use deliver significant savings over the scenario period across all scenarios.

In the buildings sector, efficiency measures provide the vast majority of cumulative emissions reductions in both the 2DS and the B2DS. The aggressive measures deployed in the B2DS reduce the final energy demand in the buildings sector by almost one-third of the RTS in 2060 and a further 12% beyond that achieved in the 2DS. This is a strategically important contribution to the energy sector transformation, reducing pressure on the power sector as it works to support greater electrification in other sectors (primarily transport and, to a lesser extent, buildings).

Energy efficiency measures also support more than half of the cumulative emissions reductions achieved in the transport sector in the 2DS and B2DS. This includes improved fuel and vehicle efficiency for light- and heavy-duty vehicles, aviation and shipping, as well as efforts to alter the structure of transport demand through avoid and shift strategies. The latter serve to reduce passenger activity (light duty vehicles) by as much as 30% to 2060 in the 2DS relative to the RTS.

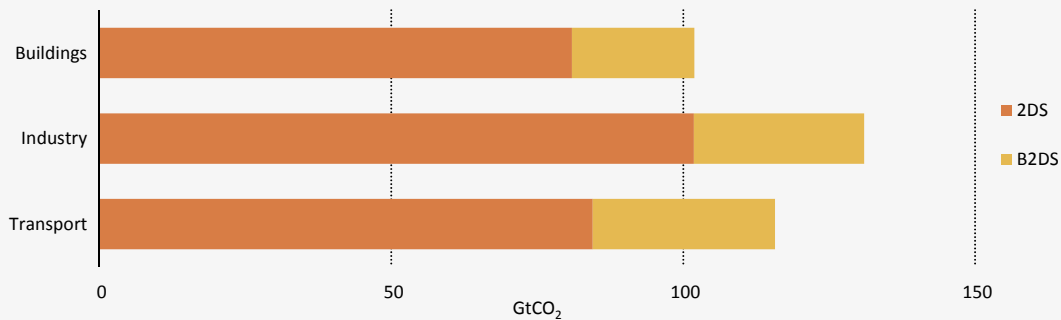
For industry, energy efficiency accounts for around two-thirds of the sector's cumulative emissions reductions in the 2DS and around one-third of the additional reductions needed to shift from the 2DS to the B2DS. Energy and materials efficiency measures, together with deployment of best available technologies (BATs), contribute around half of the cumulative emissions reductions in industry before 2030, underscoring the importance of early action (Figure 1.10).

Improvements in materials efficiency are particularly important in the B2DS, where significant levels of key materials must be produced in the most efficient way possible to

minimise their impact on energy demand and their carbon footprint. Minimising the use of energy in manufacturing processes is a priority, but maximising the use of locally available resources and optimising material use while delivering the same service will also be important. Materials efficiency in the manufacturing stage of key materials could deliver 144 EJ of cumulative savings globally in the B2DS relative to the RTS.

Figure

1.10. Contribution of energy efficiency to cumulative CO₂ reductions in the 2DS and B2DS



Key point

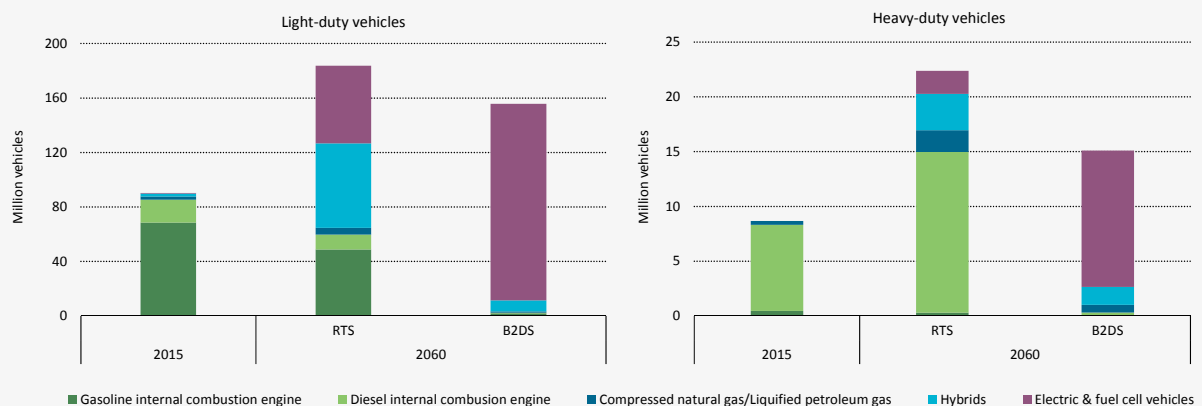
Energy efficiency measures play a critical role in delivering emissions reductions across end use sectors

Electrification of end-use sectors

Electrification is a key lever for CO₂ emissions reductions in both the 2DS and the B2DS, enabling the shift from direct reliance on fossil fuels to decarbonised power across industry, transport and buildings sectors. This higher demand also provides additional options for flexibility enhancements through demand-response measures, in addition to providing more favourable business cases for investment in clean power generation

Figure

1.11. Vehicle sales and technology shares in 2015 and in 2060 in the RTS and B2DS



Key point

Electricity can become the primary fuel for land-based transport, but not without assertive policies and directed investment.

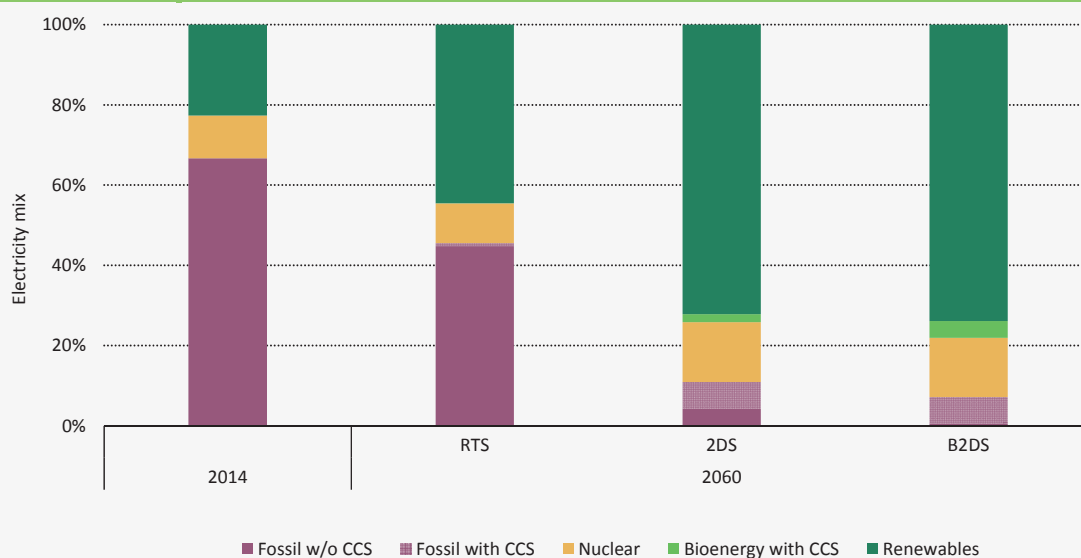
The share of electricity in final energy demand across all end-use sectors almost doubles from 18% today to 35% in the 2DS in 2060, and 41% in the B2DS. The shift is particularly notable in transport, where electricity becomes the primary fuel for on-road vehicles in the B2DS (Figure 1.11). The additional electricity consumption by end-use sectors in the B2DS in 2060 is about 1 700 terawatt hours (TWh) more than the 2DS, equivalent to the combined annual electricity consumption of India and the Russian Federation today.

Decarbonisation of power generation

The shift to electrification in the B2DS increases the pressure on the power sector, not only to accommodate additional generation but to do so while rapidly decarbonising and becoming a source of negative emissions. This transformation will require a considerable change in the traditional trends in power sector investment, with the carbon intensity of electricity generation declining at an average rate of -3.9% in the next decade for the 2DS or -4.5% for the B2DS, compared with -0.5% over the past decade.

In the 2DS, renewables deliver around two-thirds of the emissions reductions achieved in the power sector, with CCS providing 18% and nuclear 16% of reductions. By 2060, 98% of electricity generation is from low-carbon sources (Figure 1.12), with the carbon intensity of generation approaching zero — a colossal effort relative to today's level of around 520 grammes of CO₂ per kilowatt hour (gCO₂/kWh) and the 254 gCO₂/kWh achieved in the RTS. In the B2DS, the carbon intensity of electricity generation falls below zero, to -10 gCO₂/kWh in 2060, effectively making the power sector a source of negative emissions to offset residual emissions in industry and in transport.

Figure 1.12. Power generation fuel mix by scenario, 2014 and 2060



Key point

The fuel mix to generate electricity in the 2DS and B2DS would be vastly different from today's mix.

Increased development and use of sustainable bioenergy

A significant contribution from sustainably sourced bioenergy is needed as part of the transition to a clean energy future in both the 2DS and the B2DS. Bioenergy can play an important role across the energy sector: in electricity production, in heating for buildings, for industrial uses and in transport.

The role of bioenergy will largely be defined by the availability of sustainably sourced bioenergy feedstock. Its supply will need to grow from 55 EJ today to almost 100 EJ in 2060 in the RTS and to around 145 EJ in both the 2DS and B2DS. While this is within

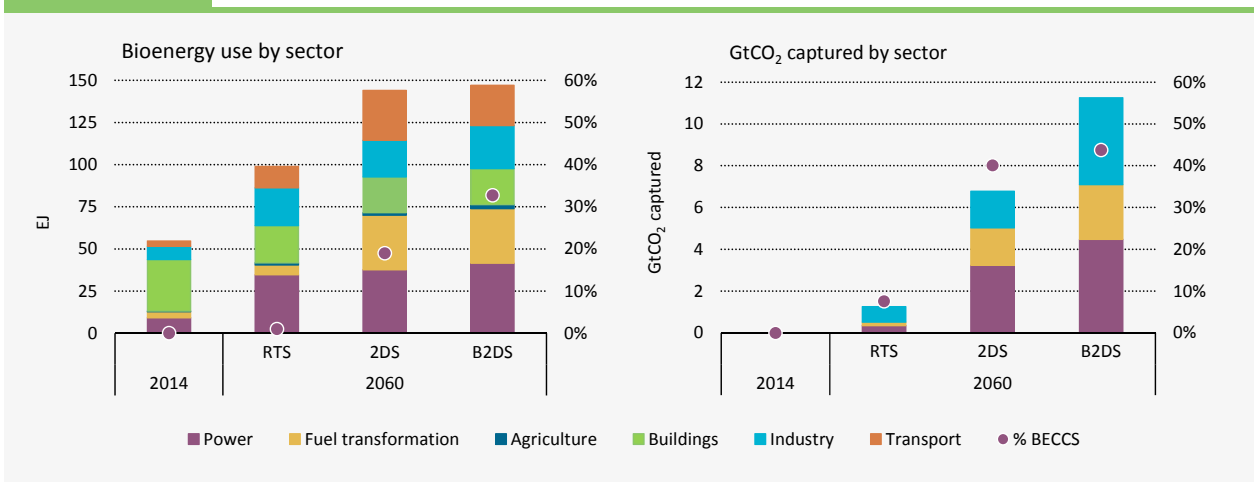
the range of many global estimates of available sustainable bioenergy resources, mobilising it is a major challenge.

In the 2DS, the use of bioenergy in the transport sector rises significantly (more than double that in the RTS), reaching 30 EJ in 2060, and complementing other measures in the sector. In particular, biofuels play an important role in decarbonising shipping and aviation.

In the B2DS, the use of bioenergy shifts among end-use sectors compared with the 2DS to maximise climate benefits. In particular, there is an expanded role for BECCS in the power sector and in fuel transformation in order to generate negative emissions (Figure 1.13). The role of biofuels in transport is lower in the B2DS than in the 2DS in 2060 – 24 EJ compared with 30 EJ – due in part to a 20% overall reduction in transport energy demand between the two scenarios.

The future role of bioenergy is dependent on unambiguous and significant carbon savings, as well as assurances as to its environmental and social sustainability. Having a clear sustainability governance structure will be essential to delivering bioenergy resources at the levels contemplated in the 2DS and B2DS.

Figure

1.13. Bioenergy use and CO₂ capture in the RTS, 2DS and B2DS

Key point

A growing percentage of bioenergy use will need to have CO₂ capture in the 2DS and B2DS.

Accelerated deployment of CCS

CCS technologies provide an important cross-sectoral emissions abatement solution in both the 2DS and the B2DS, supporting deep emissions reductions across the power, industry and fuel transformation sectors. There are now 17 large-scale CCS projects operating globally across a range of applications, including coal-fired power generation and steel manufacturing, however realising a 2DS pathway for CCS in practice would require a significant and urgent increase in current investment levels. In particular, investment in CO₂ transport and storage infrastructure would need to grow rapidly to accommodate the vast quantities of CO₂ movement required for the 2DS and B2DS pathways.

In the 2DS, CCS technologies deliver 14% of the cumulative CO₂ emissions reductions, with around 142 GtCO₂ captured in the period to 2060. The annual rate of CO₂ capture would need to ramp up at an unprecedented rate: from around 30 million tonnes (Mt) today to more than 1 Gt in 2030 and 6.8 Gt in 2060. This is equivalent to more than 1 700 CO₂ storage projects at the scale of the Australian Gorgon CCS project.¹⁰ Around half of this annual CO₂ capture will be from the power sector (48%), with the remainder split between

10. The Gorgon CCS Project will capture and store up to 4 Mt of CO₂ annually, with operations to commence in 2017 (GCCSI, 2016).

industry (26%) and fuel transformation (26%). In the power sector, around half of the CO₂ captured is from coal-fired power generation and a quarter each from gas and biomass.

The challenge of scaling up investment in CCS is heightened in the B2DS, with CCS playing a leading role in the additional emissions reductions needed to shift from the 2DS pathway to the B2DS. In the B2DS, the cumulative CO₂ emissions captured increases to 227 Gt in the period to 2060. By 2060, 11.2 GtCO₂ is being captured and stored each year from power (40%), industry (37%) and fuel transformation (23%). CCS and innovative processes are particularly critical in delivering the deep emissions reductions needed in the industry sector in the 2DS to B2DS shift, accounting for around one-third of the additional emissions reductions achieved in industry.

The greater role for CCS in the shift from the 2DS to B2DS also relates to the need for negative emissions if the energy sector is to reach net zero by 2060. In the 2DS, 36 Gt of CO₂ capture in the period to 2060 is from biomass combustion, but this is increased to 72 Gt in the B2DS. Chapter 8 provides an in-depth discussion on the challenges and potential for scaling up CCS to these levels.

Clean energy technology investment

The investment costs associated with the 2DS across the power, buildings and transport sectors, and within the energy-intensive industries, would not require unreasonable additional financial contributions from the global economy. In the power sector, a 2DS pathway would require about 16.7 trillion United States dollars (USD) in additional investment between 2017 and 2060 compared with the RTS, which is equivalent to around 0.15% of cumulative global GDP over the same period.¹¹ Achieving the potential energy savings and efficiency improvements in the buildings sector would entail an additional investment of USD 9.7 trillion between 2017 and 2060. In the energy-intensive industries, reductions in primary materials demand and shifts to lower-carbon process routes result in cumulative cost savings (compared with the RTS) of between USD 0.5 and 0.7 trillion between 2017 and 2060 compared with the RTS. Similarly, if the full potential for reduced demand for on-road vehicles – and associated reductions in demand for roadway and parking infrastructure – attributable to avoid and shift options is considered, the 2DS pathway for the transport sector (vehicles and infrastructure) could be achieved with investment cost reductions of USD 28 trillion (cumulative from 2017 to 2060) compared with the RTS.

In the B2DS, cumulative additional investments (compared with the RTS) would rise to USD 23 trillion in the power sector, USD 11 trillion in the buildings sector, USD 13.5 trillion in the transport sector (vehicles and infrastructure), and between USD 0.2 and USD 0.7 trillion in the energy-intensive industries. Combined, these additional totals are equivalent to around 0.4% of cumulative global GDP over the period 2017–60.

Achieving climate ambitions: The gap to 2°C and beyond

The heightened ambition implicit in “well below 2°C” and pursuing efforts towards 1.5°C has been recognised as a major achievement of the COP21 climate negotiations. This success was followed by governments sending a strong signal of the seriousness of their commitments: the entry into force of the Agreement within a year made it one of the fastest multilateral agreements to come into force in the history of the United Nations. This also suggested that the climate momentum generated in Paris was carried forward into the domestic context in many key countries.

Governments and policy makers around the world are now faced with the very significant challenge of identifying and implementing an energy sector transformation consistent with this level of ambition. The scale of the challenge is underscored by the already large gap between a 2°C target and the expected outcome of current efforts and commitments.

11. For further details on the data sources and assumed regional growth rates used in *ETP 2017* global GDP projections, see Annex A, Table A.1.

Achieving a 2°C target requires a 40% reduction in cumulative CO₂ emissions to 2060 — or around 760 Gt — compared with the RTS pathway. This effort is over and above the projected impact of announced policies, current trends and the non-conditional commitments contained in the NDCs.

Moving to a 2DS pathway would require the power sector to be virtually decarbonised by 2060, with 98% of all generation from low-carbon sources. Unabated coal would need to be phased out in the 2040s, and around 60% of gas-fired generation would come from plants equipped with CCS by 2060. Emissions from the buildings sector would need to decrease by 85% (cumulatively) compared with the RTS, and the share of EVs or fuel cell electric vehicles (FCEVs) in the light-duty road vehicle fleet would reach about 60% and in the heavy-duty vehicle fleet about 40% by 2060. In industry, 19% of the cumulative reductions needed to 2060 would come from technologies and processes that are not yet commercially available, including significant penetration of CCS.

The policy and technology challenges of bridging the gap to the 2DS would be further amplified for even more ambitious climate goals, particularly as the deeper emissions reductions will be more difficult and costly to achieve. While not definitive of a well-below 2°C pathway, the B2DS provides an illustration of this challenge and also highlights a possible limit of what could be achieved with currently proven or demonstrated technologies, even when assuming continued technological innovation and improvement. In the B2DS, cumulative emissions would need to be reduced by almost 60% in the period to 2060 compared with the RTS, representing more than 1 000 GtCO₂.

A 1.75°C pathway would require the emissions intensity of power generation to fall from around 520 gCO₂/kWh today to become carbon negative, at -10 gCO₂/kWh, in 2060. This decarbonisation occurs while concurrently supporting electricity demand growth at levels similar to the RTS. Coal-fired power generation with today's CCS technology performance would become relatively high-emissions options by 2050, while in industry as much as 80% of global cement emissions would need to be captured by 2060. A majority of petrol and diesel vehicles would need to be phased out between 2030 and 2060, and around 72 GtCO₂ of negative emissions would be generated from BECCS in the period to 2060, equivalent in scale to the cumulative energy-related CO₂ emissions in the People's Republic of China (hereafter China) between 2005 and 2014.

Moving to a 1.5°C pathway would require a transformation of the energy sector at a scale and pace that can barely be imagined from today's perspective. It would most likely require considerable economic restructuring, behavioural changes or as-yet-unknown technology breakthroughs, including those with the capacity to deliver large-scale negative emissions in the second half of the century (Box 1.4).

A decoupling of economic growth and CO₂ emissions will be a critical factor in achieving climate targets and will be a key indicator of policy success. While global growth in energy-related CO₂ emissions appears to have flattened, this trend would need to be maintained and accelerated in each of the *ETP* scenarios. The drivers of the recent slowdown in CO₂ emissions growth are varied, but reduced coal use in the United States and China has been a major factor. In China, the decline in coal reflects weakening power demand, a diversification away from coal and efforts to address serious air pollution (IEA, 2016g). In the United States, the emergence of abundant and cheap unconventional gas has impacted coal's competitiveness. Further, lower CO₂ emissions growth has been associated with lower GDP growth in China, Europe and the United States in the 2005–15 decade compared with 1995–2005.

Recent studies have highlighted the potential for emissions growth to rebound in the event of a return to stronger GDP and energy demand growth, particularly through increased capacity utilisation of existing coal power plants and rapid construction of new ones (Peters et al., 2017). Therefore, recently observed progress could be vulnerable to a change in economic conditions, policies and relative fuel costs. This underscores that a more resilient and significantly strengthened climate policy response would be required to lock in recent progress and to shift the energy transformation towards a 2°C or well-below 2°C pathway.

Box

1.4. Pursuing efforts to 1.5°C: Are negative emissions the key?

The implications of pursuing a 1.5°C objective are currently not well understood, with limited research available. However, for the energy sector, the very restricted carbon budget for a 1.5°C target suggests that nothing short of an immediate, aggressive and sustained ramp-up of all low-carbon technology options is required to keep this target within reach. According to analysis in the *WEO 2016*, a 1.5°C target requires the energy sector to achieve net-zero emissions before 2040, around 20 years earlier than the B2DS. Within the next two decades, the emissions intensity of power generation must fall to almost zero while electricity demand more than doubles; virtually all residential and commercial buildings need to be carbon-neutral; and all passenger and light-commercial vehicles are electric (IEA, 2016c).

Even with efforts at this scale, the potential for carbon budgets to be exceeded is immense: in fact, studies have highlighted that in all 1.5°C scenarios assessed in the IPCC *AR5*, the cumulative carbon budget in the period 2011 to 2050 is higher than for the period 2011 to 2100. This indicates that active removal of CO₂ from the atmosphere in the second half of the century, including through significant deployment of negative-emission technologies, is needed to keep within the budget (Rogelj et al., 2015).

Negative-emissions technologies could also play an important role in compensating for residual emissions in sectors where direct mitigation is difficult or more expensive, for example in aviation, shipping, some industrial processes and agriculture. In both the 2DS and B2DS scenarios, BECCS is deployed at a large scale for this purpose, delivering 36 GtCO₂ of cumulative negative emissions in the 2DS and 72 GtCO₂ in the B2DS in the period to 2060. Negative emissions would likely need to be much greater in the case of a 1.5°C trajectory.

BECCS is not the only technology capable of delivering negative emissions, but it is the most mature. The costs and potential of other negative-emissions technologies, such as direct air capture, biochar and enhanced weathering, remain uncertain although in theory they could offer a promising complement or alternative to BECCS if proven commercial and able to be deployed at sufficient scale. Notably, technologies such as direct air capture also rely on geological storage of CO₂.

Policy action to bridge the gap

The assessment that current policy efforts are insufficient to achieve climate goals holds true irrespective of the specific temperature target under consideration. The gap for achieving a 2°C target is sufficiently large as to require a profoundly accelerated and intensified policy response compared with current progress: ambition would need to increase on multiple entry points simultaneously, e.g. carbon pricing, efficiency standards and labelling programmes; enabling market and regulatory frameworks; targeted technology deployment measures; and technology push for innovative solutions. All energy sectors and all technology options will need to be supported to deliver steep emissions reductions globally. Moving beyond 2°C would require even greater policy momentum and ambition and, as illustrated in the B2DS, may test the limits of currently proven or demonstrated clean energy technologies.

The Paris Agreement implicitly recognises this gap and has implemented a framework to support an increase in global climate ambition over time. The review-and-revise approach for submitting NDCs every five years promotes progression of the Parties' efforts, each of which is to reflect its "highest possible ambition". NDCs can be revised at any time, and the first formal collective review of progress is scheduled for 2023. An important, near-term impetus to raise ambition will be the 2018 facilitative dialogue in the UNFCCC. The dialogue is expected to focus attention on the shortfall between the current collective efforts and progress towards the long-term climate goal. It will also consider input from the IPCC on pathways to a 1.5°C target. These 2018 discussions are considered the best occasion to spur Parties to lift their collective and individual ambition prior to the formal start of the Paris Agreement in 2020.

The 2DS and B2DS analysis offers insights into the mitigation options and policy measures that would be required for an energy sector transition consistent with long-term climate goals. These policy implications are considered on a sectoral basis in the following chapters, but three overarching priorities are highlighted.

1. Support for technology innovation

Policy support for technology innovation will be central to the transformation to a low-carbon energy system. The experience with onshore wind and solar PV has demonstrated the positive impact of strong and targeted policy support for technology innovation, delivering substantial cost reductions and rapid investment growth over the last decade. This level of commitment and policy support will be needed across a much broader range of clean energy technologies to provide options for clean, secure and affordable energy.

The *Tracking Clean Energy Progress 2017 (TCEP)* report (Chapter 2) shows that progress with almost all technologies is currently falling well short of the 2DS targets, with onshore wind, solar PV, EVs and energy storage being the key exceptions (see Chapter 2). While promising, progress with these technologies alone is insufficient to achieve the 2DS. Many key technologies for achieving the 2DS were not recognised in the national climate strategies pledges prior to COP21. For example, collectively the NDCs have limited reference to a role for CCS, improved efficiency in buildings, nuclear power or alternative vehicle fuels in the period to 2030. This lack of progress and policy attention could impede the availability of these technologies to contribute the achievement of energy and climate goals and exacerbate the future policy challenge.

Accelerated technology innovation across the full portfolio of technologies is integral to each of the *ETP 2017* scenarios. Technologies considered in these scenarios are currently commercially available, or likely to become so within the outlook period, yet accelerated technology innovation remains critical to bring forward more advanced technologies, improve technology performance and decrease costs through technology learning. This requires policy support at all levels of the technology cycle, targeted to the varied maturity and development stage of particular energy technologies. For example, in the industry sector, RD&D for improved material efficiency and innovative technologies is important to secure options that will provide added value in the case of processes that are not yet commercially available. In parallel, technology-pull policy support is needed to incentivise deployment of BATs and encourage the phase-out of less efficient processes across the industry sector. In the case of bioenergy applications, continued technology support will be needed, including RD&D for emerging transport fuel options alongside policy measures to support commercial investment in biomass-fired power plants.

Investment in early-stage research for radically innovative energy technologies will also be important. This potential role for “breakthrough” technologies recognises the technology challenges and limitations inherent in both the 2DS and the B2DS, particularly for achieving net-zero emissions across the global energy system. In the B2DS, net-zero emissions are achieved in 2060 with reliance on negative emissions from large-scale deployment of BECCS; however, future constraints on the availability of sustainable biomass could impact this contribution in practice.

More nascent negative-emissions technologies, such as direct air capture, could offer an alternative if commercially available at large scale. Alternatively, breakthroughs in industrial process technologies, for example renewable-based hydrogen direct reduced iron production, could help to support the industry sector to move closer to net-zero emissions and reduce the need for BECCS. With strong public and private investment in early-stage research, the potential for delivering energy technology breakthroughs in the 40-plus-year time horizon of the *ETP 2017* scenarios is considered substantial, particularly given the rapid acceleration of technology developments across a wide range of sectors in recent decades.

Enhanced global co-operation and collaboration can also play a major role in accelerating technology innovation. A recent example is the Clean Energy Ministerial (CEM), which brings together 24 governments alongside industry leaders to accelerate clean energy technology development and adoption through CEM initiatives focusing on EVs, smart grids, appliance efficiency, and numerous other clean energy topics. The IEA has been a key collaborator within a number of CEM initiatives, and is now further supporting this important collaboration by hosting the CEM secretariat in Paris.

The IEA is also actively engaged with Mission Innovation (MI), an initiative announced during the COP21 climate conference that is emerging as a valuable platform for an internationally co-ordinated approach to clean energy technology R&D (Box 1.5). The Paris Agreement itself also provides a framework to support technology collaboration, with an explicit focus on the development of endogenous capacities and technologies in developing countries. It provides for a new technology framework that has the potential to be an important platform for identifying technology needs and supporting financial solutions.

Box

1.5. Mission Innovation as a catalyst for heightened innovation investment

Mission Innovation (MI) is a landmark initiative by the leaders of 20 major economies to significantly accelerate public and private clean energy innovation. Launched at COP21, the initiative has expanded to include 22 countries plus the European Union. MI members now represent more than 80% of the world's public funding for energy RD&D.

At the core of the MI initiative is the pledge of the signatory countries to double their collective annual spending on R&D of clean energy technologies from the estimated USD 15 billion in 2015 to over USD 30 billion by 2021. MI countries have also recognised the need to co-ordinate the implementation efforts to maximise the impact and benefit of this research investment.

The announcement by MI of seven Innovation Challenges at the 22nd Conference of the Parties (COP22) in November 2016 marked an important step towards the delivery of its objectives. The challenges are:

- Smart Grids Innovation – to enable future grids that are powered by affordable, reliable and decentralised renewable electricity systems
- Off-Grid Access to Electricity Innovation – to develop systems that enable off-grid households and communities to access affordable and reliable renewable electricity
- Carbon Capture Innovation – to enable near-zero CO₂ emissions from power plants and carbon-intensive industries
- Sustainable Biofuels Innovation – to develop ways to produce, at scale, widely affordable, advanced biofuels for transportation and industrial applications
- Converting Sunlight Innovation – to discover affordable ways to convert sunlight into storable solar fuels
- Clean Energy Materials Innovation – to accelerate the exploration, discovery and use of high-performance, low-cost clean energy materials
- Affordable Heating and Cooling of Buildings Innovation – to make low-carbon heating and cooling affordable for everyone.

MI participants share the common goal of leveraging private sector leadership. They are seeking opportunities to collaborate with the associated Breakthrough Energy Coalition, a partnership of 28 individual investors from ten countries committed to investing in the new energy technologies emerging out of government-funded early-stage research in MI countries.

A notable example of international collaboration on energy technology RD&D and information dissemination is the portfolio of IEA Technology Collaboration Programmes (TCPs), formally organised under the auspices of Implementing Agreements co-ordinated by the IEA.¹² Functioning within a time-tested framework, these technology initiatives

12. For further information on the IEA Technology Collaboration Programmes, see: www.iea.org/tcp/

provide a convenient mechanism for multilateral collaboration, research and analysis on energy technologies among IEA member and association countries, non-member countries, businesses, industries, international organisations and non-governmental entities. The IEA's 39 TCPs bring together several thousand researchers, scientists, government officials and industry representatives to co-ordinate research and innovation in energy technologies.

2. Alignment of long-term climate strategies and near-term policy action

Improved alignment of long-term policy objectives and near-term policy action is needed to support a minimally disruptive, least-cost pathway to achieving a clean energy system. Near-term mitigation measures that deliver early wins, including targeted measures to support energy efficiency and investment in renewables, will be important to keep efforts on track, but a 2DS or B2DS pathway will also be critically dependant on ensuring a foundation for very deep GHG emissions reductions over the coming decades. As pointed out in the IPCC's *AR5*, "efforts to begin the transformation to lower concentrations must also be directed towards developing the technologies and institutions that will enable deep future emissions cuts rather than exclusively on meeting particular near-term goals" (IPCC, 2014).

The value of this long-term policy planning is highlighted in the 2DS and B2DS analysis. For example, early action in supporting building envelope efficiency could save as much as 130 EJ of energy demand in the period to 2060, alleviating pressure on the future power system and avoiding long-term lock-in of inefficient buildings.¹³ Yet much of this potential remains untapped (see Chapter 4).

Similarly, CCS technologies are needed for deep emissions reductions in the power and industry sectors in the 2DS and B2DS, particularly in the post-2030 period. However, the ability to realise these future emissions reductions will be dependent on near-term investment in CO₂ storage characterisation as well as planning for the associated transport infrastructure. As highlighted in Chapter 8, progress with CCS development has been slow, and very limited movement is expected in the project pipeline after 2017. This stalling of progress and lack of adequate policy support could directly impact the capacity of CCS to contribute to clean energy goals in the coming decade.

The Paris Agreement NDCs focus the timeframe for climate action in the period to 2030, and the actions undertaken in this period will also have a critical role in preparing what comes after that (Rogelj et al., 2016). It is important that technology and policy needs for the pre- and post-2030 periods are aligned to the greatest extent possible. An opportunity to promote this is contained within the Paris Agreement, which invites Parties to communicate, by 2020, "mid-century, long-term low-GHG emission development strategies". Several of these strategies have been submitted, with many containing a comprehensive vision of climate effort to 2050, including technology needs.¹⁴ Countries should be actively encouraged to reference these strategies in the development of the next round of NDCs to promote alignment of these commitments with long-term policy and technology needs.

3. Improved integration of policy measures across the energy sector

The 2DS and B2DS analysis reinforces the need for effective integration of climate policy measures in order to support an accelerated transformation of the energy sector. The scale and pace of the transformation required to limit future temperature increases to 2°C or below mean that strong and consistent policies will be required, co-ordinated across the various energy sectors and within broader economic planning. In practice, this could include accounting for climate objectives across almost all facets of government and business decision making, including taxation, trade policy, urban planning and innovation (OECD, 2015).

Within the energy system, long-term planning across sectors is needed to optimise policy and investment strategies. The deployment of CO₂ storage infrastructure is one example: CCS will be important for emissions reductions in the power sector and also in industrial applications. For many industrial applications – including some BECCS applications – the relatively smaller quantities of CO₂ will mean that project-specific transport and storage infrastructure is unlikely to be economical. Effective co-ordination and planning across

13. Compared with a ten-year delay in the implementation of the B2DS. See Chapter 3 for further discussion.

14. These climate strategies are published on the UNFCCC website at: http://unfccc.int/focus/long-term_strategies/items/9971.php.

different applications, including at a regional level, could help to alleviate these challenges. For example, a fossil fuel-fired power plant could potentially act as an anchor project for industrial projects, or alternatively multiple industrial projects could form a CCS hub from which to develop the necessary infrastructure. Targeted policies to support this integrated approach to CCS infrastructure planning could deliver significant cost savings and support improved understanding of the economy-wide value of these capital-intensive investments.

Similarly, sustainable biomass is likely to be a constrained resource in the future, with biomass supply increasing by a factor of 2.6 in the 2DS compared with the RTS. Promoting optimal use of biomass across the energy sector will be important, recognising that the most valuable use will vary depending on particular policy objectives and in different jurisdictions. Promotion of integrated systems that co-produce a number of useful energy streams from biomass could support the most efficient production and use of this limited resource. For example, this could include the production of energy along with co-products (such as food, material and chemicals) or the integrated production of electricity, heat, and transport fuels or chemicals (see Chapter 7).

The introduction and expansion of financial incentives can play an important role in supporting economy-wide emissions reductions and promoting investment decisions that are consistent with long-term goals. A carbon price can be an efficient mechanism in this regard; however, in the 2DS and B2DS, reliance only on carbon pricing schemes could result in very high, economy-wide costs to deliver deep emissions reductions. Complementary, dedicated support mechanisms for the higher marginal cost abatement options may alleviate the overall economic impact of a carbon price and lower the cost burden across the energy sector during the transition phase. Targeted support measures will also be important to “pull through” nascent technologies.

Conclusions: Shaping energy technology transformations

A clear transformation of the global energy sector is under way. Technology advances and innovations are shaping today’s energy trends, including through increasingly competitive options for low- or zero-emissions power generation, supporting greater end-user participation and choice, and radically shifting the dynamics of traditional energy markets in the case of unconventional oil and natural gas. Many of these developments are challenging energy policy makers, not only in terms of how to respond to the unprecedented pace of technological change, but in understanding how to best encourage and harness these developments to meet the parallel objectives of energy security, affordable energy access and environmental sustainability.

The *ETP 2017* scenario analysis confirms that early action is critical to meeting long-term energy and climate policy objectives. Among the immediate policy responses important in avoiding the lock-in of GHG emissions are: the phase-out of fossil fuel subsidies; measures to actively discourage or ban new subcritical coal-fired power generation while rapidly phasing out inefficient coal generation; and promoting investment in BATs and energy efficiency measures across all end-use sectors. In parallel, supporting development and deployment of low-emissions technology options, including the integration of variable renewable energy options in power systems, is needed to ensure that growing energy demand is met in an environmentally sustainable way.

A significantly broader and more comprehensive policy response will also be required for an effective transition to a low-carbon energy system. The *ETP 2017* and the *TCEP* analyses highlight that many important areas for action are currently being overlooked, particularly outside the power sector. Technologies such as bioenergy and CCS will also require more policy support and attention in the near term if they are to contribute to future energy and climate objectives.

The *ETP 2017* analysis is intended to inform global energy and climate policy discussions, including in advance of the 2018 IPCC *Global Warming of 1.5°C* Special Report and UNFCCC facilitative dialogue. It is one of several reports that the IEA will publish this year, providing further detailed analyses of some of the key policy and technology challenges identified in this *ETP*. These include a *WEO* Special Report titled *Energy Access Outlook: from Poverty to Prosperity*, an IEA Special Report on “Digitalization and Energy” (see Box 1.3), and an update to the IEA *Technology Roadmap Bioenergy for Heat and Power*.

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Chapter 2



Tracking clean energy progress

The annual assessment of the latest progress in technology and market developments shows advances in a number of clean energy technology areas. However, only 3 of the 26 surveyed technologies are on track to meet a sustainable energy transformation. Progress has been substantial where policies have provided clear signals on the value of clean energy technology deployment, such as in electric vehicles (EVs), energy storage and more mature variable renewables: solar photovoltaics (PV) and onshore wind. The “on track” status of these technologies depends on all other technologies also playing their part in the transition, which is not currently the case. 15 technologies showed only some progress, and 8 are significantly off-track.

Key findings

- **Tracking energy system transformation is essential for understanding progress and priorities related to both national and global greenhouse gas (GHG) mitigation goals and other political imperatives such as reducing air pollution.** Tracking is also critical to aid countries, companies, and other stakeholders as they identify specific ways to further step-up their effort. International Energy Agency (IEA) tracking and metrics could play an important role in the United Nations Framework Convention on Climate Change (UNFCCC) Facilitative Dialogue, a collective assessment of progress toward the Paris Agreement’s long-term goal taking place in 2018.
- **Only 3 out of 26 surveyed clean energy technologies are on track to meet a sustainable energy transformation:** EVs, energy storage, and mature variable renewables (solar PV and onshore wind).
- **A new historic record has been reached in the electrification of passenger transportation, with over 750 000 EVs sold in 2016, raising the global stock to two million.** A slowdown in market growth of 40% in 2016 from 70% in 2015 still maintains EVs on track to reach 2°C Scenario (2DS) levels in 2025, but puts the technology at significant risk of missing the 2020 interim milestone and in turn raises risks toward the 2025 goal.
- **Storage technologies continued rapid scale-up in deployment, reaching almost 1 gigawatt (GW) in 2016.** These advances were driven by favourable policy environments and reductions in battery prices. Storage technologies are on track with 2DS levels, but reaching cumulative capacity of 21 GW — the 2DS level projected by 2025 — will need further policy action.

- **Strong annual capacity growth continued for both solar PV and onshore wind in 2016, with record low long-term contract prices in Asia, Latin America and the Middle East.** Prospects for renewable electricity are bright over the medium term, driven by cost reductions and policy improvements in key markets. With only solar PV and onshore wind fully on track, however, renewables overall are still falling short of longer-term 2DS levels, despite a record-breaking 6% overall generation growth in 2016.
- **Nuclear power saw 10 GW of capacity additions in 2016, the highest rate since 1990. Yet doubling of the 2016 annual capacity addition rate to 20 GW annually is required** to meet the 2DS to offset planned retirements and phase-out policies in some countries. Closures of reactors struggling to compete in markets with depressed wholesale electricity prices are also looming, and 2016 brought only 3 GW of new construction starts, posing risks to the future growth rates of nuclear power generation.
- **The global portfolio of large-scale carbon capture and storage (CCS) projects continues to expand.** However, the capture and storage rate would need to increase tenfold in order for CCS to be on track to meet global climate objectives.
- **A growing number of countries have put in place policies to improve building energy performance, but average energy consumption per person in the global buildings sector still remains practically unchanged since 1990.**
- **A good potential exists globally for a shift to renewable heat, but the resource remains largely untapped.** Heat accounts for more than 50% of final energy consumption and is mainly fossil fuel-based. Growth in renewable heat has been steady but slow, and an increase of 32% would be needed by 2025 relative to 2014 to meet 2DS goals.

Opportunities for policy action

- **Detailed information on technology deployment and development is needed.** This information can help countries understand and track progress toward their national energy transition goals, and aid in effective national policy making.
- **Clean energy research, development and deployment (RD&D) has been essential in providing clean technology options of today, and will continue to be important into the future.** Investment in clean energy RD&D needs to pick up to be on track for a sustainable energy transition.
- **Accelerated growth of renewable electricity generation could be achieved through policy improvements** focused on both system-friendly deployment and technology development.
- **Targeted policy incentives to drive large-scale CCS projects forward into deployment are needed** to meet the 2DS target of over 400 million tonnes of carbon dioxide (MtCO₂) being stored per year in 2025.
- **To stay on 2DS track, coal-based CO₂ emissions must decline by around 3% annually to 2025,** led by a retirement in the least efficient technologies and a decline in coal generation not equipped with CCS after 2020.
- **Numerous first-of-a-kind commercial-scale advanced biofuel plants are increasing their production, but mandates for advanced biofuels or reducing the carbon intensity of transport fuels are needed** to accelerate uptake.
- **Nearly two-thirds of countries still do not have building energy codes in place. Global co-operation should seek to ensure that all countries implement and enforce building energy codes and standards** for both new and existing buildings.

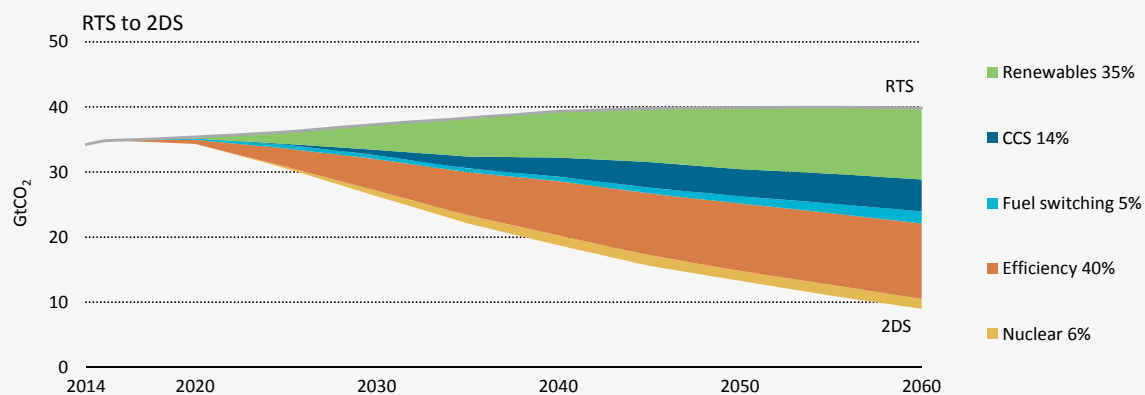
Tracking progress: How and against what?

Published annually, *Tracking Clean Energy Progress (TCEP)* examines the progress of a variety of clean energy technologies. For each, *TCEP* identifies key measures to further scale up and drive sectors to achieve a more sustainable and secure global energy system.

TCEP uses interim 2025 benchmarks set out in the 2°C scenario (2DS), which is consistent with the goal of limiting the global average temperature increase to 2°C (see Global Outlook chapter for scenarios description), as well as the milestones identified in the IEA Technology Roadmaps to assess whether technologies, energy savings and emissions reduction measures are on track to achieve the longer-term 2DS objectives by 2060. *TCEP* evaluates whether a technology or sector is on track (green), needs further improvement (orange) or is not on track (red) to meet 2DS targets. Where possible, this “traffic light” evaluation provides a quantitative metric to track performance. The most recent trend for each technology is highlighted with arrows and tildes and relevant descriptions. An evaluation is also made of past trends.

The report is divided into specific technology or sector sections, and uses graphical overviews to summarise the data behind the key findings. The 2DS relies on development and deployment of lower-carbon and energy-efficient technologies across the power generation, industry, transport and buildings sectors (Figure 2.1).

Figure 2.1. Sector contribution to emissions reduction



Note: GtCO₂ = gigatonnes of carbon dioxide.

Key point *Reduction efforts are needed on both the supply and end-use sides; focusing on only one does not deliver the 2DS.*

For each technology, *TCEP* examines recent sectoral trends, the latest technology developments and current policy ambition to determine progress against meeting low-carbon technology development pathways. Using a multitude of metrics, *TCEP* provides this analysis under the headings of recent trends, tracking progress and recommended actions.

Tracking overall progress: for each technology, the progress towards 2DS objectives is evaluated, and forward-looking indicators of progress needed to 2025 are provided.

Recent trends are assessed with reference to the three *TCEP* measures that are essential to the success of individual technologies: technology penetration, market creation, and technology development.

- Technology penetration evaluations include: What is the current rate of technology deployment? What share of the overall energy mix does the technology represent?

- Market creation examines: What mechanisms are in place to enable and encourage technology deployment, including government policies and regulations? Where relevant, what is the level of private-sector involvement in technology progress through deployment?
- Technology development discusses: Are technology reliability, efficiency and cost evolving, and if so, at what rate? What is the level of public and private investment for technology RD&D?
- Recommended actions: Policy measures, practical steps and other actions required to overcome barriers to 2DS objectives are identified. A specific “recommendation for 2017” is highlighted as a recommendation for the year for each sector or each technology in summarising progress and is based on findings in technology sections.

Tracking clean energy progress and the Paris goals

The Paris Agreement was a historic milestone and establishes various processes to evaluate progress towards emission goals. IEA is well placed to leverage its various tracking activities to provide a comprehensive picture of energy system transformation and to help assess collective progress towards multiple energy policy objectives, including the Paris Agreement’s long-term goals. Such metrics and tracking can help inform countries as they consider additional efforts and policies, and the impacts of certain decisions on a multitude of objectives.

Under the Paris Agreement, a common “transparency framework” is being developed to help track progress toward, and achievement of, countries’ Nationally Determined Contributions (NDCs). The Agreement also establishes a 2018 Facilitative Dialogue and subsequent Global Stocktakes to assess progress toward collective long-term goals, including the well below 2°C temperature objective. Finally, it encourages countries to develop long-term low-emissions development strategies to guide domestic policy making. IEA energy data and indicators, low-carbon technology tracking through the *TCEP*, and tracking of investment trends could all contribute to the 2018 Facilitative Dialogue and regular Global Stocktake processes.

A keyword search of NDCs for 189 countries in 2017 shows that 188 NDCs mentioned energy, 168 energy efficiency, 147 renewable energy, 10 nuclear power and 11 CCS (UNEP, 2017), 35 countries set specific NDC goals framed in terms of energy metrics, with all of them including targets for renewable energy or clean energy supply, while 15 also set energy efficiency or energy demand targets.

Tracking energy system transformation will be essential for understanding progress and priorities related to both national and global GHG mitigation goals. This tracking will require metrics relevant to different sectors, time frames (short- to long-term) and levels (aggregated metrics for outcomes, detailed metrics for drivers of energy sector change) (see Box 2.1). Information across a wide suite of metrics will also help countries develop NDCs that are consistent with global long-term temperature objectives as called for in the Paris Agreement,¹ and with their national mid-century, long-term low-GHG emission development strategies. It will also help ensure that these NDCs are compatible with a multitude of other objectives, such as energy security and economic development.

Metrics are useful not only to monitor action, but also to help inform future decisions; how goals are expressed can influence the policies chosen to implement them, and how ambitiously they are applied. Meeting the Paris temperature goals implies tight constraints on emissions budgets even over the short term. In the 2DS, 38% of the CO₂ budget to 2060 is expected to be used up by 2025, which means that short-term measures play a very important role. Certain short-term actions, such as investments made today in long-lived infrastructure (e.g. buildings and power plants) may not significantly affect GHG emissions over the NDC time period, but will be significant drivers of emissions in the long term. This point is also true for actions taken today that may bring down the cost and improve the

1. Each country’s NDC is meant to “be informed by the outcomes of the global stocktake” of progress toward the Agreement’s long-term goals (Article 4.9).

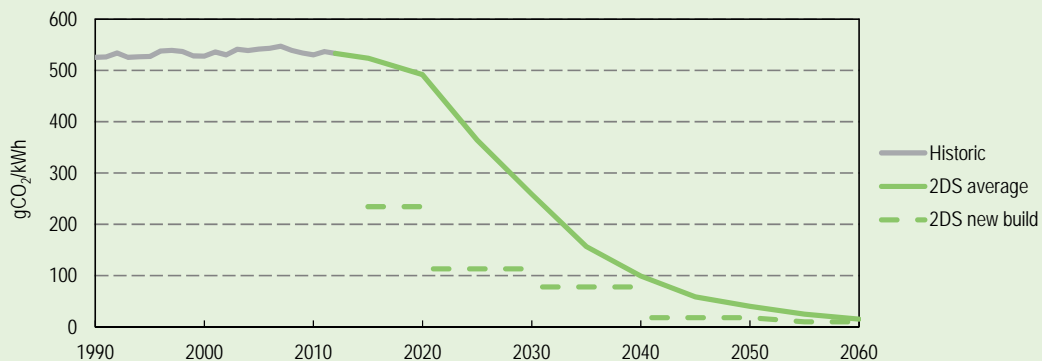
performance of key low-carbon technologies over the long term (e.g. research, development, demonstration and deployment).

Box

2.1. Tracking energy sector transformation: Outcomes and drivers

A small number of high-level energy indicators can provide an integrated view of progress and trends across the energy sector, identifying the essential drivers as well as the outcomes of energy sector change. For instance, the CO₂ intensity of new-build electricity plants is a driver metric, while the average CO₂ intensity of electricity generation is an outcome metric. The average carbon intensity of new power capacity declined 27% since 2005 (IEA, 2016d), but needs to be at around 100 grammes of CO₂ per kilowatt hour (gCO₂/kWh) in 2025, requiring further steep reduction. The global fleet average emissions intensity of power generation in 2DS needs to be reduced from the current level of 524 gCO₂/kWh to close to zero gCO₂/kWh in 2060 (Figure 2.2). Metrics should comprehensively track changes in both energy production (e.g. oil, gas, electricity) and use (e.g. in buildings, transport and industry).

2.2. Figure: Global fleet average and new-build plants emissions intensity in 2DS



Key point: Tracking of different types of indicators is needed to understand both current status and future trends.

Outcome metrics will be essential for the global stocktake of collective progress towards the Paris Agreement goals, because they can effectively track the overall state of the energy system. However, a broader set of indicators is needed to understand energy sector evolution and to support sound domestic policy. Tracking driver metrics for specific sectors or technologies can pinpoint where progress is needed and inform policy decisions. *TCEP* employs a multitude of metrics to examine recent sectoral trends, the latest technology developments and current policy ambition to determine progress in meeting low-carbon technology development pathways. The *ETP* analytical framework offers a long-term outlook on potential technology choices that are available to ensure delivery of the Paris Agreement goals. Tracking energy sector investment also enables an assessment of short-term actions' consistency with long-term goals. The *World Energy Investment* report examines this leading indicator of the energy transition: the investment analysis of capacity installed in a given year indicates the shape of the energy system to come.

Energy metrics can thus provide policy makers and investors with guidance on the means to achieve long-term emissions pathways consistent with multiple energy policy goals, and the

immediate policy priorities that underpin them. Many important metrics fall outside the NDC tracking that will formally occur through the Paris Agreement transparency framework, but will be particularly important for the five-year collective stocktakes of progress to better inform the next round of NDCs, and for countries' long-term low-emissions development strategies.

In the near term, IEA tracking and metrics could play an important role in the Facilitative Dialogue, a collective assessment of progress toward the Paris Agreement's long-term goal taking place in 2018. Occurring before NDCs take effect in 2020, metrics used to inform the dialogue could facilitate revision of 2030 NDC targets and improve the consistency of short-term actions in NDCs with long-term goals. Equally, metrics can provide useful information regarding the benefits of sustainable energy transition for other objectives, including energy security, energy affordability or air pollution.

Summary of progress

Summary of progress tables evaluate progress in clean energy technology using a traffic-light system to provide a mid-term tracking (colour) and a recent trend indicator (arrow) to evaluate latest developments. The three tables contain 26 technology areas classified by sector and subsector, encompassing the entire energy system. The subsequent 18 sections contain in-depth tracking information.

Table 2.1 Energy supply

Overall on track?

- Not on track
- Improvement, but more effort needed
- On track, but sustained deployment and policies required

Recent trends

- ↘ Negative developments
- ~ Limited developments
- ↗ Positive developments



Renewable power



Over 2010–15, renewable power generation expanded by more than 30%, and it is forecast to grow by another 30% between 2015 and 2020. However, renewable power generation growth needs to accelerate by an additional 40% over 2020–25 to reach the 2DS target.

Renewable power capacity additions broke another record in 2016, with over 160 GW of capacity additions. Renewable electricity generation grew an estimated 6%, representing over half of global power generation growth.

Recommendation for 2017: Accelerate growth of renewable electricity generation through policy improvements focused on both system-friendly deployment and technology development.



Solar PV and onshore wind



Solar PV and onshore wind electricity generation are expected to grow by 2.5 times and by 1.7 times respectively, over 2015–20. This growth trend is on track with the 2DS target, providing a solid launching pad for the further 2 times increase in solar PV and 1.7 times increase in onshore wind respectively, required over the 2020–25 period.

Strong capacity growth continued for both solar PV and onshore wind, and record-low contract prices were announced in 2016.

Recommendation for 2017: Implement system-friendly solar PV and wind deployment and address market design challenges to improve grid integration of renewables.



Offshore wind and hydropower



Offshore wind generation has grown fivefold over 2010–15 and is expected to double over 2015–20. However, over 2020–25, offshore wind generation needs to triple to be fully on track with its 2DS target.

Offshore wind additions in 2016 declined by a quarter year on year (y-o-y).

For hydropower, the trend of capacity and generation growth is expected to slow down over the 2015–20 period compared with the previous five years. To be on track with 2DS 2025 targets, an increase in capacity growth rates is required.

Hydropower additions decreased for the third consecutive year in 2016.

Recommendations for 2017: Ensure timely grid connection of offshore wind plants, and continue implementing policies that spur competition to achieve further cost reductions for offshore wind. Improve market design to better value the system flexibility of hydropower.



Bioenergy, concentrated solar power (CSP), ocean energy and geothermal

Progress in renewable technologies at earlier technology development stages remains behind the performance needed to get on track to reach their 2DS targets.

Generation costs and project risks remain higher than conventional alternatives, preventing faster deployment.

Recommendations for 2017: Devise plans to address technology-specific challenges to achieve faster growth. Strategies could include: better remuneration of the market value of storage for CSP; improved policies tackling pre-development risks for geothermal energy; facilitating larger demonstration projects for ocean technologies; complementary policy drivers for sustainable bioenergy.



Nuclear power

The average construction starts over the last decade were about 8.5 GW per year. To meet the 2DS targets, more than a doubling is needed – to over 20 GW per year by 2025.

Nuclear power saw 10 GW of capacity additions in 2016, the highest annual increase since 1990, but the year brought only 3 GW of new construction starts.

Recommendation for 2017: Provide clear and consistent policy support for existing and new capacity that includes nuclear power in clean energy incentive schemes and that encourages its development in addition to other clean forms of energy.



Natural gas-fired power

Global natural gas-fired power generation increased by 2.2% in 2014. Organisation for Economic Co-operation and Development (OECD) countries experienced 7.1% growth in 2015 with indications of the continuation of this trend in 2016. Generation growth in non-OECD countries is estimated to have equally remained strong into 2015 and 2016. While this is generally in line with the annual growth rate needed to achieve the 2025 2DS target of 2.4%, recent declines show the fragility of the growth path. Additional progress is also needed in efficiency and flexibility performance of plants to provide support for the integration of variable renewables and serve as a short-term, lower-carbon alternative to coal plants, while preventing long-term stranding of natural gas plants.

Gas-fired power capacity investment declined by 40% y-o-y in 2015 to United States dollars (USD) 31 billion, leading to gas capacity additions of 46 GW.

Recommendation for 2017: Support natural gas-fired power generation as a lower carbon alternative to coal through electricity market mechanisms that establish competitiveness of gas with coal, including carbon pricing and additional support policies, such as maximum emission caps and capacity markets.



Coal-fired power



To get on track with the 2DS, emissions from coal power would need to decline on average by 3% per year until 2025. Adding to the challenge, in 2015, new coal capacity additions stood at 84 GW, 25 GW of which was subcritical. Under the 2DS, unabated coal capacity additions would have to slow down, with subcritical technology deployment abandoned altogether.

Global coal generation increased by 0.7% y-o-y in 2014 and continued to dominate global power generation in 2014, with a share of over 40%. Coal generation in 2015 and 2016 is estimated to have decreased, but pronounced regional and annual variations can be found.

Recommendation for 2017: Implement national energy plans and policies to rapidly phase out construction of coal plants using subcritical technology.



Carbon capture and storage



The total potential annual capture rate of existing projects is over 30 MtCO₂, but given its current proven rate of 9.3 MtCO₂, storage is falling short of meeting the 2DS. Average storage must accelerate to reach over 400 MtCO₂ annually to be on track to meet the 2DS in 2025.

The global portfolio of large-scale CCS projects continued to expand, with the first steel plant CCS project and the first bioenergy with carbon capture and storage (BECCS) plant being deployed.

Recommendation for 2017: Strengthen public and private investment in large-scale projects and CO₂ transport and storage infrastructure plans, across jurisdictions where applicable.

Table

2.2 Energy demand

Overall on track?

- Not on track
- Improvement, but more effort needed
- On track, but sustained deployment and policies required

Recent trends

- ↘ Negative developments
- ~ Limited developments
- ↗ Positive developments



Industry



Decoupling of industrial production from CO₂ emissions is critical to achieve the 2DS targets. Annual growth in CO₂ emissions between 2014 and 2025 needs to be limited to 0.1%, compared to 1.1% in the current pathway, with peaking of industrial CO₂ emissions by 2020.

The industrial sector has continued to progress in energy efficiency and low-carbon technology deployment, limiting its final energy consumption y-o-y growth to 1.3% in 2014. To meet the 2DS, action must accelerate to limit the growth in energy consumption to 1.2% per annum by 2025 and stabilize CO₂ emissions.

Recommendation for 2017: Incentivise energy efficiency improvements through mechanisms facilitating retrofitting of existing capacity and deployment of current best available technologies.



Chemicals and petrochemicals



Average annual growth in the sector's final energy consumption and direct energy-related CO₂ emissions was 2.3% and 2.6%, respectively, during 2000–14, slowing down mainly by switching to lighter feedstocks made economical by price trends in some regions. This trend towards lower CO₂ emissions feedstocks must be sustained in the long term to bring the sector on track to meet the 2DS. Annual increases in process energy consumption and direct CO₂ emissions must stay below 3.1% and 2.8%, respectively, in spite of considerable production increases.

The chemicals and petrochemicals sector has made progress in shifting towards lower-carbon feedstocks in recent years, driven by price changes in some regions.

Recommendation for 2017: Improve publicly available statistics for the chemicals and petrochemicals sector, so as to robustly track progress and set appropriate targets for emissions reductions.



Pulp and paper



The sector's energy use has grown only 1% since 2000, despite a 23% increase in paper and paperboard production. However, major reductions in energy use and CO₂ emissions are still needed in the 2DS, with energy use and direct non-biomass CO₂ emissions declining by 0.8% and 17%, respectively, by 2025.

Research and development on innovative low-carbon processes and products, such as deep eutectic solvents, has become a priority for the pulp and paper sector in recent years, which could lead to CO₂ and energy benefits.

Recommendation for 2017: Encourage optimal use of by-products as a substitute for fossil fuels, and incentivise increased recycling of paper products and pulp.



Iron and steel



Global crude steel production in electric arc furnaces (EAFs) grew from 29% in 2010 to 30% in 2014. To meet the 2DS targets, global crude steel production in EAFs needs to grow to 40% by 2025, shifting away from basic oxygen furnaces/open hearth furnaces, with the overall energy demand of the sector declining by 6% and CO₂ emissions declining by 11%.

Despite economic difficulties in some regions, crude steel production in EAFs continues to grow.

Recommendation for 2017: Deploy best available technologies and energy efficiency improvements in existing capacity to meet 2DS goals, including maximising deployment of scrap-based EAF production.



Aluminium



Meeting the 2DS pathways will require continued efforts to improve specific energy consumption (SEC) of both primary and secondary aluminium, as well as improvement of scrap collection and recycling rates and new technologies to mitigate process CO₂ emissions. To stay on track towards 2DS, overall average energy use increase by the aluminium sector needs to be limited to 4.3% per annum by 2025.

World average energy intensities of primary aluminium smelting and alumina refining decreased by 1.9% and 5.3%, respectively, from 2013 to 2014. In 2014, 31% of aluminium was produced from scrap, maintaining nearly the same share as in 2013, despite 6.7% growth in overall production.

Recommendations for 2017: Further incentivise the secondary production of aluminium through increased recycling of all scrap types to significantly decrease the energy and emissions intensity of production. Also, incentivise material efficiency strategies to provide significant CO₂ and energy savings.



Cement



To stay on track towards 2DS, biomass and waste fuels need to reach 12.1% of thermal energy consumption by 2025 in the 2DS, and the overall energy use increase by the sector needs to be limited to 0.5% per annum by 2025.

Thermal energy intensity of cement kilns continues to improve, with the shift toward higher-efficiency dry kilns. Alternative fuels combined, including biomass and waste, contributed about 5.3% of thermal energy consumption in 2014.

Recommendation for 2017: Increase public and private support for RD&D of alternative products, clinker substitutes and process routes to decrease cement production CO₂ emissions in the long term.



Transport



Transport emissions grew by 2.5% annually between 2010 and 2015. To reach 2DS targets, the sector's well-to-wheel (WTW) greenhouse gas (GHG) emissions must remain stable from 2015 to 2025 and decrease rapidly afterwards. More specifically, WTW GHG emissions from OECD countries need to decline by 2.1% annually between 2015 and 2025 to reach 2DS targets.

CO₂ emissions from transport are still growing, and the transport measures laid out in the nationally determined contributions (NDCs) to the Paris Agreement are not sufficiently ambitious to reach 2DS targets.

Recommendations for 2017: Increase the ambition of the Energy Efficiency Design Index (EEDI) and expand this framework to also include operational efficiency standards for existing ships. This requires swift action to ensure the adequate collection of data along trading patterns of individual vessels.



Electric vehicles



With over 750 000 plug-in electric cars² sold worldwide in 2016, a new historic record has been hit in the electrification of personal transportation. The global EV car stock has reached 2 million units in circulation. Policy efforts need to be sustained and reinforced to accelerate wider adoption and ensure that EV deployment will not fall short of 2DS growth rates in the coming years.

Even though EV sales grew by 40% between 2015 and 2016, in line with 2DS objectives, this is a slowdown from the 70% growth observed between 2014 and 2015, suggesting an increasing risk to start diverging from a 2DS trajectory.

Recommendations for 2017: Prioritise financial incentives for purchasing PEVs and the availability of charging infrastructure. Offer local incentives favouring PEVs over conventional cars, such as access to urban areas restricted to conventional cars and preferential parking rates. Use public procurement programmes for vehicle fleets to support PEV uptake and support RD&D efforts aiming to reduce battery costs and improve performances.

2. See an explanation of the scope and definition of “plug-in electric car” and “EV” in the “Electric Vehicles” section.



Fuel economy of light-duty vehicles



Progress in improving the average tested fuel economy of light-duty vehicles (LDVs) has slowed in recent years, from an annual rate of 1.8% in 2005–08, to 1.2% in 2012–15 and only 1.1% in 2014–15. To stay on track with the 2DS, this trend must be reversed, and an annual fuel economy improvement rate of 3.7% through 2030 must be achieved.

Globally, the average rate of fuel economy improvements has slowed in recent years to only 1.1% in 2014–15.

Recommendations for 2017: Introduce fuel economy regulations, starting from labels and consumer information, developing fuel economy baselines and setting fuel economy improvement targets in countries that do not yet have them in place. Strengthen regulatory policies in countries where they already exist, spelling out ambitions for the long term. Make sure that annual improvement rates are compatible with long-term ambitions that match the Global Fuel Economy Initiative (GFEI) goal. Adopt supporting policy tools, including differentiated taxation and low-interest loans, also targeting second-hand vehicles traded between developed and developing countries.



Trucks/heavy-duty vehicles



Countries with vehicle efficiency standards account for about 60% of new heavy-duty vehicle (HDV) sales worldwide. The resultant 10% annual improvement in truck fuel economy over the coming decade is insufficient to counterbalance emissions growth due to increasing trucking activity. To attain 2DS goals, annual WTW GHG emissions growth of heavy-duty trucks must be capped at 1.75% between 2015 and 2025.

Heavy-duty vehicle efficiency and GHG standards have only been recently implemented in Canada, the People's Republic of China (hereafter, "China"), Japan and the United States. Nowhere else do such standards exist, but they would need to be adopted more broadly to achieve 2DS goals.

Recommendations for 2017: Develop vehicle efficiency and/or GHG standards for new HDV sales in major markets that do not yet apply them (e.g. Association of Southeast Asian Nations [ASEAN], Brazil, the European Union, India, Korea, Mexico, South Africa, etc.). Better data collection on truck operations is also needed to exploit opportunities to improve systems and logistics efficiencies.



International shipping



Meeting the 2DS requires the global shipping fleet to improve its fuel efficiency per vehicle-km at an annual rate of 2.3% between 2015 and 2025. Yet, the Energy Efficiency Design Index (EEDI) of the International Maritime Organization (IMO), applying to new ships only results in a fleet average improvement of 1% to 2025.

The IMO has made progress in agreeing on regulations on reducing sulphur oxide (SOx) and nitrogen oxide (NOx) emissions from ships. Yet its GHG policy is still under consideration: an initial GHG strategy is expected by 2018, which will be a stepping stone to the final strategy expected by 2023. Implementing IMO's final GHG strategy only by 2023 will have very little impact on the possibility of meeting 2025 2DS targets.

Recommendations for 2017: Strengthen enforcement mechanisms for emissions from ships and the EEDI, including inspections, sanctions and legal frameworks, to ensure compliance with IMO measures. Stimulate the engagement of ports in encouraging GHG reductions in ships, e.g. with bonus/malus schemes supporting clean ships from fees applied to ships with poorer environmental performances. Introduce carbon taxes on shipping fuels based on their life cycle GHG emissions.



Aviation



Recent annual average fuel efficiency improvements of 3.7% have exceeded industry aviation targets. Yet, with few alternatives to fossil fuels, aircraft efficiency needs to continue to improve at a rapid rate, and incremental shares of advanced biofuels need to be adopted, to be in line with 2DS targets.

The WTW GHG emissions of the aviation sector are expected to grow at a rate of 2.0% per year from 2015 to 2025. However, to align with the 2DS emissions must stabilise by 2025 and rapidly decrease afterwards.

The pace of improvement required for the recently proposed CO₂ standard by the International Civil Aviation Organization (ICAO) for new aircrafts falls short of 2DS targets.

Recommendations for 2017: Introduce carbon taxes on aviation fuels based on their life cycle GHG emissions. Align the ambition of ICAO CO₂ standard with the sectorial mitigation targets (carbon-neutral growth by 2020, 2% annual efficiency improvement to 2050, and halving of emissions by 2050 compared with 2005) and clarify the magnitude of the emission savings expected from the recently adopted Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).



Transport biofuels



Conventional biofuels are generally on track to meet 2DS requirements by 2025. However, over 57 billion litres of advanced biofuels are required by the 2DS in 2025. Based on forecasted advanced biofuel production growth to 2020, rapid commercialisation will be necessary over 2020–25 to deliver a twenty-five-fold scale-up in output to stay on track with the 2DS.

Global biofuel production increased by 2% in 2016, a significantly slower rate than pre-2010 levels. However, policy support for advanced biofuels is growing, including the announcement of advanced biofuel mandates in an increasing number of European countries.

Recommendation for 2017: Enhance advanced biofuel policies, including mandates, frameworks limiting the life-cycle carbon intensity of transportation fuels, and financial de-risking measures for advanced biofuel plant investment while costs remain high.



Buildings



Global average building energy use per person since 1990 has remained constant at 5 MWh per person per year. This rate would need to decrease to less than 4.5 MWh per person by 2025 to be in line with 2DS targets. Furthermore, current investments in building energy efficiency are not on track to achieve the 2DS targets.

Average global building energy intensity per square metre only improved by 1.3% last year, while total floor area grew by 3%. Progress in some countries is promising, but overall, buildings are still not on track to meet 2DS objectives by 2025.

Recommendation for 2017: Countries can take immediate action to put forward commitments for low-carbon and energy-efficient buildings to implement their NDCs as a first step and a clear signal to scale up actions across the global buildings sector.

**Building envelopes**

Global annual average building envelope energy intensity improvements of 1.4% have been achieved since 2010. Building envelope intensities need to improve by 30% by 2025 to keep pace with growth in floor area and the demand for greater comfort.

Progress on building energy codes in developing regions last year is a positive step toward 2DS ambitions, but two-thirds of countries still do not have mandatory building energy codes in place.

Recommendation for 2017: Global co-operation should seek to ensure that all countries implement and enforce building energy codes and standards for both new and existing buildings, with improvement in enforcement and verification of codes and standards to overcome barriers to their implementation.

**Lighting, appliances and equipment**

Electricity consumption by lighting, appliances and building equipment needs to halve from the current 3% average increase per year over the last decade to a 1.5% annual increase in the 2DS.

The growing shift to light-emitting diodes (LEDs) in the last two years is encouraging, with LEDs representing 15% of total residential lamp sales in 2015 (expected to have grown to nearly 30% in 2016). Effort is needed in markets everywhere to ensure that progress carries over to high-performance appliances and equipment.

Recommendation for 2017: Countries should seize on momentum under the recent Kigali Agreement to rapidly move global markets for cooling equipment to much higher energy performances.

Table

2.3 Energy integration**Overall on track?**

- Not on track
- Improvement, but more effort needed
- On track, but sustained deployment and policies required

Recent trends

- ↘ Negative developments
- ~ Limited developments
- ↗ Positive developments

**Renewable heat**

The direct use of renewables for heat (efficient biomass, solar thermal and geothermal) increased by 8% from 2010 to 2014. Renewable heat use remains largely unexploited, in spite of its promising potential. An increase in the consumption of direct renewables for heat by 32% is needed by 2025 to meet the 2DS. For solar thermal, heat production would have to triple by 2025, requiring doubling of the current annual deployment rate.

Renewable heat has seen some growth in recent years but at a much slower rate than for renewable electricity.

Recommendation for 2017: Governments should set targets and develop strategies for heat decarbonisation that cover all sectors and consider the appropriate balance between renewable heat deployment, heat electrification and energy efficiency improvement.



Energy storage



Energy storage deployment is on track with 2DS due to positive market and policy trends, but an additional 20 GW of capacity is needed by 2025. To remain on track with the 2DS targets, technology deployment will need to continue at its current growth trajectory and grow twenty-fold over the next decade.

Deployed storage reached 930 megawatts (MW) in 2016, with remarkable year-on-year growth of over 50% for non-pumped hydro storage.

Recommendation for 2017: Clarify the position of storage in the different steps of the electricity value chain to enhance systems-friendly deployment of energy storage and improve business cases for the use of storage in vertically-integrated markets.

Renewable power

- Improvement needed
- Positive developments

Renewable power capacity additions continued to reach new record highs in 2016, driven by cost reductions and policies aimed at enhancing energy security and sustainability and improving air quality. According to the IEA *Medium-Term Renewable Energy Market Report 2016*, onshore wind and solar PV are expected to drive the majority of renewable capacity growth over the next five years. They are also the only two technologies on track to reach 2DS targets. Accelerated action is needed to address both policy- and technology-specific challenges for renewables to be firmly on track with the 2DS target.

Recent trends

In 2016, global renewable electricity generation grew by an estimated 6% and represented around 24% of global power output. Hydropower remained the largest source of renewable power, accounting for around 70%, followed by wind (16%), bioenergy (9%) and solar PV (5%). In 2015, net additions to grid-connected renewable electricity capacity reached a record high at 153 GW, 15% higher than in 2014. For the first time, renewables accounted for more than half of new additions to power capacity and overtook coal in terms of world cumulative installed capacity.

In 2016, solar PV annual additions surpassed that of wind, breaking another record, with 70 GW to 75 GW coming on line, almost 50% higher growth versus 2015. Annual grid-connected solar PV capacity in China more than doubled in 2016 versus 2015, with 34.5 GW becoming operational. Developers rushed to connect their projects before feed-in tariffs (FiTs) were reduced as planned in August 2016. In the United States, solar PV annual additions doubled, with over 14 GW coming on line in 2016, followed by Japan (7.5 GW). The European Union's annual solar PV market contracted by a third to 5.5 GW in 2016 as growth slowed in the United Kingdom. India's annual solar PV additions doubled, with 4 GW added to the grid last year.

In 2016, onshore wind capacity grew by 50 GW, about 15% less versus 2015. This decline was mainly due to China, which connected 19 GW of new onshore wind capacity, significantly less than 32 GW in 2015, when developers rushed to complete their projects to benefit from higher FiTs. However, despite slower capacity growth, China curtailed around 50 terawatt hours (TWh) of wind power last year, with average nationwide curtailment rate increasing from 15% in 2015 to around 17% in 2016. The European Union added over 11 GW, led by Germany and France, followed by the United States (8.2 GW), India (3.6 GW) and Brazil (2.5 GW). In 2016, global offshore wind new additions are estimated to have

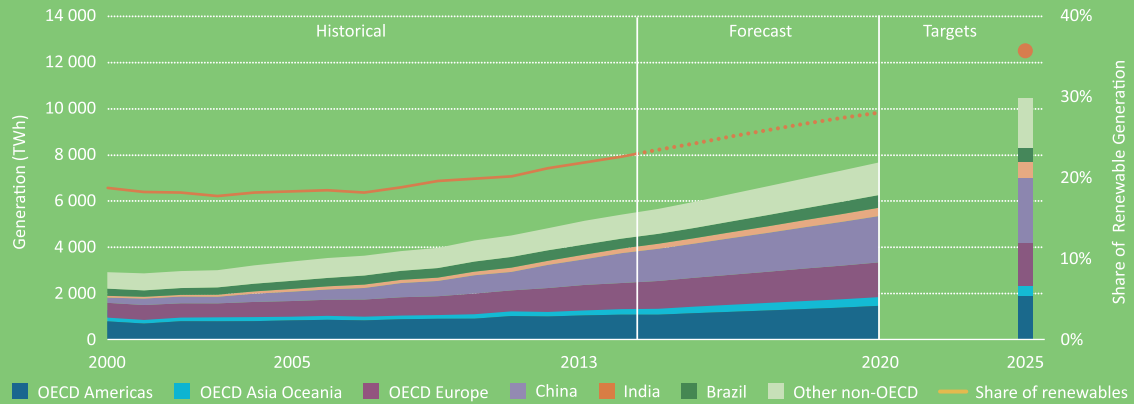
declined versus 2015 by a third, with annual grid-connected capacity decreasing by about half in Europe as a result of a lull in the United Kingdom and Germany project pipelines.

Hydropower additions are estimated to have decreased for the third consecutive year since 2013, with fewer projects becoming operational in China (12.5 GW). Brazil added almost 5 GW of new capacity. In 2016, CSP capacity grew by almost 0.3 GW, driven almost entirely by Africa. Phase 1 of Morocco's NOOR Ouarzazate Plant, a 160 MW parabolic trough plant with three hours of storage, came on line, while South Africa commissioned two plants.

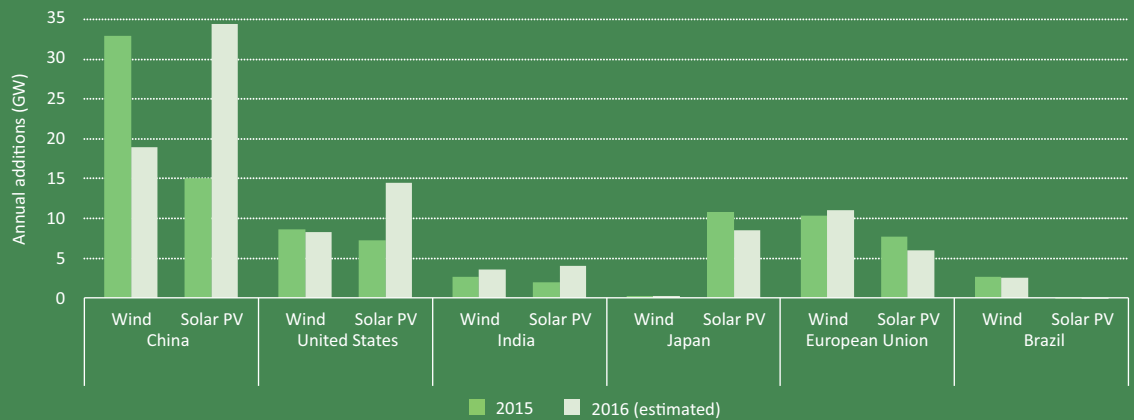
Over the last year, renewable policies for utility-scale projects continued to shift from government-set tariffs to competitive tenders with long-term power purchase agreements. By 2016, almost 70 countries had employed auction/tender schemes to determine support levels, compared with fewer than 20 in 2010. While the first adopters were primarily emerging economies (Brazil and South Africa), this trend has now spread to mature renewable markets (the European Union and Japan). Tender schemes have become a preferred policy option, because they combine competitive pricing with volume control and can support a cost-effective deployment of renewables. As a result, record low prices were announced over the last year in markets as diverse as Latin America, Europe, North America, Asia and North Africa.

In Chile and the United Arab Emirates, solar PV developers signed contracts for projects at below USD 30/MWh, a global record low. In Mexico's energy auctions, winning bids ranged from USD 28/MWh to USD 55/MWh for both solar PV and onshore wind. In India, solar PV contract prices decreased on average by more than a third to USD 55/MWh in 2016 versus 2015/14. For offshore wind, record low contracts were signed in the Netherlands (USD 55/MWh to USD 73/MWh) and Denmark (USD 65/kWh) for a near-shore project, excluding grid connection costs. These contract price announcements reflect a subset of

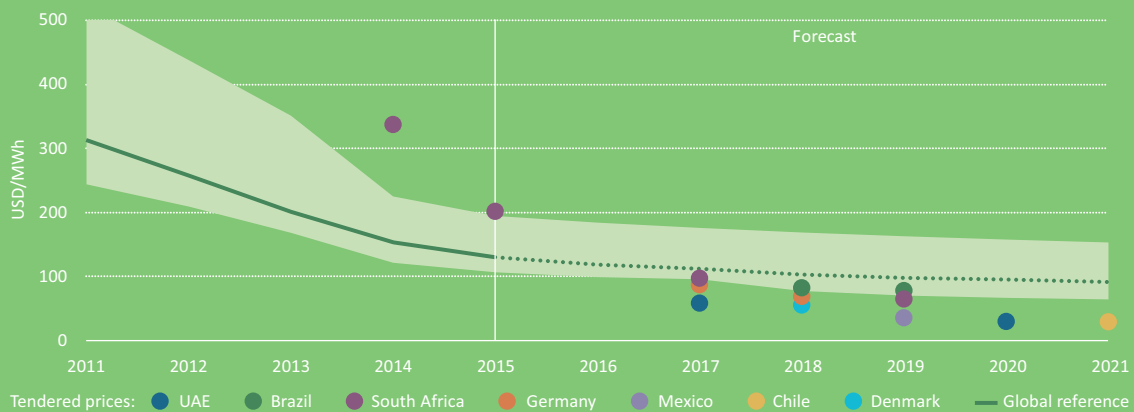
2.1 Total renewable power generation by region



2.2 Wind and solar PV annual additions 2015 and 2016 (estimated)



2.3 Solar PV LCOE and contract prices



For sources and notes see page 104

projects that are expected to be commissioned over 2017–20 and should not be directly compared to average generation costs that indicate higher values. Still, they signal a clear acceleration in cost reductions, increasing the affordability and improving the attractiveness of renewables among policy makers and investors.

Tracking progress

Renewable power is forecast to grow by 36% over 2015–21, making it the fastest-growing source of electricity generation globally. Generation is expected to exceed 7 650 TWh by 2021, but needs to accelerate further and expand by an additional 26% over 2021–25 for renewables to be firmly on track to reach the 2DS target of 10 300 TWh.

Solar PV and onshore wind are the only two renewable power technologies that are on track to reach their 2DS targets by 2025. Electricity generation is forecast to triple for solar PV and double for onshore wind over five years, driven by strong policy support and further cost reduction expectations. This growth is driven by China, with higher targets announced under China's 13th Five-Year Plan (FYP), and the United States with the multi-year extension of federal tax credits combined with continued supportive policy environment at the state level. India's solar PV growth is also expected to accelerate driven by auctions; however, challenges concerning grid integration and the financial health of utilities hamper a faster growth towards the country's ambitious renewable targets. In Europe, the growth of both solar PV and onshore wind is expected to slow as incentive reductions, policy uncertainties at the country and EU level, and overcapacity remain challenges.

Offshore wind's progress towards the 2DS targets has improved as countries in the European Union are fully on track to reach their 2DS generation targets driven by technology improvements and faster-than-expected cost reductions and grid connection improvements. In addition, the deployment is forecast to accelerate in China with improving economic attractiveness. Hydropower also needs improvement to reach its 2DS generation target. Overall, hydropower new capacity additions are expected to slow over 2015–21 compared with the previous six years owing to the large influence of China's slowdown in large-scale project development due to increasing environmental and social concerns. However, large hydropower growth is forecast to be robust in emerging markets in Southeast Asia, Latin America and sub-Saharan Africa for large-scale projects, though environmental concerns and the availability of financing remain challenging.

Other renewable technologies are not on track to reach their 2DS targets. For CSP, the growth is seen mostly coming from emerging economies, especially South Africa, China and Morocco, where the largest plants with longer storage hours are expected to come on line. However, investment costs remain high, and further deployment needs a better remuneration of storage capacity. For bioenergy, despite a more optimistic outlook in Asia, with increasing co-firing and waste generation, most generation costs remain higher than conventional alternatives. For geothermal, pre-development risks remain high overall, and drilling costs have been increasing over the last decade. Ocean technology holds a great potential but requires faster cost reductions.

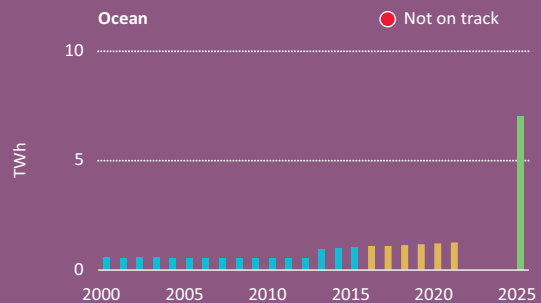
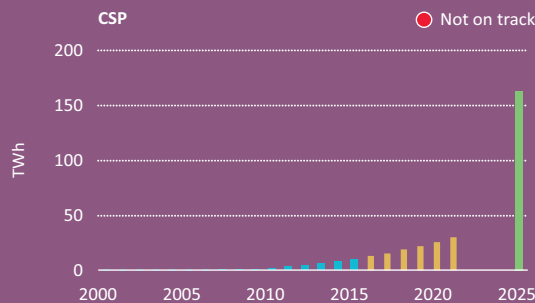
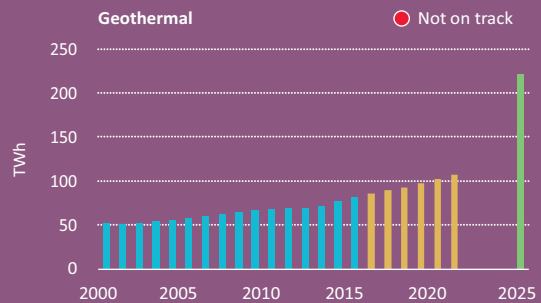
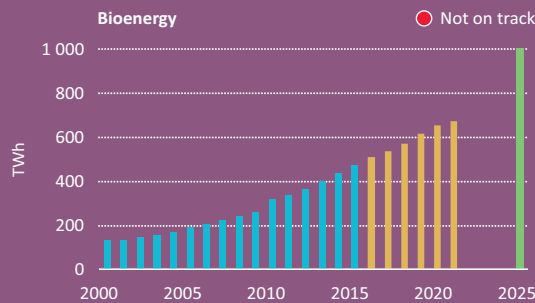
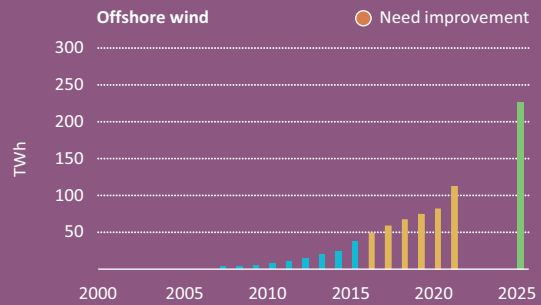
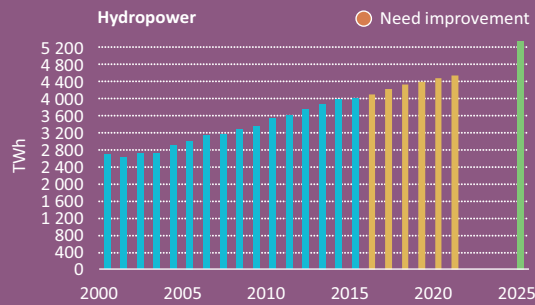
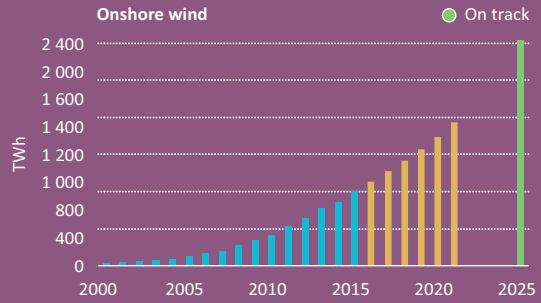
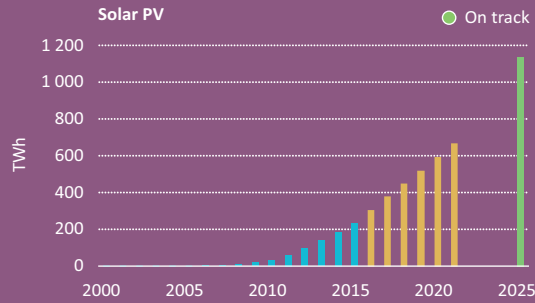
Recommended actions

In 2016, prospects for renewable electricity were more optimistic over the medium term, driven by policy improvements in key markets, cost reductions mainly for wind and solar technologies, and efforts to improve air quality. However, renewables are still at risk of falling short of longer-term 2DS power generation targets, with only solar PV and onshore wind being on track.

Accelerated growth of renewable electricity generation requires policy improvements focusing on three main challenges to deployment. First, policy makers should implement stable, predictable and sustainable policy frameworks, giving greater revenue certainty to renewables, and reducing policy uncertainties. Second, policies should address infrastructure challenges and market design issues to improve grid integration of renewables. Third, countries should develop policy mechanisms that reduce the cost of financing and lower off-taker risks, especially in developing countries and emerging economies.

In addition, some policies could also address technology-specific challenges. These policies could include: better remuneration of the market value of storage for CSP and pumped-storage technologies, ensuring timely grid connection and continued implementation of policies that spur competition to achieve further cost reductions for offshore wind, improved policies tackling pre-development risks for geothermal energy, and facilitating larger demonstration projects for ocean technologies. Other needed actions would involve developing the means to reflect the wider complementary policy drivers for sustainable bioenergy such as rural development, waste management and dispatchability, especially in competitive renewable energy auction framework.

2.4 Tracking by technology and region



■ World ■ Forecast ■ Target

Nuclear power

● Improvement needed
~ Limited developments

In 2016, nuclear power saw the highest capacity additions since 1990 (10 GW gross). New construction continued to fluctuate, with 3.2 GW commencing in 2016, down from 8.8 GW during the previous year, and averaging 8.5 GW over the past ten years. Capacity additions of 20 GW per year are needed to meet the 2DS targets.

Recent trends

Nuclear power accounts for approximately 11% of total electricity production and one-third of electricity from low-carbon sources. While the Paris Agreement is not technology specific, out of the 163 Intended Nationally Determined Contributions (INDCs) submitted by the end of 2016, only ten countries explicitly mentioned nuclear energy in their national strategies. These include countries with ambitious nuclear development programmes (China and India, for example). Premature closure of operational nuclear power plants (NPPs)¹ remains a major threat to meeting 2DS targets. A number of reactors in the United States are in jeopardy of shutting down in liberalised markets dominated by low natural gas prices, with nuclear largely excluded from financial incentives to other low-carbon generation technologies. In 2016, a considerable part of French nuclear capacity was offline owing to safety reviews.²

Projected nuclear growth remains strongest in Asia, as China released a new five year plan to more than double its 2015 capacity to 58 GW (net) by 2020, with an additional 30 GW (net) under construction at that time. However, with 31.4 GW (net) in operation at the end of 2016 and 21.5 GW (net) under construction, China will likely miss that target by a year or two. Korea also projects considerable growth – from 23 GW in 2016 to 38 GW by 2029. The Russian Federation (hereafter, “Russia”) reduced its projections during 2016, noting that the reductions were to better align with reduced projections of electricity demand. In the United Kingdom, final approvals were given for the Hinkley Point C Contract for Difference after a government review of the entire project, and EDF Energy made the final investment decision in July 2016. Poland delayed a decision on its nuclear programme until mid-2017, citing the need to find a suitable financing model for the country, and Viet Nam abandoned plans to build two reactors due to lower electricity demand and the cost of nuclear technology compared with coal.

In terms of technology, the majority of reactors under construction today are Generation III/III+ designs. The first APR1400 and VVER1200

(Novovoronezh 2 in Russia) were connected to the grid in 2016. Efforts to develop and deploy small modular reactor (SMR) designs continued, with Argentina’s CAREM reactor and Russia’s and China’s floating NPPs. In the United States, NuScale Power submitted the first-ever design certification application for an SMR to the US Nuclear Regulatory Commission. All of these SMRs are 100 megawatts electrical (MWe) or smaller.

Tracking progress

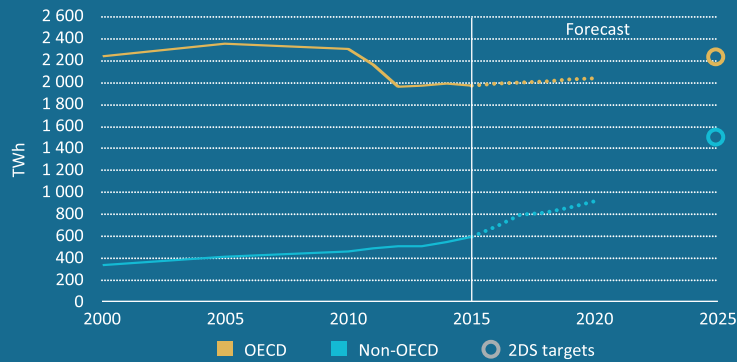
According to the most recent Red Book (NEA and IAEA, 2016), gross installed capacity is projected to be 402 GW to 535 GW by 2025; in the 2DS, global nuclear capacity would need to reach 529 GW by that time. Considering currently installed capacity of 413 GW and new capacity under construction of 66 GW, progress towards near-term targets has been positive. With another 20 GW of planned construction in the next three to four years, the remaining gap to the 2025 2DS target would be approximately 30 GW, which could be met if construction starts were sustained at the levels of 2009–10. However, retirements due to phase-out policies in some countries, long-term operation limitations in others or loss of competitiveness against other technologies could offset these gains. Up to 50 GW could be lost by 2025. Without action to address these reductions due to non-technical factors, the capacity will more likely be 70 GW to 90 GW short of the 2025 2DS target, unless annual grid connections double compared with the 2016 rate.³

Recommended actions

Increasing nuclear capacity deployment could help bridge the 2DS gap and fulfil the recognised potential of nuclear energy to contribute significantly to global decarbonisation. This requires clear and consistent policy support for existing and new capacity, including clean energy incentive schemes for development of nuclear alongside other clean forms of energy. In addition, efforts are needed to reduce the investment risk due to uncertainties, such as licensing and siting processes that have clear requirements and that do not require significant capital expenditure prior to receiving a final approval or decision. Industry must take all actions possible to reduce construction and financing costs in order to maintain economic competitiveness.

1–3. Refer to Technology overview notes on page 104.

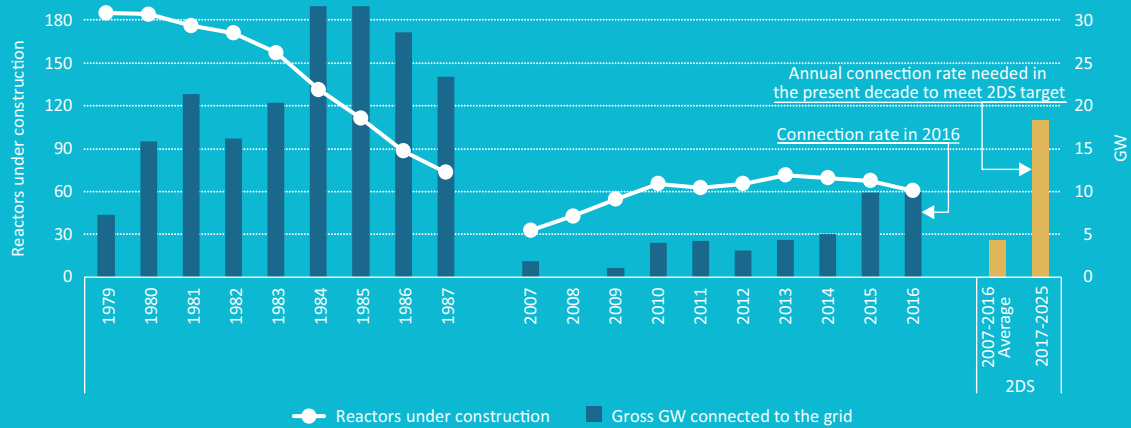
2.5 Nuclear electricity generation



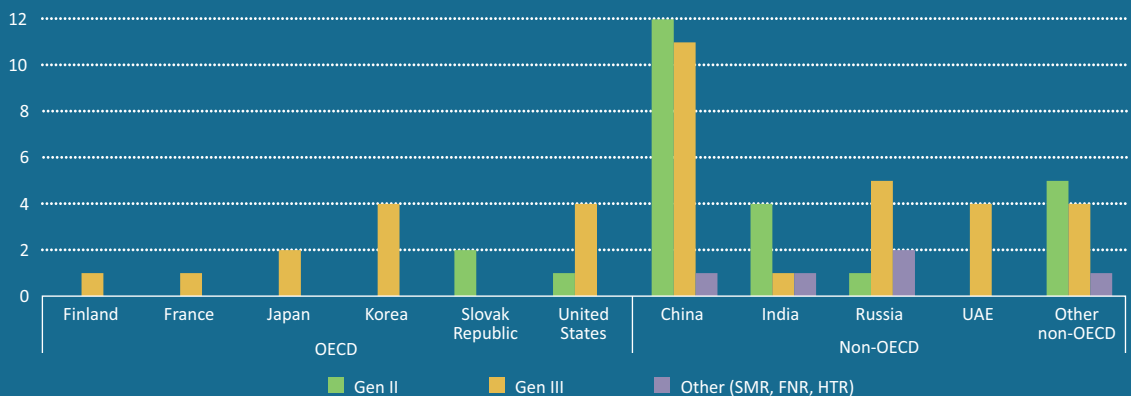
10GW

OF NUCLEAR
CAPACITY ADDED
IN 2016, THE
HIGHEST ADDITION
SINCE 1990

2.6 Capacity additions and reactors under construction



2.7 Reactors under construction



For sources and notes see page 104

Natural gas-fired power

● Improvement needed
~ Limited developments

Natural gas-fired power generation, which has an important role in the 2DS in helping reduce emissions by gradually displacing unabated coal-fired baseload generation, increased by 2.2% in 2014 (reaching 5 155 TWh). While this is generally in line with the 2.4% annual growth needed to achieve the 2025 2DS target, decline in 2013 and strong regional differences show the fragility of the growth path.

Recent trends

Gas-fired power generation in OECD countries recovered from the declines of the previous two years and increased by 7.1% in 2015 to 2 803 TWh. In the United States, 2015 gas-fired power generation reached a new record high (1 374 TWh) with coal-to-gas switching in the country also continuing to be strong in 2016. This trend is in contrast to gas generation in Europe, which remains well below its peak in 2008, despite strong growth in 2015 and 2016. Reductions in Japanese and Korean gas-fired power generation led a 5.7% decline in OECD Asia in 2015. Outside the OECD, gas generation in 2014 increased by 5.6% to 2 540 TWh and growth is estimated to have remained strong in 2015 and 2016. While demand grew in all major regions in 2014, the Middle East was responsible for around half of the increase.

Investments in gas-fired power declined by 40% in 2015 to USD 31 billion, leading to gas capacity additions of 46 GW. Combined-cycle plants accounted for roughly three-quarters of the additions in 2015. The Middle East, China and the United States were responsible for over half of the investment activity. Infrastructure considerations remain the main obstacle to stronger gas-fired power development in many developing countries, because the gas pipeline network needed to take advantage of low liquefied natural gas (LNG) prices often remains underdeveloped. As a result, coal remains the preferred fuel in many regions. In the United States, where gas prices are low and coal plants are being retired for economic and environmental reasons, investments have remained robust, although capacity additions were slightly lower than in previous years.

A major focus of gas turbine design is on flexibility performance, both for new-build plants and for retrofits of existing plants. Improvements in ramping capabilities, start-up times, turndown ratios and part-load behaviour are continuing in parallel with more moderate full-load efficiency improvements. Research on novel thermal coatings and cooling technologies continues to enable higher temperatures and efficiencies. State-of-the-art combined-cycle gas turbine (CCGT) efficiency now exceeds 60%, with

expected improvements to 65% efficiency over the next decade. Top open-cycle gas turbine (OCGT) efficiency is at around 42%, up from around 35% in 1990.

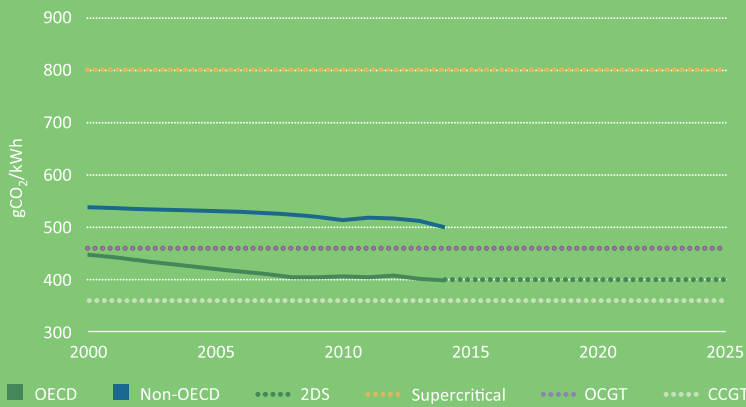
Tracking progress

The role of natural gas-fired power generation in the 2DS is twofold: first, to provide flexibility to support the integration of renewables, and second, as a lower-carbon alternative to coal-fired generation. Coal-to-gas switching will be of particular importance in the short term until 2025–30 in the 2DS, with strong deployment of both gas turbines and combined-cycle plants at the expense of coal. In the 2DS, gas-fired power generation increases over the next decade by roughly 2.4% per year. While this is markedly lower than the 2.2% observed in 2014 and the average over the last decade (3.9%), the volatility of the growth path over the last several years and pronounced regional differences indicate the fragility of gas generation growth. Additional progress is also needed in efficiency and flexibility performance of plants to provide support for the integration of variable renewables and serve as a short-term, lower-carbon alternative to coal plants, while preventing long-term stranding of gas plants. Gas is, however, increasingly competing not only with coal but also with other low-carbon alternatives that are already contributing to decarbonising the power sector in many regions, such as energy efficiency and renewable power generation.

Recommended actions

The competitiveness of natural gas relative to alternative generation technologies in the electricity system is highly dependent on regional market conditions. Carbon pricing, maximum emission caps and strict pollution regulations have proven their ability to establish competitiveness of gas with coal, and technology-neutral competitive mechanisms can ensure electricity supply security. With gas being a source of carbon emissions, R&D should increasingly also focus on gas power generation with CCS, because unabated gas, just like coal, is too carbon-intensive in the long run to reach the 2DS target.

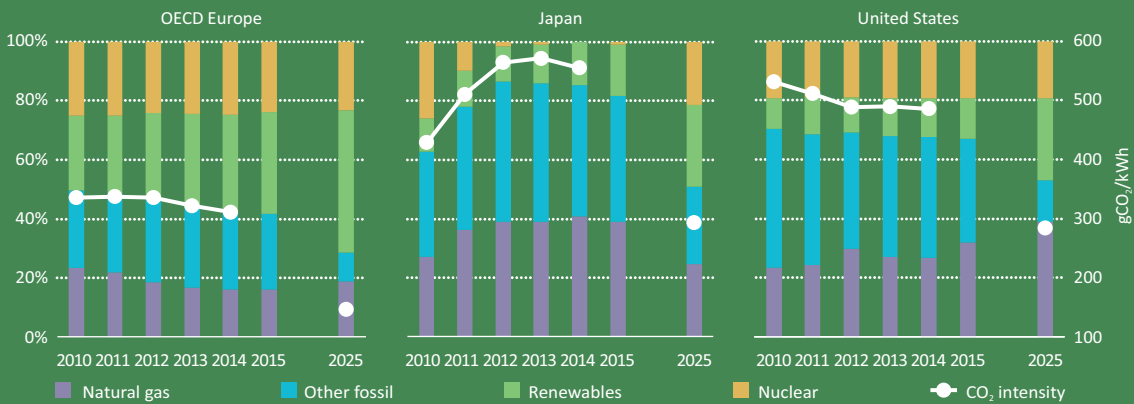
2.8 Natural gas-fired power technology intensity



2016

GAS FIRED POWER GENERATION EXCEEDS COAL GENERATION IN THE UNITED STATES FOR THE FIRST TIME

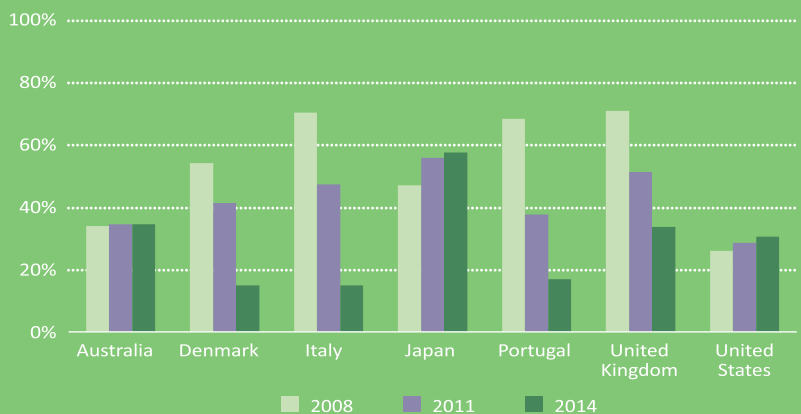
2.9 Power generation mix and related CO₂ intensity



31 USD BILLION

GAS FIRED POWER PLANT INVESTMENTS IN 2015

2.10 Natural gas-fired power capacity factors



Coal-fired power

● Not on track
~ Limited developments

Coal continues to dominate global power generation, with a share of over 40%. While generation growth has slowed, emissions from coal power would need to decline on average by 3% per annum until 2025 to be on track with the 2DS. In 2015, capacity additions stood at 84 GW, of which around 25 GW use subcritical technology. Under the 2DS, unabated coal capacity additions would have to slow down, with subcritical technology deployment abandoned altogether.

Recent trends

Coal's share in power generation remained at a notable level of 41% (9 690 TWh) in 2014, with generation growth of 0.7% from 2013 to 2014. Coal generation in 2015 and 2016 is estimated to have decreased, but pronounced regional and annual variations can be found. Coal-fired power generation in the major developed countries, in particular the United States, is on a steep downward trajectory while developing countries are still experiencing coal generation growth.

In OECD countries, power generation from coal decreased from 2014 to 2015 by 7.5% (–260 TWh) to an estimated 3 201 TWh, setting a new record low for the past decade. The main contributor to the decrease was the United States, which experienced a sharp decline of 14% (–239 TWh) compared with 2014, due to competitive gas-fired generation and the expansion of renewables. Electricity demand growth in OECD countries remains weak, and the share of coal in the overall generation mix fell from 32% to 30% in 2015.

Outside the OECD, coal generation in China, the centre of global coal demand, decreased in 2015 due to a reduction in electricity demand, coupled with an increased generation from hydro and nuclear.¹ Despite the decrease in generation in 2015, 52 GW of coal-fired generation capacity was added in China in 2015, and roughly 150 GW is currently under construction. In India, the third-largest coal consumer in the world, coal-fired power generation increased by 3.3% in 2015, which is considerably lower than the 11% growth of 2014, mostly due to lower demand growth.

Tracking progress

While coal generation growth has markedly slowed compared with the average of the past decade, and is estimated to have even contracted in 2015 and 2016, 84 GW of new coal capacity were still

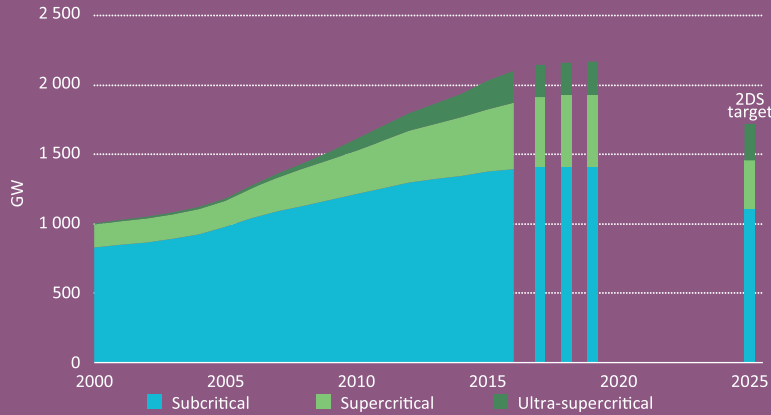
installed in 2015, almost 30% (25 GW) of which comprised subcritical technology, and around 280 GW are currently under construction worldwide, with roughly 10% being subcritical. According to 2DS projections, coal-based CO₂ emissions must decline by around 3% annually by 2025. Further, to meet the 2DS targets, unabated coal generation needs to start to decline after 2020, led by a reduction in generation from the least efficient technologies.

Recommended actions

Policy measures need to address both the long-term and short-term challenges associated with generation from coal. Ultimately, a long-term carbon price signal will be needed to set adequate investment incentives and hence enable a low-carbon energy transition. For the short term, carbon pricing and more stringent pollution control regulations may be used to reduce emissions, minimise local air pollution, and limit and ultimately phase out generation from subcritical coal-fired power stations. Examples are emissions performance standards in Canada and the United Kingdom for power generation capacity additions as well as the carbon price support in the United Kingdom. In OECD countries, and especially in many emerging economies, where coal-fired power generation is set to expand in the near future, new-build coal-fired power units should aim for best available efficiencies (currently, through application of supercritical or ultra-supercritical technologies), where feasible, and be designed in view of potential future CCS retrofits, if they are not equipped initially with CCS. Further, coal plant designs should ensure sufficient operation flexibility to balance electricity supply and demand and to support the introduction of increasing shares of intermittent renewables onto the power grid.

1. Refer to Technology overview notes on page 104.

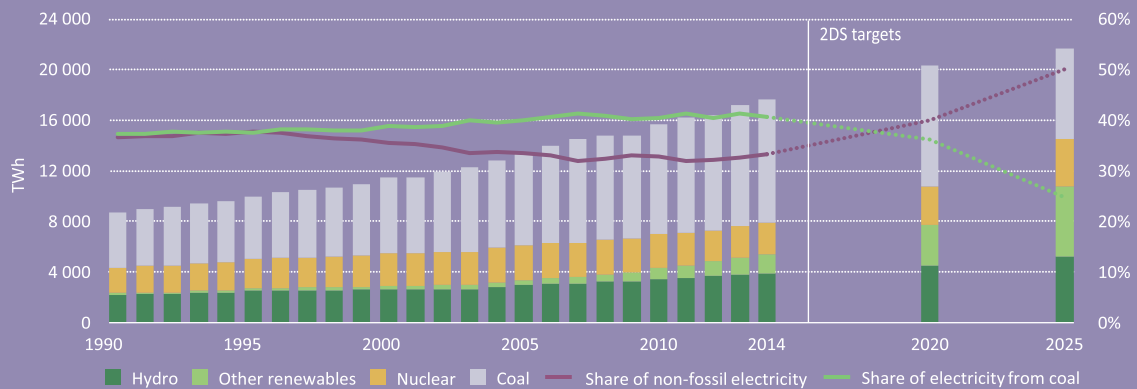
2.11 Coal capacity development



75%

**OF INDIA'S
ELECTRICITY
IS GENERATED
FROM COAL**

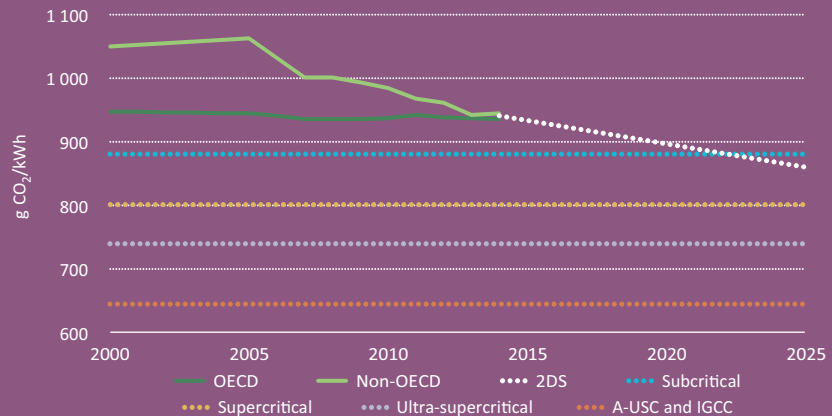
2.12 Coal and non-fossil power generation



**84
GW**

**NEW COAL
FIRED
CAPACITY
IN 2015**

2.13 Emission factors from coal power generation



For sources and notes see page 104

Carbon capture and storage

● Not on track
 ↗ Positive developments

The global portfolio of large-scale CCS projects continues to expand. The first steel plant CCS project began operations in 2016 and the largest coal-fired CCS power plant started up in January 2017. Nevertheless, capture and storage capacity would need to expand tenfold to be on track to meet the 2DS in 2025. A renewed emphasis on CCS in long-term climate strategies and targeted support for project deployment are vital.

Recent trends

In 2016, the Sleipner CCS project in Norway marked 20 years of successful operation, having stored almost 17 MtCO₂ in a saline aquifer deep under the North Sea. The world's first large-scale CCS project in the iron and steel industry also commenced operation in 2016 in Abu Dhabi, capturing up to 800 000 tonnes of CO₂ annually.¹ At the beginning of 2017, the Texas Petra Nova project also came into operation as the largest post-combustion carbon capture system installed on an existing power plant, capturing up to 1.4 MtCO₂ annually.² The Illinois Industrial CCS Project is the world's first CCS project linked with bioenergy. The Tomakomai project in Japan also began CO₂ injection in April 2016. While not large-scale (it will capture 100 000 tonnes of CO₂ per year), the project will demonstrate the feasibility of CO₂ storage in formations under the seabed in Japan.³

Two further projects are expected to come on line in 2017, bringing the number of large-scale CCS projects operating globally to 19.⁴ The Norwegian government announced it has included a grant of 360 million Norwegian kroner (NOK) (USD 45 million) in its 2017 budget for the continued planning of further full-scale demonstration facilities.⁵ The Oil and Gas Climate Initiative (OGCI) has also announced its intention to invest up to USD 1 billion for CO₂ and methane reduction technologies and projects over the next ten years.

Tracking progress

CCS is not on a trajectory to meet the 2DS target of over 400 MtCO₂ being stored per year in 2025. The 17 operational large-scale projects have a total potential capture rate of over 30 MtCO₂ per year.⁶ The capture and storage rate would need to increase tenfold in order to be on track to meet the 2DS in 2025. Furthermore, the 2DS annual target for CO₂ captured and stored from bioenergy projects leading to negative emissions is nearly 60 million tonnes (Mt) in 2025. A

constant flow of projects through development to operation is crucial to meeting the targets under the 2DS and for maintaining and growing the global technical capacity in CCS.

While there is a surge in projects beginning operation over the 2016–17 timeframe, no CCS project took a positive investment decision or began advanced planning in 2016, causing concern that global progress will stall. Moreover, the number of projects under development has shrunk over the past years. Currently 10 projects are in development, with 5 under construction and 5 in advanced planning, down from a total of 18 in 2015.

Recommended actions

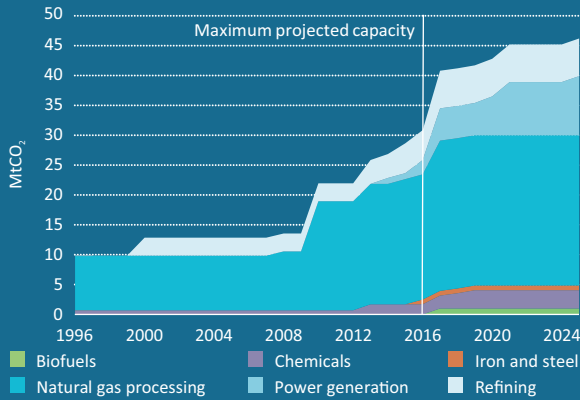
Governments should assess the value of CCS for their climate strategies. Early CCS deployment requires targeted financial and policy support to deliver deep emissions reductions. The current absence of adequate policy support is impeding progress with CCS, with implications for the achievement of long-term climate targets. Furthermore, an observed trend in decreasing CCS-related public RD&D investment over the last few years by IEA member countries should urgently be reversed.

Investment in geological CO₂ storage is an urgent priority, and government leadership is essential. Co-ordinated and extensive CO₂ storage assessment programmes are required to prove secure, practical and bankable CO₂ storage areas and sites in all key regions. Given the long lead times involved in developing CO₂ storage facilities, this effort must start now. Governments and industry should also ensure appropriate planning for and development of large-scale CO₂ transport and storage infrastructure, across jurisdictions where applicable.

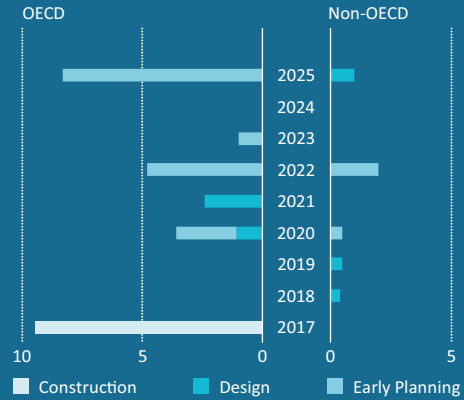
Creating the conditions for a separate CO₂ transport and storage business could address challenges experienced with integrated projects and underpin investment in CO₂ capture technology across power and industrial applications.

1–6. Refer to Technology overview notes on page 104.

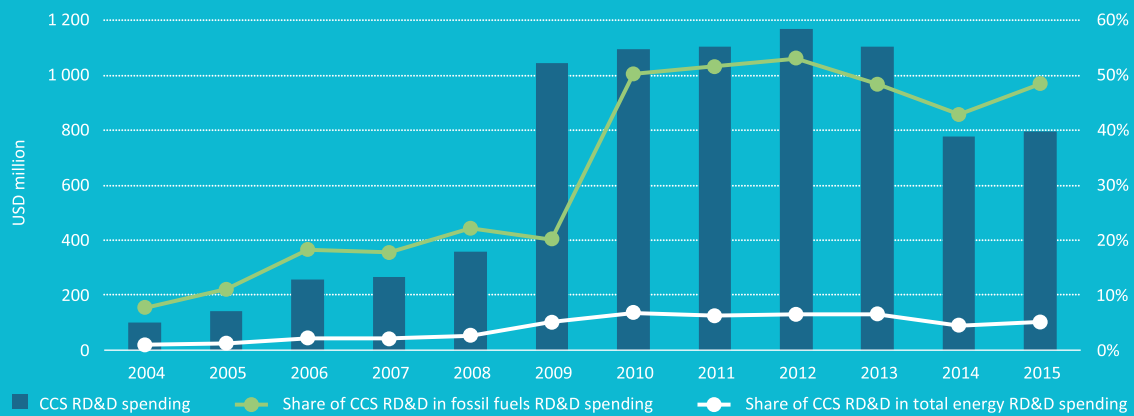
2.14 Large-scale CO₂ capture potential



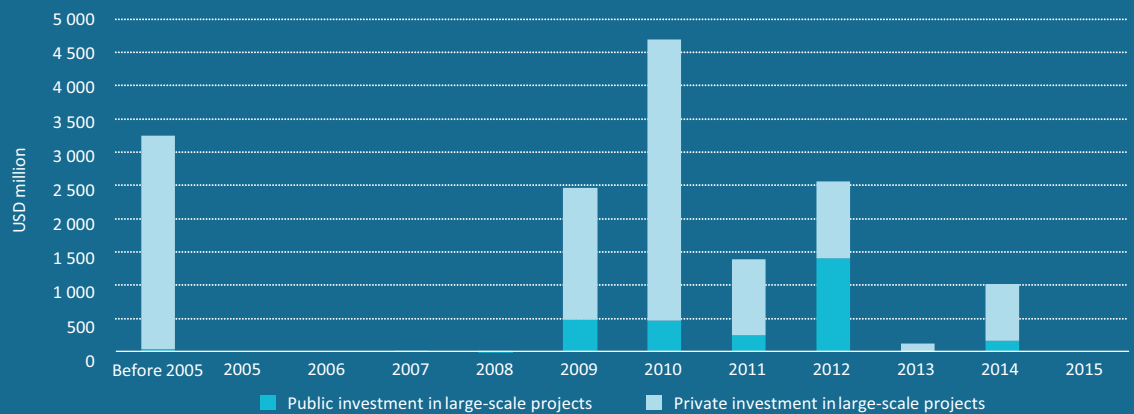
2.15 Capacity additions (MtCO₂)



2.16 IEA member public RD&D spending



2.17 Investments in large-scale CCS projects



For sources and notes see page 104

Industry

- Improvement needed
- ↗ Positive developments

The industrial sector¹ accounted for 154 exajoules (EJ),² or 36% of global total final energy consumption (TFEC) in 2014. The long-term trend of production growth in energy-intensive industrial sectors has continued, along with growth in the industrial sector's TFEC, which grew by 1.3% in 2014. Even as production continues to grow in the future, annual growth in energy consumption must be limited to 1.2%, to stay on a 2DS pathway, less than a half of the average 2.9% annual growth since 2000. Decoupling of industrial production from CO₂ emissions is also critical to meeting the 2DS pathway, which envisions 0.1% annual growth in CO₂ emissions by 2025 from 2014, compared with 1.1% in the RTS. In the 2DS, industrial CO₂ emissions need to peak by 2020.

Recent trends

Industrial sector energy consumption has grown by about 1.5% annually since 2010. Consumption of coal has grown fastest in recent years, more than doubling since 2000. Strong growth has also occurred in non-biomass renewables, such as solar thermal and geothermal, which have increased 80% since 2000 and have had the strongest growth of any fuel in 2014, at 7%. Structural effects based on changing shares of industrial subsectors, as well as regional shifts in production, could partly explain this, but the growth in renewable energy use in industry is nonetheless an encouraging sign.

The highest growth rate of industrial energy use occurred outside the OECD; the energy use of non-OECD countries grew 1.9% in 2014 compared with 0.2% for OECD countries, and continued to gain share of global industrial energy use, reaching 69% in 2014, up from 49% in 2000. Growth in energy use was strong in China (3.1%) and India (4.3%) in 2014.

Tracking progress

Energy-intensive industrial sectors have made progress in moving towards best practices and improving process energy efficiency. Industrial CO₂ emissions³ have reached 8.3 GtCO₂ in 2014, 24% of global CO₂ emissions. ISO 50001, a certification for industrial energy management systems, continues to be deployed, reaching more than 12 000 sites in 2015, though 90% of those are located in North America and Europe, and deployment in other regions has been limited. Globally, post-consumer recycling has also been on an upward trend. Long capacity lifetimes and lack of co-ordinated international policies for industrial decarbonisation pose particular

challenges in this sector, but energy-intensive industry has made some progress, which will need to accelerate to meet the 2DS. Annual growth in final energy consumption in industry must be limited to 1.2% from 2014 to 2025 to meet the 2DS, compared with 2.9% from 2000 to 2014.

Chemicals and petrochemicals

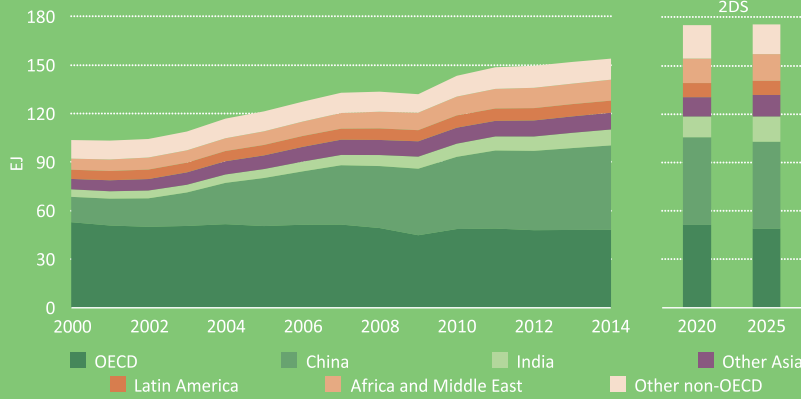
The chemicals and petrochemicals sector's share of global final energy consumption has grown from roughly 6% to 10% over the last four decades, and an increasing proportion of that energy input is used as feedstock, signifying this sector's growing prominence and an increase in process energy efficiency. Price trends in North American natural gas have contributed to a shift towards lighter feedstocks. Longer-term decarbonisation post-2025 requires additional effort on continuing to move towards less carbon-intensive production processes, improving process energy intensity, improving recycling of final products and continuing research on innovative, particularly bio-based, process routes.

Iron and steel

In 2014, 30% of global crude steel production was produced in electric arc furnaces (EAFs), growing from 29% in 2010,⁴ and aggregated global energy intensity of crude steel production grew slightly to 21.3 gigajoules per tonne (GJ/t) from 20.7 GJ/t in 2011. Scrap availability puts an upper limit on the EAF share, though additional material efficiency and recycling will be important strategies for meeting the 2DS. New process routes, such as innovative direct reduced iron and smelting reduction technologies, which facilitate CCS, play important roles later in the 2DS.

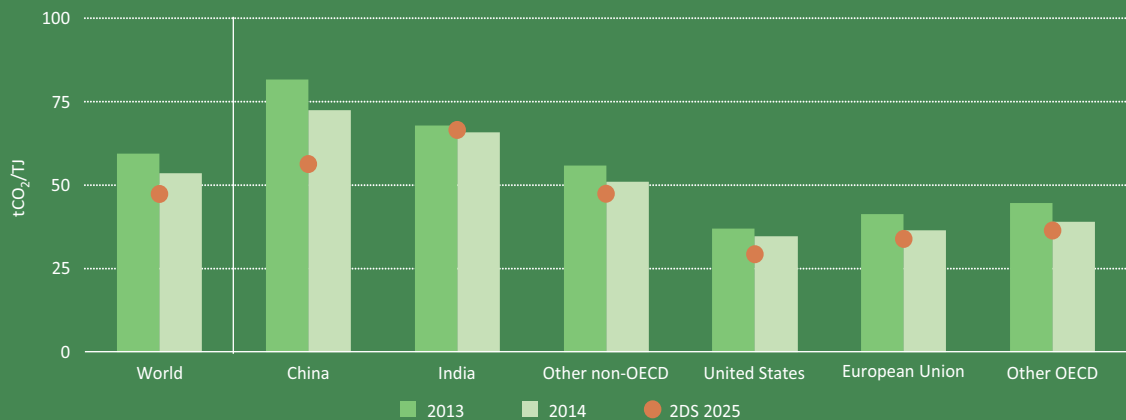
1–7 Refer to Technology overview notes on page 105.

2.18 Total final industrial energy consumption by region

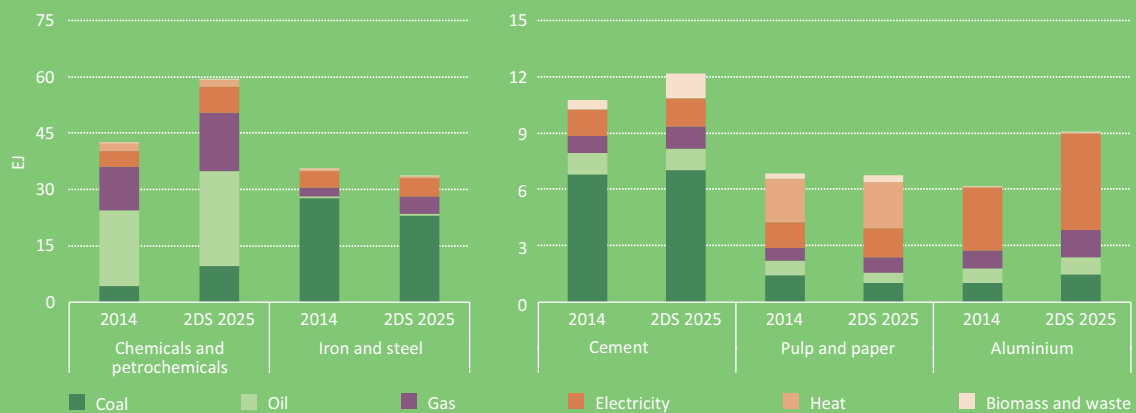


IN 2014,
69%
OF INDUSTRIAL
ENERGY USE
WAS IN FIVE
ENERGY-
INTENSIVE
SECTORS

2.19 CO₂ intensity of industrial energy consumption by region



2.20 Energy consumption by sector and fuel



For sources and notes see page 105

Short-term emissions reductions come mainly from energy-intensity improvements (47% of cumulative CO₂ reductions in the sector by 2025) and greater shifts to scrap-based EAF production (26% of CO₂ reductions by 2025).

Cement

Thermal energy intensity of cement kilns continues to improve, as higher-efficiency dry kilns replace older ones. Clinker ratio was about 0.65⁵ on average in 2014 although in some regions significant potential exists to improve this ratio further to decrease the sector's CO₂ emissions, using new and existing clinker substitutes. Globally, biomass makes up about 2.0% of thermal energy consumption, and waste makes up an additional 3.3%; together they are envisioned to reach 12.4% by 2025 in the 2DS. The share of fossil fuels globally continues to decline. Process CO₂ emissions from the calcination of limestone remain an important challenge for the cement sector, and continued R&D for alternative products and processes, including CCS and new low-carbon cements, remains critical to the sector's pathway to 2DS.

Aluminium

The downward trend in energy intensity of both primary aluminium smelting and alumina refining continued, with the world averages decreasing by 1.9% for aluminium smelting and by 5.3% for alumina refining from 2013.⁶ In 2014, 31% of aluminium was produced from scrap, maintaining nearly the same share as in 2013, despite 6.7% growth in overall production.⁷ Meeting the 2DS pathways will require continued efforts to improve collection and recycling of scrap and SEC of both primary and secondary aluminium, along with R&D focused on alternative production routes, particularly those that address the process CO₂ emissions from primary smelting, such as inert anodes. Further, because this is an electricity-intensive sector, options to enable low-carbon grids, including demand-side management and decarbonised electricity sources, should also be considered.

Pulp and paper

Production of paper and paperboard has been increasing, with demand growth in household and sanitary paper due to rising incomes counteracting the effects of digital technology displacing printing and writing paper. These structural effects have

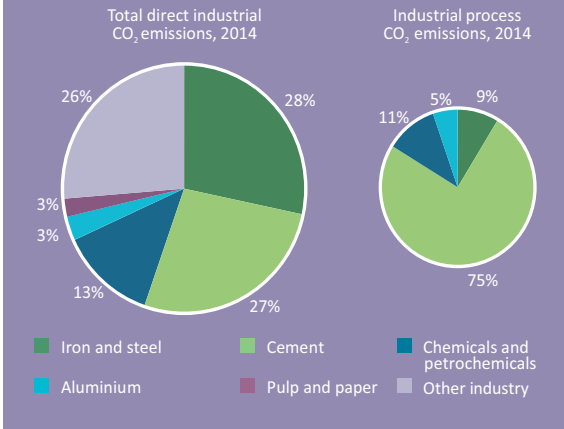
an impact, though growth in production has recently outpaced growth in energy consumption, suggesting a decoupling, and recovery and recycling of waste paper have also improved to 55.3% in 2014. The sector's energy use already includes a large share of biomass fuel and bio-based by-products. Energy intensity improvements, along with system-level thinking including utilisation of by-products, integration of pulp and paper mills, and integration of mills with grids or other sites with heat and electricity demand, will play a growing role in the 2DS. Growth in energy consumption must be limited to 0.1% per year to meet the 2DS, and CO₂ emissions must decrease 1.7% per year, compared with 0.2% and 0.9% growth, respectively, in the RTS.

Recommended actions

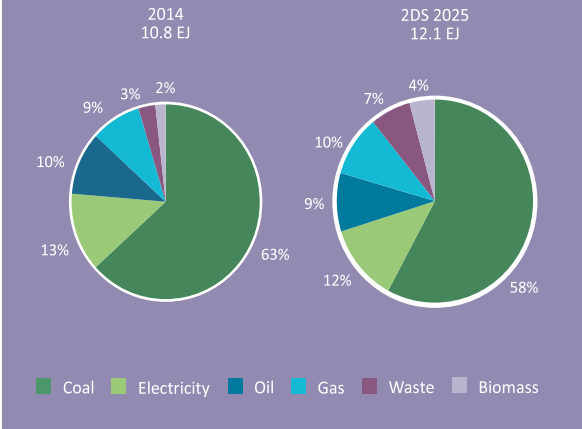
Throughout the industrial sector, pre-2025 emissions reductions rely on implementation of best available technology (BAT) and continued work towards energy efficiency. Increasing post-consumer scrap recycling rates and utilising this scrap to offset primary production of materials would significantly reduce the energy and emissions intensity of production, and thus should be promoted. All sectors should also consider possibilities for sustainable utilisation of industrial wastes and by-products as well as recovering excess energy flows. Implementation of these existing solutions, especially the low-cost, low-risk commercially available processes and technologies, will be a critical driver of the early phase of the 2DS transition. Policy makers should put in place a policy framework that incentivises decarbonisation while considering the impacts in terms of carbon leakage and competitiveness.

In the longer term, deeper cuts in industrial CO₂ emissions will require innovative new low-carbon process routes and products. To ensure the future availability of those processes and technologies, the sector should focus R&D in the near term on low-carbon production and mitigation options. Furthermore, deployment of innovative technologies is needed at both pilot and commercial scale. This deployment will require collaboration across companies, sectors and national borders. Existing efforts should be accelerated, and policy frameworks put in place to incentivise low-carbon innovation.

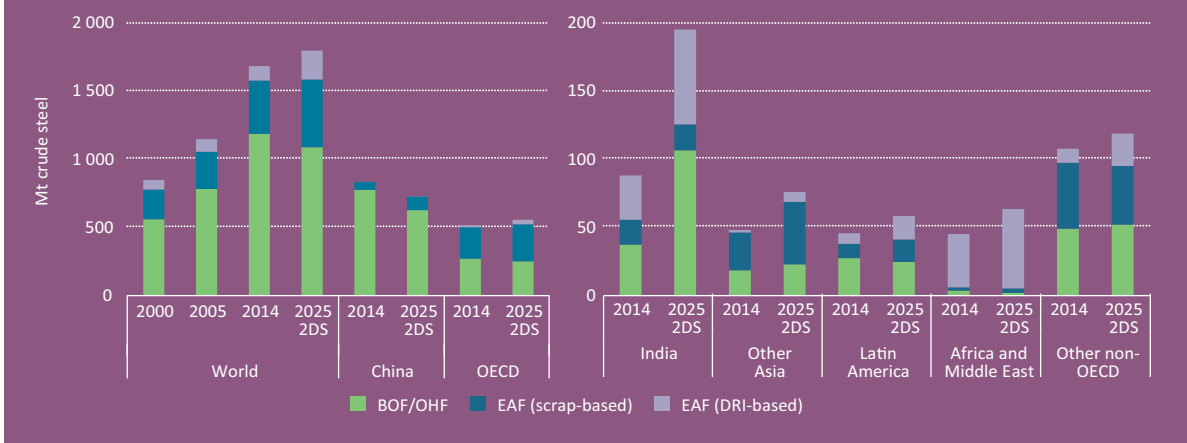
2.21 Direct industrial CO₂ emissions



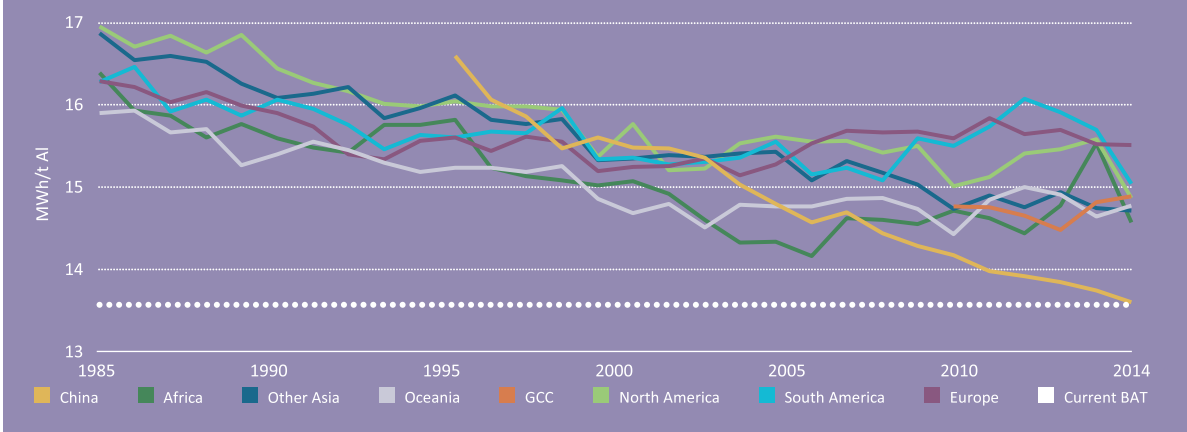
2.22 Cement production energy use



2.23 Crude steel production by process route



2.24 Primary aluminium smelting electricity intensity



For sources and notes see page 105

Chemicals and petrochemicals

● Improvement needed
 ↗ Positive developments

The chemicals and petrochemicals sector remains the largest industrial energy user, accounting for 28% of industrial final energy consumption in 2014. Of the sector's total energy input, 58% was consumed as feedstock. To remain on a 2DS trajectory, annual increases in process energy consumption must stay below 3.6% and direct CO₂ emissions below 3.6% during 2014–25, a period in which demand for primary chemicals¹ is projected to increase by 47%.

Recent trends

Global production of high-value chemicals (HVCs),² ammonia and methanol recovered the ground lost during the global financial crisis, growing by 19% (HVCs), 13% (ammonia) and 51% (methanol) over the period 2009–14.

Major shifts in the fossil fuel landscape in recent years have had significant impacts on the global feedstock mix. Notably, the shale boom in the United States has contributed to a regional divergence in natural gas prices, resulting in a cost advantage for US chemical producers reliant on lighter feedstocks³ such as ethane and liquefied petroleum gas (LPG). A 16% increase in global ethane steam cracker capacity between 2010 and 2014 accompanied this shift.

The production of HVCs, ammonia and methanol accounted for 73% of the chemicals and petrochemicals sector's total energy use in 2014. Actual SEC⁴ values for these large volume processes are 12.5 GJ/t HVC to 34.6 GJ/t HVC of process energy for HVCs, 10.4 GJ/t to 31.4 GJ/t for ammonia, and 11.6 GJ/t to 25.1 GJ/t for methanol.⁵

Bio-based routes to both primary chemicals and downstream chemical products present promising avenues for decarbonisation. Bio-routes to primary chemicals, such as bioethanol-to-ethylene and biomass-based ammonia and methanol, exist mainly at pilot scale. Global production capacity of bioplastics totalled 1.7 Mt in 2014, but was dwarfed by the overall plastic materials demand of 311 Mt.

Tracking progress

Average annual growth in the sector's process energy consumption⁶ and direct energy-related CO₂ emissions was 2.3% and 2.6%, respectively, during 2000–14. Energy use as petrochemical feedstock, which grew 2.3% annually during the same period, also plays an important role, with over half of the sector's energy consumption and 19% of its direct CO₂ emissions. Annual average increases in process energy consumption and

direct energy-related CO₂ emissions through 2025 must stay below 3.6% and 2.8%, respectively to meet the 2DS trajectory. Future evolution of energy prices, feedstock-related CO₂ emissions, and demand for chemical products could be challenges to a long term transition to low CO₂ production.

Process energy use for the production of HVCs, ammonia and methanol accounted for 32% of sector's TFEC in 2014, increasing slightly to 33% in 2025 in the 2DS. Global average declines in the process energy intensities of the sector's main products — 13% for HVCs, 5% for ammonia and 15% for methanol — are outpaced by the energy savings from shifts to higher yielding feedstocks.

Two levers provide the majority of the 2DS' direct CO₂ emissions savings in 2025, relative to the RTS: process energy efficiency (78%) and switching to lighter fuels and feedstocks (18%). The remaining 5% is provided by increased plastics recycling. Post-consumer waste plastic collection rates, recycling yield rates and the extent to which recycled polymers displace virgin resin consumption (i.e. reduced down-cycling) all increase steadily until 2025. These increases deliver 9.8 Mt of annual primary chemical savings in the 2DS in 2025, compared with the RTS.

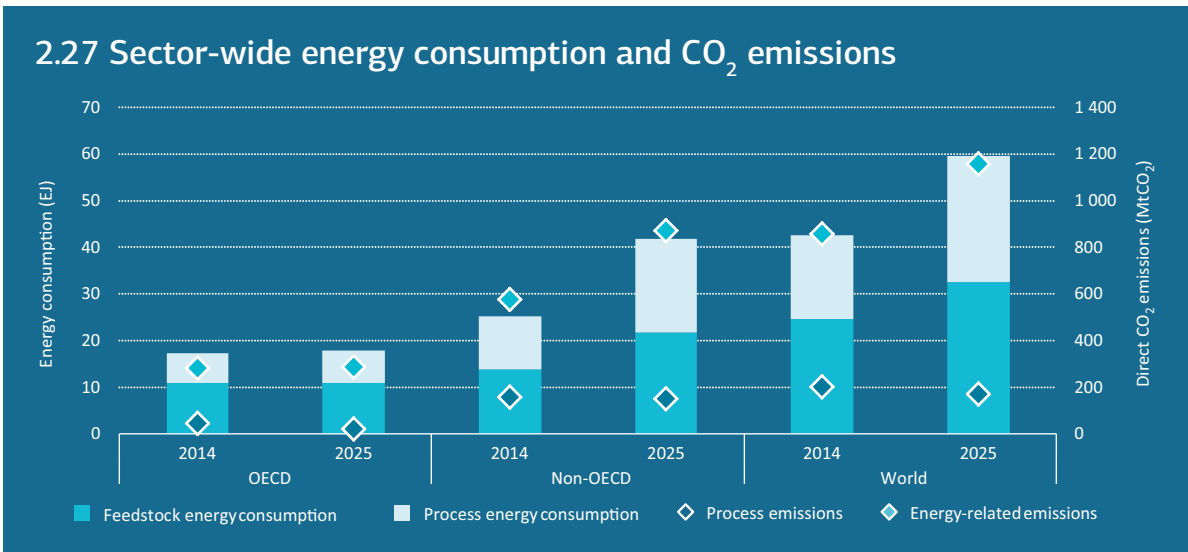
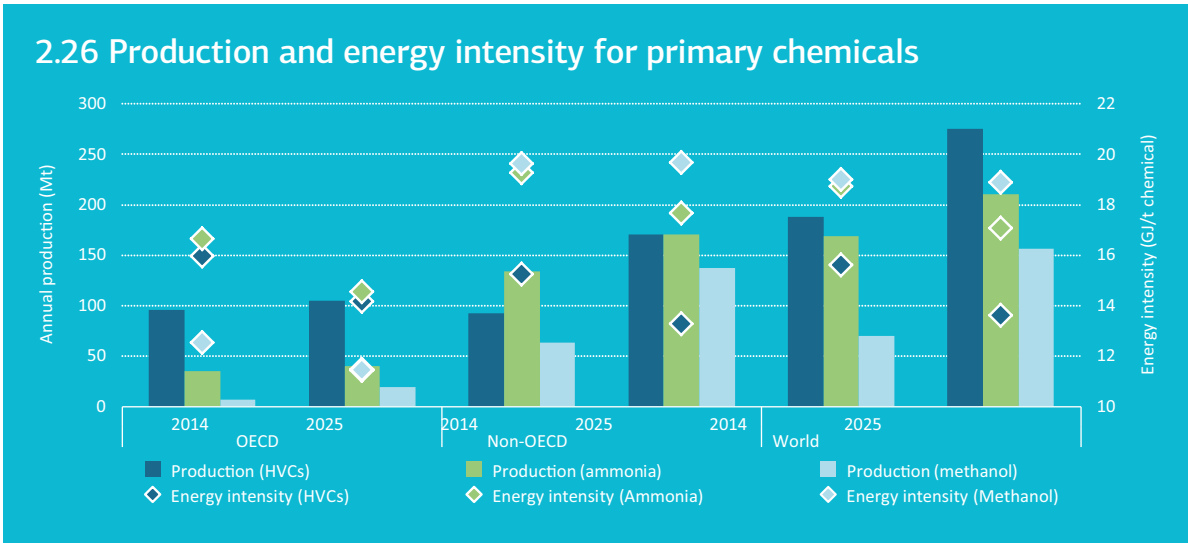
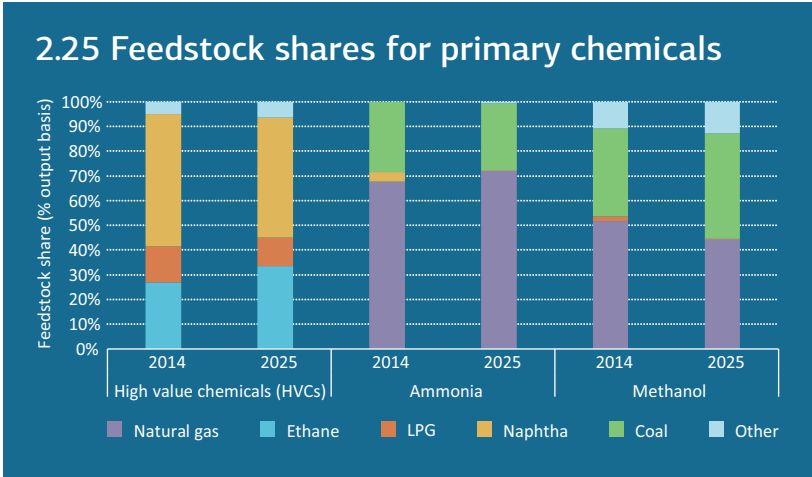
Recommended actions

Two key categories of sector-specific mitigation options should be given priority in the short to medium term. The first category is fostering best practices among existing plant operators to lower energy and emissions intensities for key production processes. The second category is removing barriers to enhancing resource-efficient production and waste treatment. Ensuring the presence of price signals to incentivise resource efficiency strategies throughout the chemicals value chain can promote positive action. Harm to competitiveness can be minimised if collective action is taken globally.

Both the quality and quantity of publicly available statistics in the chemicals and petrochemicals sector have long needed to be improved. The appraisal of policy initiatives, such as those noted above, requires detailed and robust statistics.

1–6. Refer to Technology overview notes on page 105.

THE (PETRO) CHEMICALS SECTOR ACCOUNTED FOR **28%** OF INDUSTRIAL ENERGY CONSUMPTION IN 2014



For sources and notes see page 105

Pulp and paper

- Improvement needed
- Positive developments

The pulp, paper and printing sector¹ accounted for 5.6% of industrial energy consumption in 2014. Though its share of industrial energy use has been in decline since 2000, the sector continues to be among the top industrial energy consumers, and can play an important role in the transition to a low-carbon energy system. Despite production growth, the sector's energy use must decline by 0.8% and direct non-biomass CO₂ emissions by 17% by 2025 from 2014 levels to meet the 2DS.

Recent trends

Annual production of paper and paperboard has increased by 23% since 2000 (FAO, 2016), with growth in demand for household and sanitary papers due to rising populations and incomes, and rising packaging material needs for shipping of consumer goods. These trends have offset reduced demand for printing and writing papers in an increasingly digital age. The share of wood pulp in paper production² has decreased over time, from 52% in 2000 to 43% in 2014 (FAO, 2016), as rates of waste paper recovery and recycling continue to improve.

Fossil fuels, which are primarily used for onsite utilities, accounted for 42% of total energy consumption in 2014. Decarbonising these utilities by switching to lower-carbon fuels could have an important impact.

Pulp and paper production has a high share of biomass in its energy consumption, due to the use of by-products. For each tonne of kraft process pulp,³ an estimated 19 gigajoules (GJ) of black liquor⁴ is produced, which can be used for steam and electricity generation. Sawdust, wood chips and other wood residues (called "hog fuel") are also generally burned on site. An estimated 0.7 GJ to 3.0 GJ of hog fuel is produced per tonne of wood pulp.

Tracking progress

The sector's energy use has grown only 1% since 2000, despite a 23% increase in paper and paperboard production, which points to a decoupling of growth in energy use and production. However, structural effects, such as shifts in product mix or regions of production, can also influence energy use, and data quality issues make it difficult to draw concrete conclusions about the energy intensity trends.

Recovery and recycling of waste paper have steadily been increasing. The utilisation of recovered paper in the total fibre furnish grew to 55.3% in 2014, up from 44.3% in 2000 and

33.9% in 1990. This trend is envisioned to continue, growing to 57.6% in the 2DS by 2025.

Research on innovative processes for pulp and paper manufacturing has continued to identify opportunities for decarbonisation. The Confederation of European Paper Industries (CEPI), for example, led an initiative called the Two Team Project, which brought together researchers to identify the most promising breakthrough technologies for decarbonisation, in an example of collaborative and open R&D. New concepts identified through this project will require additional research and funding to bring to scale.

Tracking of energy efficiency improvements in pulp and paper manufacturing is difficult, because publicly available data on production, capacity and energy use are limited. Additionally, some countries do not report biomass use for the pulp and paper sector, which makes it difficult to get an accurate picture of the sector's energy needs.

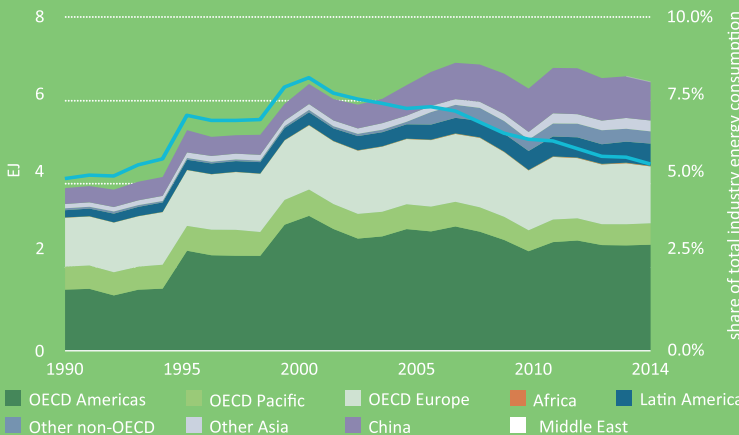
Recommended actions

Through 2025, the sector should continue to focus on improving energy efficiency, moving towards BAT-level performance and increased recycling, while also supporting R&D efforts to develop future processes and technologies.

In the longer term, the sector can also contribute to sustainable energy supply, for example, by feeding excess heat and electricity into the grid. The concept of pulp mills as integrated bio-refineries that produce low-carbon energy commodities, including biofuels for transport, from black liquor alongside their pulping activities is gaining traction, and several pilot projects are under way. The sector also has the opportunity to contribute some negative emissions by capturing biogenic CO₂ emissions. Similarly, new applications for pulp and paper products may contribute to product life-cycle CO₂ emissions reductions, for example, through improved packaging or fibre-based textiles. Private- and public-sector stakeholders should collaborate to ensure the necessary framework of incentives is put in place to encourage such strategic and systemic thinking.

1–4. Refer to Technology overview notes on page 106.

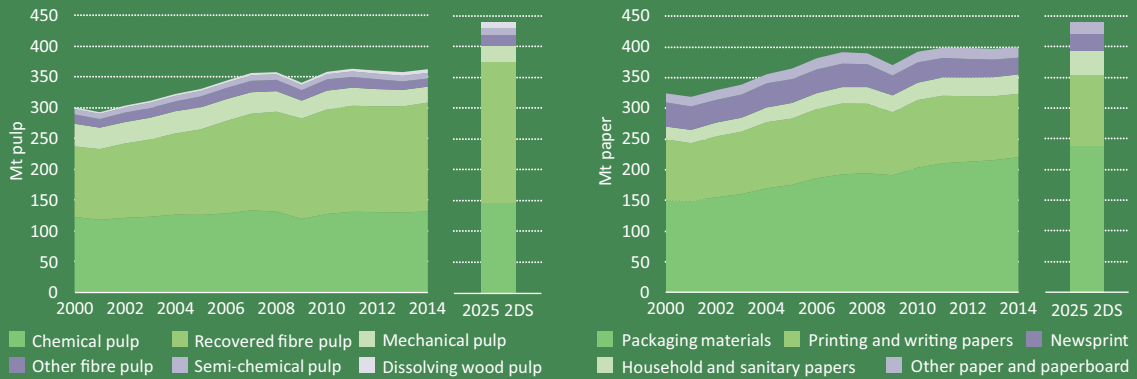
2.28 Final energy use by pulp, paper, printing



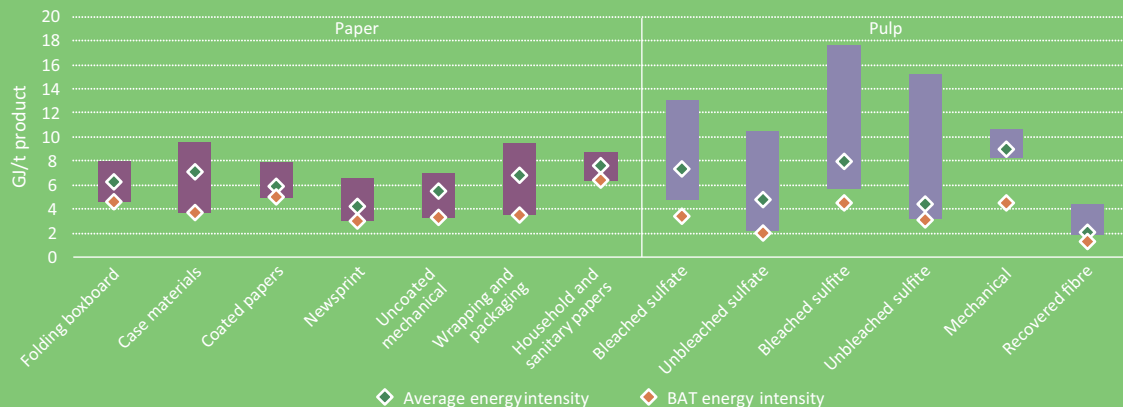
55%

OF FIBRE USED FOR PULP MANUFACTURING GLOBALLY IN 2014 WAS FROM RECOVERED WASTE PAPER, UP FROM 44% IN 2000

2.29 Production of pulp, paper and paperboard



2.30 Ranges of national average specific energy consumption



For sources and notes see page 106

Transport

● Improvement needed
~ Limited developments

Transport's share of global energy-related CO₂ emissions is 23%. Emissions increased by 2.5% annually between 2010 and 2015. This trend must be reversed to get on track with 2DS targets. NDCs to the Paris Agreement targeting transport are insufficient to bring sectoral emissions in line with the 2DS.

Recent trends

With the submission of NDCs to the Paris Agreement, a long-term political signal was sent to decarbonise the transport sector. More than three-quarters of NDCs explicitly identify transport as a mitigation priority; around two-thirds propose sectoral mitigation measures; and 9% specify a transport sector emissions reduction target (PPMC, 2016). A strong bias towards passenger transport is evident in the NDCs. Developing regions tend to highlight a commitment to urban public transit such as bus rapid transit systems (PPMC, 2016). Fuel economy standards and e-mobility pledges are also prioritised to varying degrees, especially in developed economies.¹ Freight is mentioned in only 29% of NDCs, and the most widely cited measure is to target a shift from road to rail and/or ships (PPMC, 2016).²

In 2016, a global market-based measure was introduced to mitigate CO₂ emissions from international aviation (ICAO, 2016). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to stabilise CO₂ emissions from international aviation by 2020. Emissions exceeding the threshold would be offset (ICAO, 2016).³ The IMO also agreed on a global sulphur cap of 0.5% on marine fuels (IMO, 2016),⁴ but has not yet defined a GHG emissions mitigation target.

Tracking progress

Global transport sector GHG emissions continue to grow. To reach 2DS targets, sectoral emissions must begin to decline within the coming decade. OECD economies must reduce "wheel to wheel" (WTW) GHG emissions by more than 20% by 2025 to offset continued emissions growth of more than 18% in non-OECD countries over the same period.^{5,6} Transport-related mitigation measures proposed in NDCs are expected to fall short of both medium- and long-term 2DS targets.

Positive trends continue in electrification. Sales of EVs continue to increase, with the light-duty EV market growing by 50% (EVI, 2017) compared with 2015, with China leading market growth.

Aviation, shipping and heavy-duty road are the most difficult modes to decarbonise. Despite the aforementioned adoption of new regulatory policies and other measures, these sectors are still under-regulated when compared with LDVs. The WTW GHG emissions of the shipping sector, for example, are expected to grow at a rate of 1.9% per year from 2015 to 2025 in the RTS, and aviation at 2.0% per year. However, emissions must stabilise in these sectors to align with the 2DS by 2025, and decline rapidly afterwards. Road freight WTW GHG emissions grow by 2.2% per year over the same period in the RTS, but here emissions growth must be capped at 1.0% to meet the 2DS targets.

Recommended actions

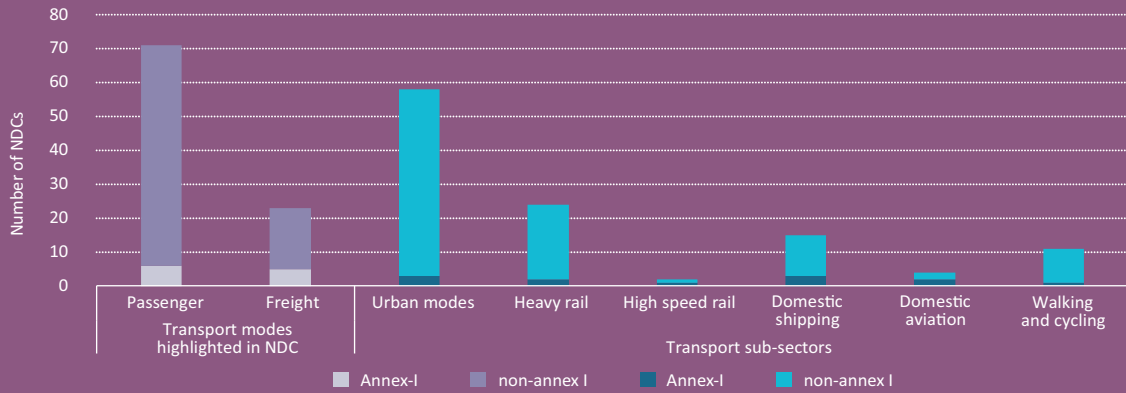
The ambition expressed in the NDCs must translate into concrete actions to put transport on track with 2DS targets. Mode-specific measures should target proven and rapid means of reducing emissions.

Policies must raise the costs of owning and operating the modes with highest GHG emissions intensity to stimulate investments and purchases of energy-efficient and low-carbon technologies and modes. A price on carbon is essential, and could be particularly effective in reducing GHG emissions from shipping and aviation, sectors that are currently subject to low or no fuel taxation. Complementary additional measures are also needed, including investments in energy-efficient transport modes (such as rail and public transport), regulations mandating ambitious vehicle efficiency improvements⁷ and measures encouraging the adoption and development of low-carbon fuels.

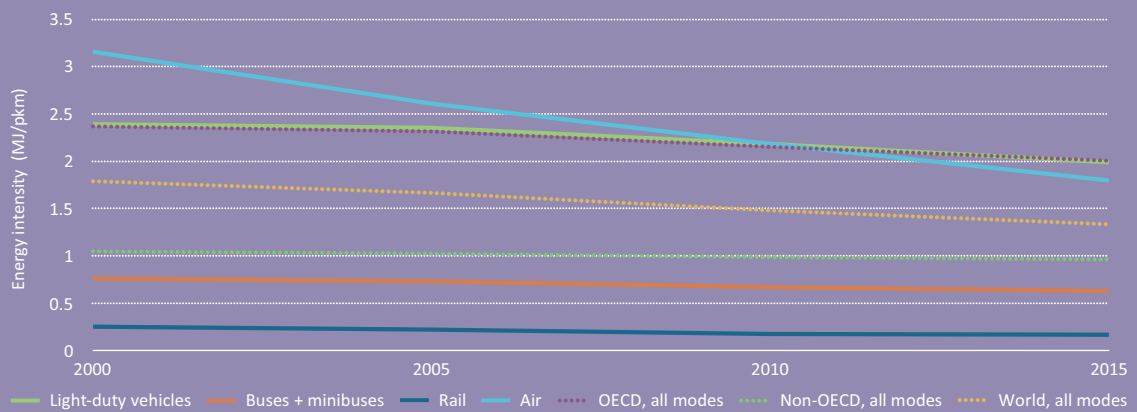
The development of CORSIA has both positive and negative implications. The acknowledgement of the need for climate change mitigation and the elaboration of a unified aspirational goal for the industry are both welcome developments. But these developments could come at the expense of reduced pressure for R&D solutions that could be achieved within the aviation industry itself. The international shipping sector should consider a similar unified mitigation goal. However, in light of the large potential to reduce specific CO₂ emissions,⁸ the international shipping sector should adopt carbon taxes rather than offsets.

1–8. Refer to Technology overview notes on page 106.

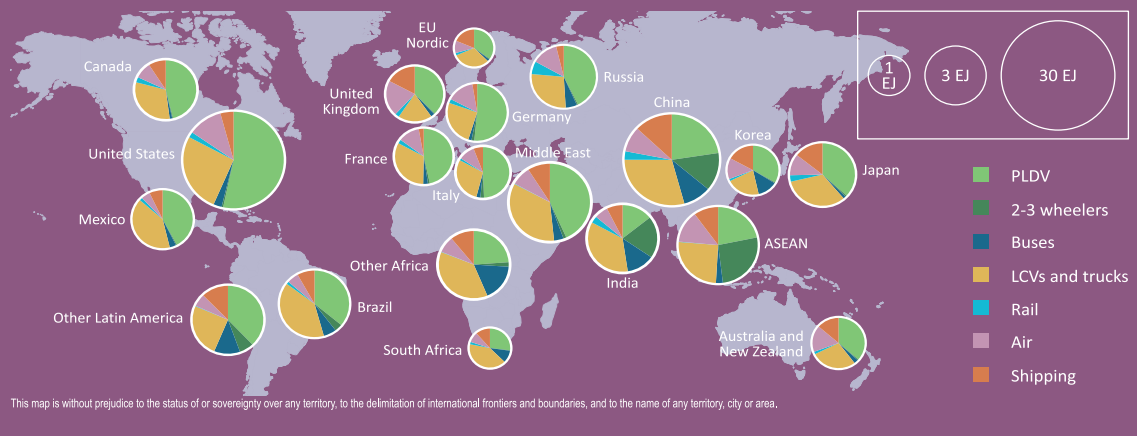
2.31 Share of mitigation measures by mode in NDCs



2.32 Energy intensity development – Passenger modes



2.33 Transport energy use, by mode, 2015



For sources and notes see page 106

Electric vehicles

● On track
~ Limited developments

With over 2 million electric cars¹ on the road and over 750 000 EVs sold worldwide in 2016, a new historic record has been achieved in the electrification of individual transportation. The 2016 sales show a slowdown in market growth rate compared with the previous year – 40% in 2016 versus 70% in 2015 – suggesting an increasing risk to diverge from a 2DS trajectory.

Recent trends

Globally, 753 000 plug-in EVs were sold in 2016, 60% of which were battery-electric cars (BEVs). These sales were the highest ever registered and allowed the global EV stock to hit the threshold of 2 million units in circulation. China remained the largest EV market for the second consecutive year and, in 2016, accounted for close to half of global EV sales. Europe represented the second-largest global EV market (215 000 EVs sold), followed by the United States (160 000 EVs sold). Plug-in hybrid electric cars (PHEVs) gained ground compared with BEVs both in Europe and in the United States. Norway, with a 29% market share,² and the Netherlands, with 6%, have the highest EV market penetrations globally. Sizeable drops in EV sales and market share took place in the Netherlands and Denmark, primarily reflecting changes in policy support. Overall, EVs are still a minor fraction (0.2%) of all cars in circulation.

Despite the slowdown in growth rates, the increase in EV production continues to favour technology learning and economies of scale. Battery costs kept declining between 2015 and 2016, and energy density continued to increase (EVI, 2017). This, combined with the improvements expected from battery chemistries that are currently being researched, gives encouraging signs on the possibility to meet the targets set by carmakers and the US DoE for the early 2020s (EVI, 2017). Battery technology improvements will enable longer ranges to be achieved at lower costs, increasing the cost-competitiveness of EVs and lowering barriers to adoption.

Publicly accessible charging infrastructure attained 320 000 chargers globally. Fast chargers, which use high-power alternating current, direct current or induction, and can fully recharge a BEV in less than an hour, are mostly located in China and make up a third of all chargers operating globally. In 2016, on a global average and with the exception of China, the deployment of fast chargers was slower than the deployment of chargers overall. This trend may reflect difficulties in their economic viability.

Tracking progress

EV sales growth remained strong, with a 40% increase in 2016 over the previous year, but declined significantly from the 70% growth of 2015. The 2016 sales still allow for the 2DS sales and stock objectives to be attained by 2025 under the condition that the 2016 growth rate is maintained in future years: meeting the 2025 target implies an annual sales growth of 35% every year from 2017 to 2025. Thus recent manufacturers' announcements regarding ambitious EV production plans must be followed by concrete investment decisions.

Recommended actions

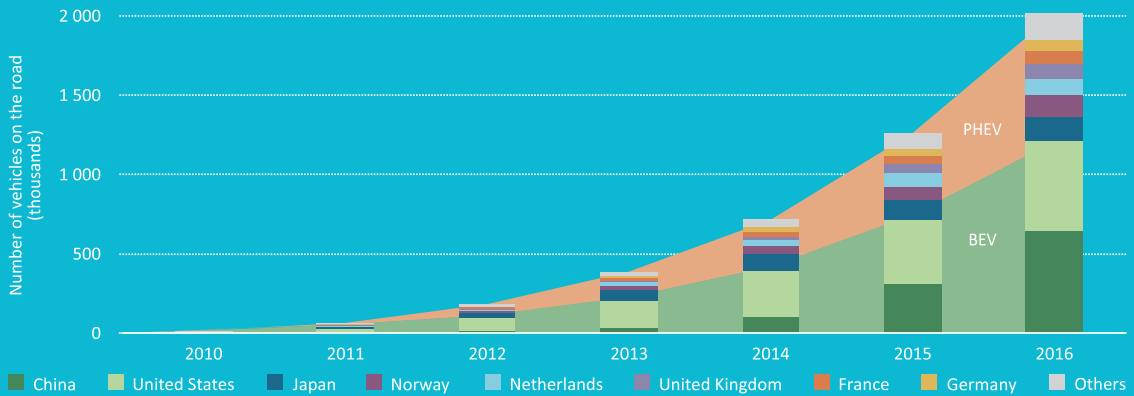
Financial incentives, EV performance and the availability of charging infrastructure emerged as factors positively correlated with the growth of EV sales. Public policies aiming to reduce the purchase cost gap between EVs and conventional cars and to improve the value proposition of EVs, including, for instance, public procurement programmes and awareness campaigns, are, therefore, well suited to stimulate EV adoption. Furthermore, a supportive policy environment also reduces risks for investors.

Policy support needs to be comprehensive by taking place at different administrative levels, from national to local, under different forms: direct support for research, vehicle purchase subsidies, zero-emission mandates, fiscal advantages for charger deployment, tightened fuel economy standards, and differentiated taxes, fees and restrictions on the basis of vehicle emissions performance, such as regulations on access to urban centres (e.g. zero-emission zones). The cost-attractiveness of EVs can also be enhanced as conventional fuels become more expensive, via fuel taxes that include carbon pricing, which needs to be implemented in parallel with grid decarbonisation efforts.

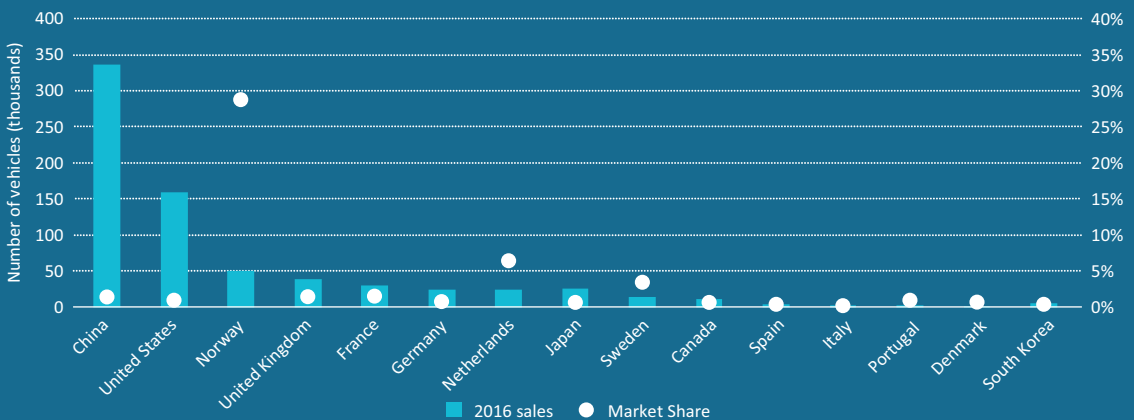
As EVs become more popular, securing affordable raw material supplies will become increasingly critical to ensure that improvements achieved in battery costs can be sustained. This task can be simplified through the early development of regulatory requirements for second life of batteries and material recycling.

1–2. Refer to Technology overview notes on page 107.

2.34 Evolution of the electric car stock (BEV and PHEV), 2010-16



2.35 EV sales and market share in a selection of countries, 2016



2.36 Focus on China



- More than 200 million electric two-wheelers
- 650 thousand electric cars
- 350 thousand electric buses

This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

For sources and notes see page 107

International shipping

● Not on track
~ Limited developments

The shipping sector is a key enabler of international trade and constitutes the most energy-efficient way to move goods. But limited policy deployments have led to a slow uptake of clean technologies in shipping. Meeting 2DS goals requires the rapid adoption of markedly more ambitious policies.

Recent trends

The shipping sector accounts for 80% of global trade in physical units and 2.0% of CO₂ emissions from fuel combustion. Shipping activity is closely linked to gross domestic product (GDP) growth.¹ Both shipping activity and GDP have increased steadily, by 3.8% and 3.6% per year from 2000 to 2015, respectively (UNCTAD, 2016; World Bank, 2017). International shipping energy demand increased by 1.6% per year from 2000 to 2014.² Historically, shipping energy use has also been closely correlated with GDP growth; however, a decoupling of this trend has been observed since around 2010 (IMO, 2014). This matches a decline in trade activity in 2009 and a slow subsequent recovery after that, as well as a trend towards upgrading of the global container fleet to larger and more efficient ships beginning in 2011.³ The vast overcapacity resulting from this led to the early retirement of old and inefficient ships, and boosted the energy efficiency per tonne kilometre (tkm) of the global fleet by an unprecedented average annual rate of 5.8% from 2010 to 2014. Slow steaming, which has become more common in response to overcapacity, also led to operational efficiency improvements (IMO, 2014; ITF, 2017).

In 2013, the IMO introduced the EEDI, the first energy efficiency standard for new ships, mandating a minimum improvement in the energy efficiency per tonne kilometre of new ship.⁴ A global sulphur cap of 0.5% on marine fuels will also come into force in 2020 (IMO, 2016). Meeting this cap will require significant changes in the fuel mix and may lead to higher maritime fuel prices. Heavy fuel oil (HFO) (currently 84% of the marine bunkers fuel mix)⁵ will also have to be desulphurised or replaced by low-sulphur diesel, LNG, biofuels or other synthetic fuels. Alternatively, vessels will need to be equipped with scrubbers to reduce emissions of SO_x.

Tracking progress

In its current form, the EEDI mandates a 1% annual improvement in the efficiency of the global fleet from 2015 to 2025.⁶ According to IEA statistics and United Nations Conference on Trade and Development (UNCTAD) activity data, the

energy used by the global shipping fleet per tonne kilometre declined by 2.2% between 2000 and 2014.⁷ This suggests that the EEDI will prevent the backsliding of energy efficiency, but not the reduction of GHG emissions beyond historical trends. Fuel price increases due to the sulphur cap could stimulate interest in efficiency and reduce energy use, but technologies that reduce SO_x emissions – except for advanced biofuels, low-carbon synthetic fuels and, to a much lesser extent, LNG – will not lower GHG emissions.⁸

Getting on track with the 2DS requires an annual efficiency improvement of 1.9% MJ per vehicle kilometre (MJ/vkm), and 2.3% MJ per tonne kilometre (MJ/tkm), between 2015 and 2025. This can be achieved by exploiting the efficiency improvement potential for new and current ships and the adoption of operational improvements. Efficiency technologies available today could roughly halve the average fuel consumption per vehicle kilometre of new ships (IEA estimate based on Smith et al., 2016). This will need to be complemented by the use of advanced biofuels.⁹

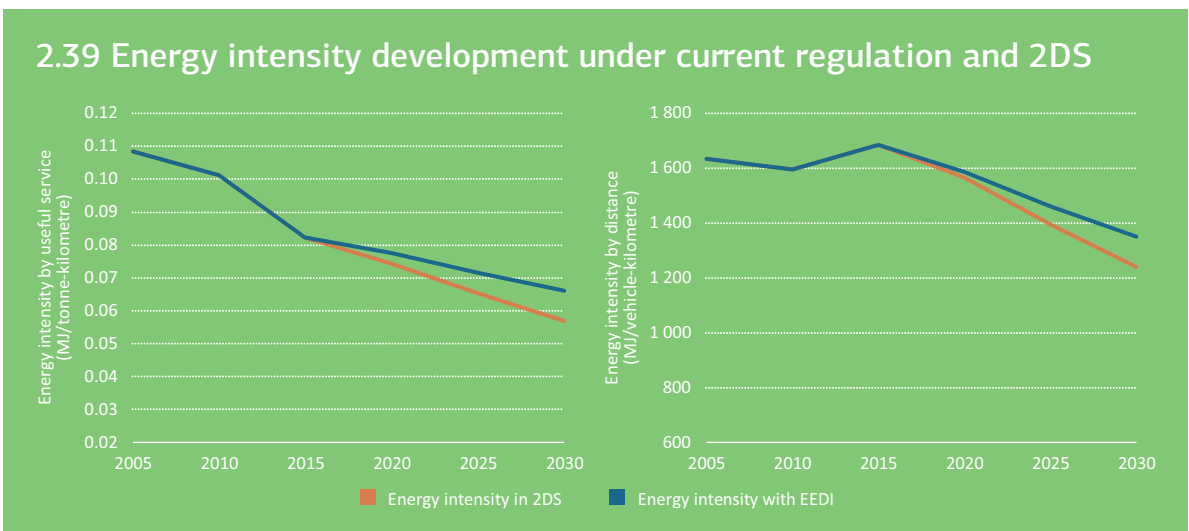
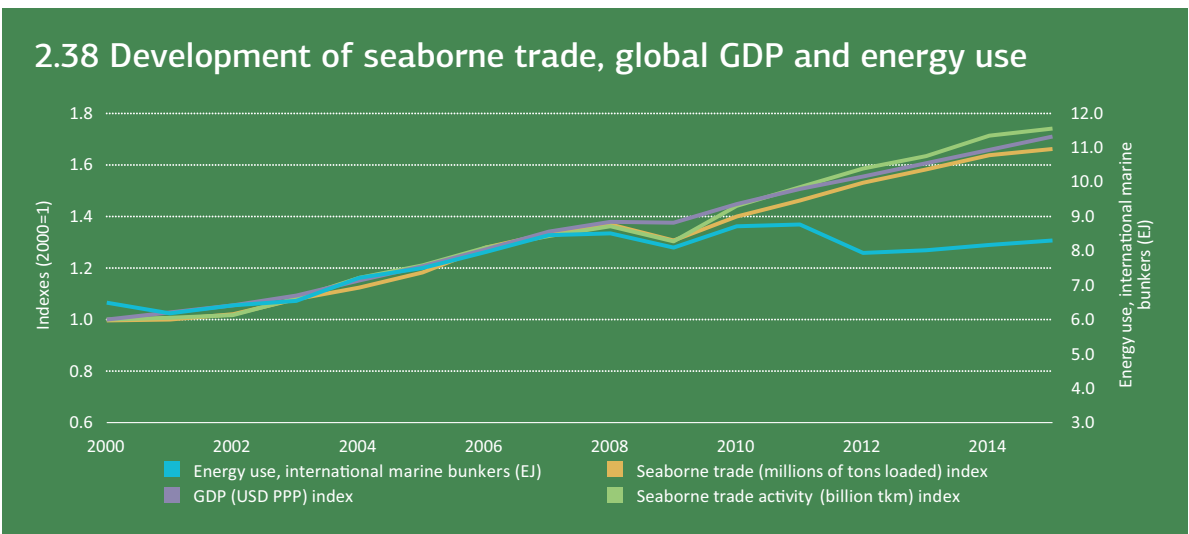
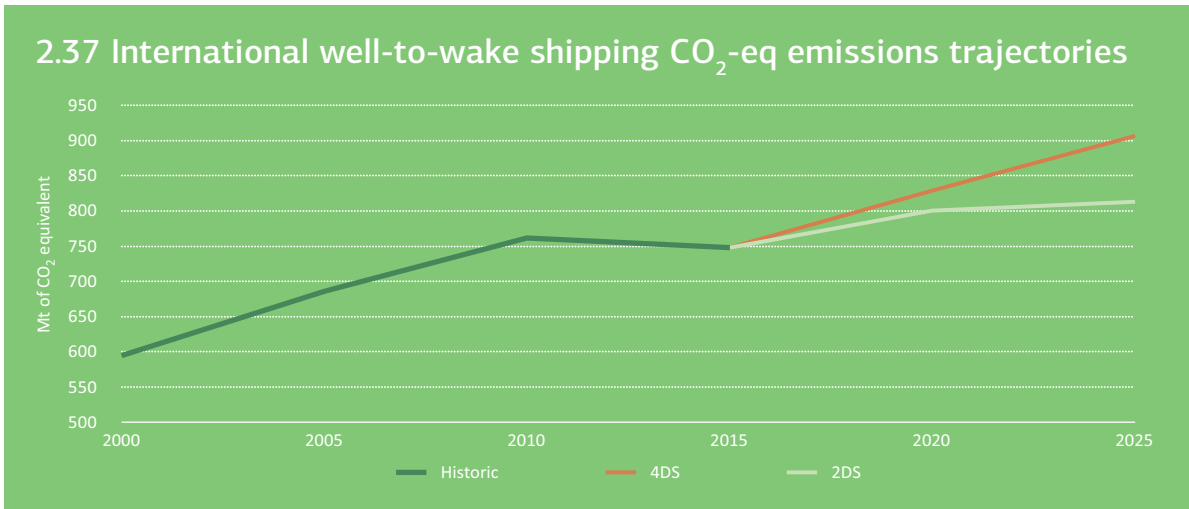
Recommended actions

Defining a GHG emissions mitigation target for international shipping is a first step to getting on track with 2DS targets.¹⁰ Raising the ambition of the EEDI, introducing mandatory standards on operational efficiency (also requiring proper monitoring of ship performances) and pricing GHG emissions are effective instruments to move in this direction.

The International Maritime Organisation (IMO),¹¹ is the major forum in which this vision can be developed and implemented. Proactive action in the IMO is paramount to successfully reduce GHG emissions from international shipping.

Long-term investment decisions will have to be taken by ship owners, operators, financiers and refiners to reduce local pollutant emissions. In the absence of rapid signals to steer these decisions towards GHG emissions reductions goals, investments aiming only to reduce only local pollutant emissions will run serious risks to be stranded when pressure on shipping to contribute to the low-carbon transition will grow.¹²

1–12. Refer to Technology overview notes on page 107.



For sources and notes see page 107

Fuel economy of LDVs

- Improvement needed
- ▾ Negative developments

While the average tested fuel economy of new LDVs continues to improve, global progress slowed recently. Since 2014, fuel economy improved faster in non-OECD countries than in the OECD. The gap between on-road and tested fuel economy also widened.¹ To stay on track with the 2DS, fuel use per kilometre (km) for new vehicles must decline by 3.7% per year through 2030.

Recent trends

In 2015, tested fuel consumption² of new LDVs in OECD ranged from 5.2 litres of gasoline equivalent (Lge) per 100 km to 9.2 Lge/100 km, with an average across all OECD countries close to 7.6 Lge/100 km. Hence, OECD countries included both the highest and lowest national averages. LDVs sold in North America and Australia use more fuel per kilometre than vehicles sold in other OECD countries.³ In 2015, the average fuel economies of LDVs sold in most non-OECD countries were clustered close to 7.9 Lge/100 km.

The annual improvement of global average fuel economy of new LDVs slowed during the past decade, from 1.8% in 2005–08 to 1.2% in 2012–15 and to 1.1% in 2014–15 (GFEI, 2017). This slowdown can be mostly attributed to OECD countries, where annual improvement dropped to 1.0% between 2012 and 2015. Conversely, fuel economy improvement in non-OECD countries accelerated to 1.4% per year between 2012 and 2015, and 1.6% annually between 2014 and 2015, due to tightened fuel economy policies in non-OECD markets.⁴

Discrepancies between on-road and tested fuel economy have been a major topic of discussion in recent years. Increasing evidence shows that this gap has been widening since 2001, especially in Europe, more than quadrupling to exceed 40% in 2015 (ICCT, 2016).

Tracking progress

Fuel economy improvement rates were significantly lower, both in OECD and non-OECD countries, than those required to meet the 2030 Global Fuel Economy Initiative (GFEI) target and the ambitions set by the IEA 2DS (GFEI, 2017). Achieving the 2DS vision requires halving the global average tested fuel consumption of new LDVs to 4.4 Lge/100 km by 2030 compared with a 2005 baseline of 8.8 Lge/100 km (the current global benchmark is 7.7 Lge/100km). This level matches an annual reduction in fuel use per kilometre, for new vehicles, of 3.7% between 2015 and 2030. To be in line with 2DS with regard

to the global fleet, the global sales-weighted average fuel economy also needs to reach 4.7 Lge/100 km by 2025.

Prospects for further improvements depend on the level of ambition of fuel economy regulations and their market coverage. The 2015 addition of India and Saudi Arabia to the set of countries regulating fuel economies helped to maintain the share of the global LDV market covered by fuel economy standards above two-thirds.

A new test procedure (the Worldwide Harmonised Light Vehicle Test Procedure [WLTP]) has recently been endorsed by the United Nations (UNECE, 2014). Progressive and widespread adoption of this standard will be a first step to reduce the gap between tested and real-world on-road fuel economy.

Recommended actions

Despite good progress over the past decade in the geographical coverage of countries using fuel economy policies, progress in fuel economy improvement is clearly lagging what is needed for the 2DS. Realigning the development of fuel economies with the GFEI objective is possible with the adoption of policies supporting energy efficiency and the use of fuel-saving technologies.

Key policies include fuel economy standards and vehicle taxes differentiated on the basis of emissions of CO₂ per km. On the technology side, improving fuel economy will require weight reduction, lower rolling resistance tyres and improved aerodynamics. Internal combustion engines can deliver initial savings, but hybrid cars and EVs need to gain market shares to achieve 2DS targets.

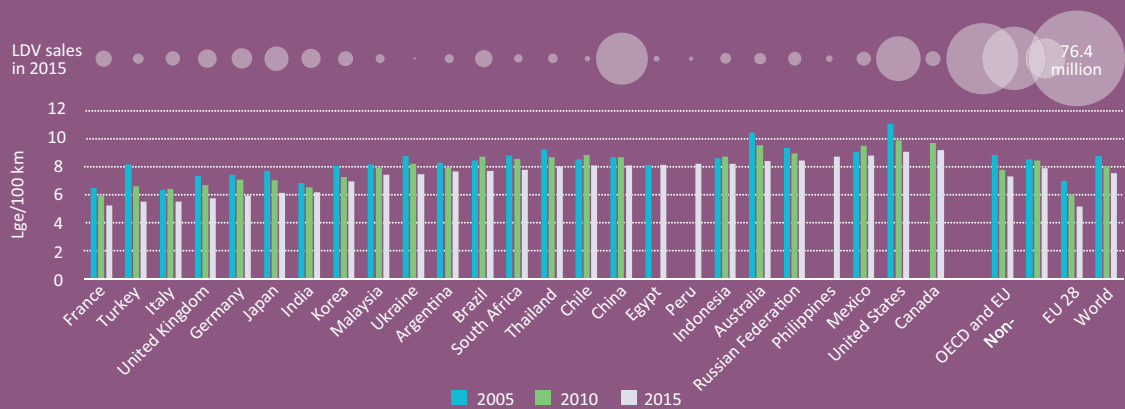
Reducing the gap between tested and on-road fuel economy is essential to meet 2DS targets. This goal requires more ambitious implementation procedures and the monitoring of fuel economy regulations, such as the WLTP, that better reflect real-world vehicle operation. Achieving increased accuracy in real driving conditions will also require the use of on-road testing and confirmatory tests of road load determinations.

1–4. Refer to Technology overview notes on page 108

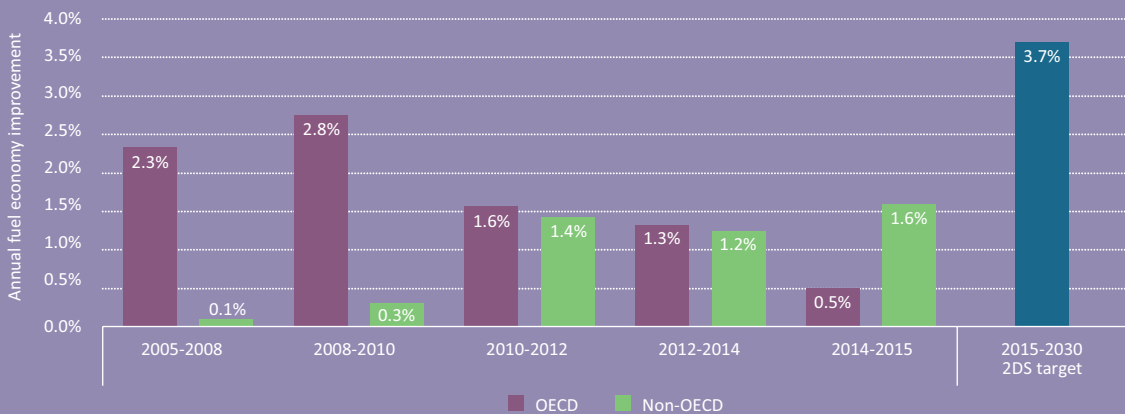
2.40 Tested fuel economy numbers for new LDVs and market size, 2015



2.41 Fuel economy development, test values, 2005-15



2.42 Annual fuel economy improvement (Lge/100 km), test values



For sources and notes see page 108

- Not on track
- Positive developments

Transport biofuels

Global biofuel¹ production increased to around 137 billion L (3.3 EJ) in 2016. Conventional biofuels are on course to meet 2DS targets for 2025; however, accelerated production of advanced biofuels is necessary to meet 2DS needs for transport sector decarbonisation.

Recent trends

In 2016, conventional biofuels accounted for around 4% of world road transport fuel. Double-digit global production growth pre-2010 slowed to a modest 2%² y-o-y, due to structural challenges and policy uncertainty in key markets.

In the United States, ethanol output is anticipated to stabilise due to lower investment in new capacity and reaching the corn ethanol limit within the Renewable Fuel Standard. Meeting Brazil's 2030 commitment to reach an 18% share of sustainable biofuels in its energy mix would equate to over 50 billion L of fuel ethanol demand, but accelerated production growth will be required if this goal is to be met. Biodiesel policy support remains robust in both countries, with production growth expected.

In the European Union, proposals for the revised Renewable Energy Directive (RED) covering 2020–30 include a scale-down of the cap on food crop-based biofuels from 7% to 3.8% (by energy) of the 2030 renewable energy target. Conversely, in Asia many petroleum product-importing countries have enhanced policy support for domestically produced biofuels, boosting markets for ethanol (e.g. India and Thailand) and biodiesel (e.g. Indonesia and Malaysia).

Advanced biofuel projects have been announced in a growing number of countries, including China, India and Thailand. Evidence also exists of strengthening advanced biofuel policy support, particularly in Europe where the aforementioned proposals for a revised RED specify an increase in the advanced biofuel share of transport energy demand from 0.5% in 2021 to 3.6% by 2030. In addition, with a growing number of commercial flights and fuel off-take agreements, aviation biofuels are poised to play a central role in the aviation industry's long-term decarbonisation plans.

Tracking progress

Conventional biofuels are on track to meet volumes required by the 2DS for 2025. For advanced biofuels, full delivery of the project pipeline, combined with a scale-up in output

towards rated capacity at commissioned plants, could deliver around 2.3 billion L (0.6 EJ) in 2020, although this level would be less than 1.5% (by volume) of total forecast biofuels production. Consequently, a twenty-five-fold scale-up in production would be necessary over 2020–25 to achieve the 57 billion L (1.6 EJ) advanced biofuels contribution to the 2DS in 2025. This projection highlights that significantly accelerated commercialisation is needed to keep pace with 2DS requirements.

Recommended actions

Stable and long-term policy frameworks can facilitate expansion of the advanced biofuels industry and enable capital and production cost reduction potential. Ambitious national transport sector targets for emissions reduction, shares of renewable energy or, as in Sweden, phasing out fossil fuels provide a favourable investment climate. These frameworks can include sub-targets for the road freight, marine and aviation sectors, which are more difficult to decarbonise.

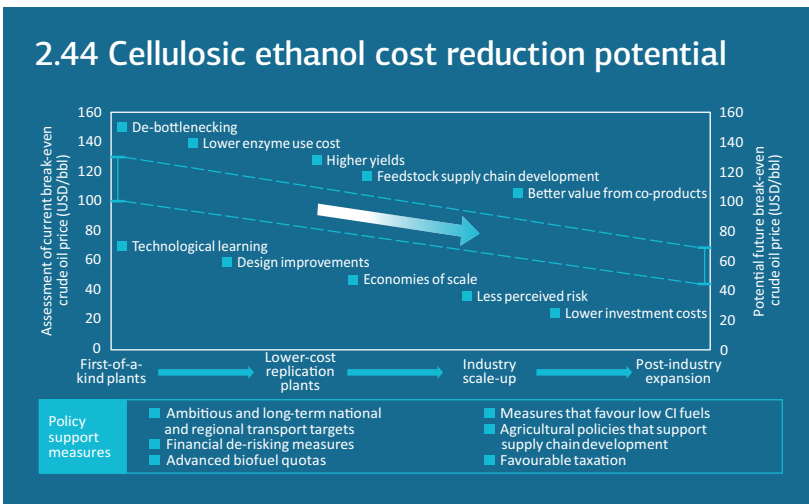
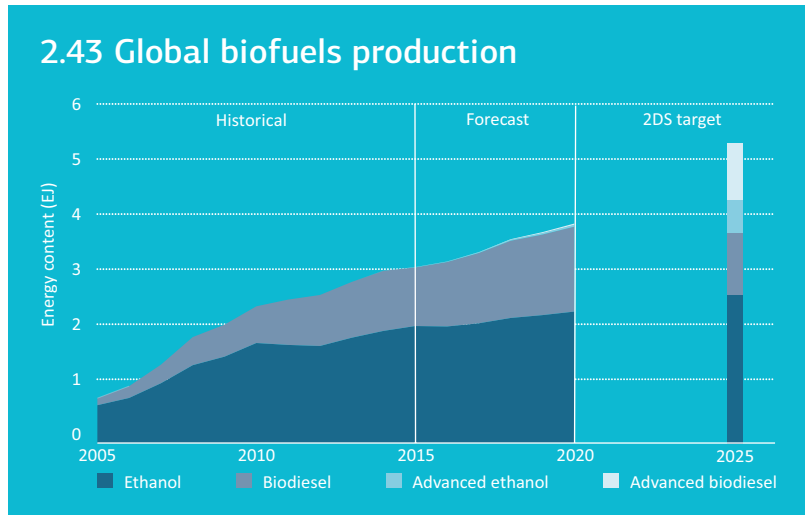
More widespread advanced biofuel mandates will be essential to accelerating uptake. Alternatively, legislation to stipulate defined reductions in the life-cycle carbon intensity (CI) of transportation fuels (e.g. as established in California and Germany) stimulates demand for biofuels with the highest emissions reduction potential.

These policies can be complemented by financial de-risking measures to support investment while costs remain high, tax incentives, and financial mechanisms to facilitate technological innovation and commercialisation. Policies to expand flexible-fuel vehicle fleets and biofuel distribution infrastructure will also support market growth. For aviation biofuels, supply chain development and measures to reduce cost premiums over fossil jet fuels are needed.

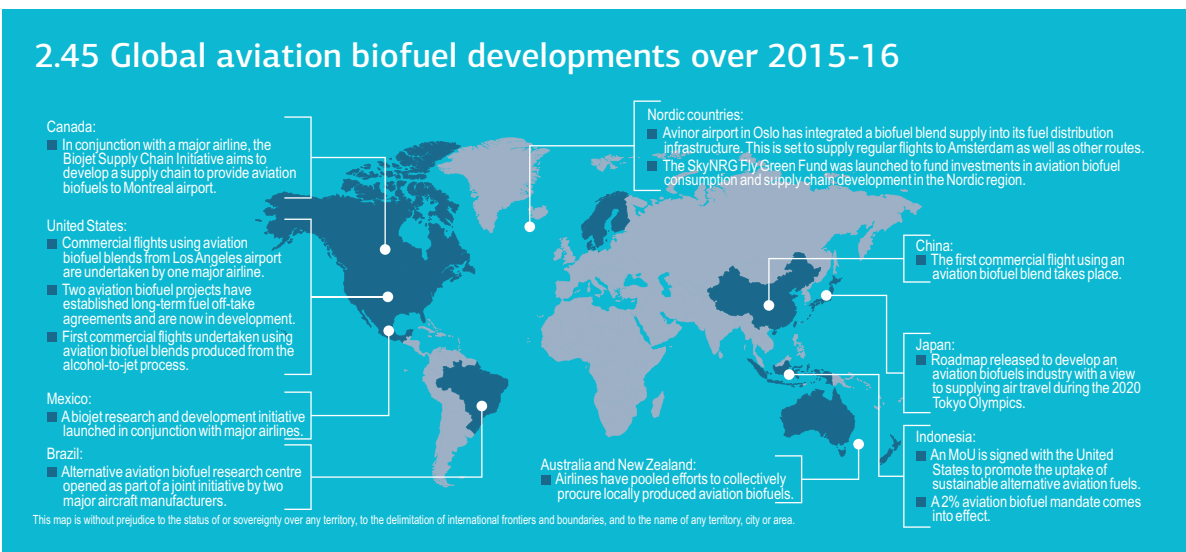
The recent launches of the Biofuture Platform and Below50 initiative are anticipated to facilitate an enabling environment for sustainable biofuels through enhanced international collaboration. Biofuels market expansion must respect environmental, social and economic sustainability considerations via industry benchmarking against recognised sustainability indicators and through the presence of strong governance frameworks.

1–2. Refer to Technology overview notes on page 108.

24%
AVERAGE ETHANOL BLEND BY 2026 SPECIFIED WITHIN THAILAND'S ALTERNATIVE ENERGY DEVELOPMENT PLAN



5
COMMERCIAL SCALE CELLULOSIC ETHANOL PROJECTS ANNOUNCED FROM INDIAN STATE OIL MARKETING COMPANIES



For sources and notes see page 108

- Not on track
- Positive developments

Buildings

A growing number of countries have put in place policies to improve building energy performance, but average energy consumption per person in the global buildings sector still remains practically unchanged since 1990. Assertive action is needed now across all countries to improve global average energy use per capita by at least 10% by 2025 using energy-efficient and low-carbon building technologies.

Recent trends

Global building-related CO₂ emissions have continued to rise by nearly 1% per year since 2010. Coal and oil use in buildings has remained fairly constant since then, while natural gas use grew steadily by about 1% per year. Global use of electricity in buildings grew on average by 2.5% per year since 2010, and in non-OECD countries it increased by nearly 6% per year. That growth is significantly faster than the 0.5% average annual improvement in global CO₂ intensity per kilowatt hour of electricity since 2010.

Global buildings sector energy intensity (measured by final energy per square metre) fell by 1.3% per year between 2010 and 2014, thanks to continued adoption and enforcement of building energy codes and efficiency standards. Yet progress has not been fast enough to offset growth in floor area (3% per year globally) and increasing demand for energy services in buildings.

More telling is energy demand per capita, where global average building energy use per person has remained practically constant since 1990, at just less than 5 MWh per person per year. In OECD countries, average energy consumption per person started to fall from a peak of 12 MWh in 2010, but this decline may be partly explained by warmer winters in recent years, as space heating accounts for 45% of OECD building final energy use. In non-OECD countries, average building energy use per capita continued to grow by around 1% per year since 2000.

To meet 2DS targets, average building energy use per person globally needs to fall by at least 10% to less than 4.5 MWh by 2025. OECD countries in particular need to shift away from historical trends and bring average energy use per capita below 1990 levels through rapid energy efficiency action. In non-OECD countries, where energy access and economic development are equally important priorities (among others), effort is needed to deploy energy-efficient and low-carbon building technologies to meet a rapidly growing demand for energy services without following an

unsustainable pathway towards high building energy consumption per person.

Tracking progress

Current policies and investments in building energy efficiency are not on track to achieve 2DS targets. Nearly two-thirds of countries still do not have any building energy codes in place. A similar share of energy-consuming equipment in buildings globally is not covered by mandatory energy efficiency policies.

Some progress towards realising the untapped potential in the global buildings sector has been seen since the Paris Agreement in 2015. Nearly 90 countries have registered building actions in their NDCs. More than 3 000 city-level and 500 private sector building commitments have also been registered under the United Nations Framework Convention on Climate Change. A number of industry and professional bodies have also mobilised to support market development of high-performance buildings, including initiatives to implement net-zero/carbon-neutral building programmes.¹

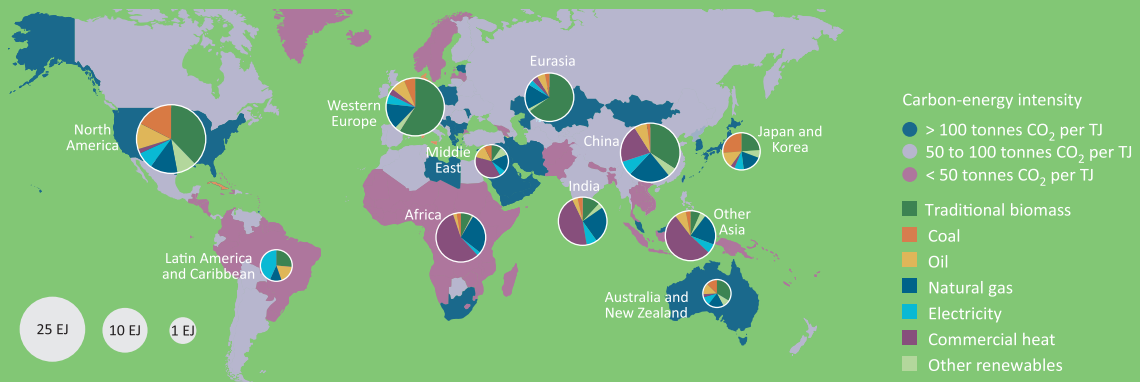
Recommended actions

Concerted global effort is needed to rapidly expand, strengthen and enforce building energy policies across all countries to prevent the lock-in of long-lived, inefficient building investments. Transitions to a 2DS pathway will require clear and consistent signals, along with incentives and appropriate financing mechanisms, to drive consumers and manufacturers to maximise energy efficiency opportunities. Educational programmes, training and capacity building, and better building energy data can also help improve energy efficiency policy design, adoption and enforcement.

Significant effort is needed in the coming decade to leapfrog best practices and high-performance technologies to developing countries. Greater access to finance is also critical to increase efficiency investments in both non-OECD and in OECD countries. Lastly, much greater effort is needed to address energy performance of existing buildings, especially in OECD countries.

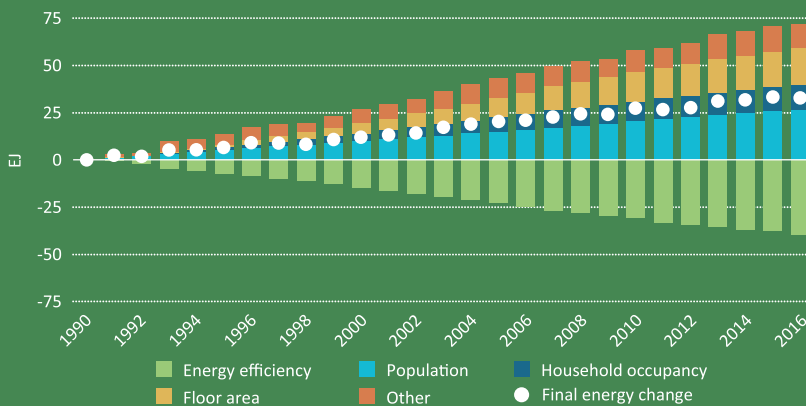
1. Refer to Technology overview notes on page 109.

2.46 Buildings energy use by fuel



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

2.47 Decomposition of final energy demand



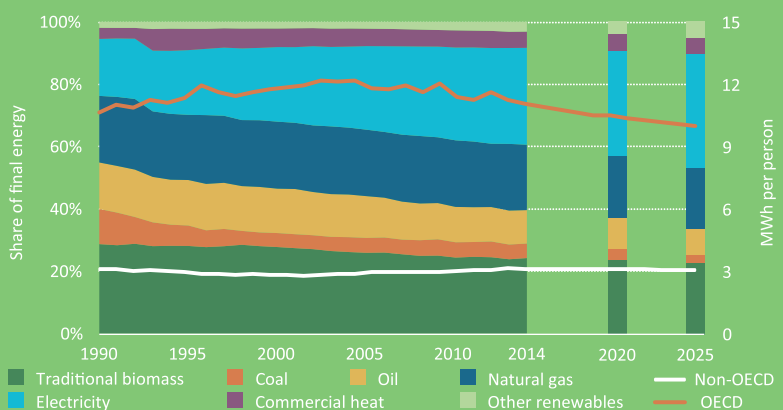
45%

INCREASE IN
BUILDING-
RELATED
EMISSIONS
SINCE 1990

10%

OR MORE
IMPROVEMENT
IN GLOBAL
BUILDING
ENERGY
PERFORMANCE
PER PERSON
BY 2025

2.48 Final energy use by fuel and per person



For sources and notes see page 109

● Not on track
~ Limited developments

Building envelopes

A growing number of countries and local jurisdictions have adopted building energy codes, but two-thirds of countries still do not have mandatory energy codes for the entire buildings sector. Deep energy renovations of existing buildings also continue to fall short of needed progress. Efforts and investments need to scale up dramatically to improve average building envelope performance by 30% by 2025 to keep pace with floor area growth and demand for thermal comfort.

Recent trends

Global building envelope performance¹ (in terms of useful energy per square metre [m^2]) improved by roughly 1.4% per year since 2010. Yet it was outpaced by growth in total building floor area (more than 2.5% per year) and the increasing demand for greater thermal comfort, especially in developing countries. Over the next decade, more than 20% of expected global building additions to 2050 will be built, and more than 50% of those floor area additions will occur in regions that currently do not have mandatory energy codes in place for the entire buildings sector.

Concerted effort is needed to improve global building envelope performance, which has the most influence over heating and cooling needs in buildings. While progress is being made in many countries and municipalities, nearly two-thirds of countries still do not have mandatory energy codes that apply to the entire buildings sector. Enforcement is also a major issue in many countries to achieving high-performance building envelopes, while many existing building energy codes need to be updated or revised to narrow the gap between existing building practices and building envelope targets.

Advancement of deep energy renovations (e.g. 30% to 50% improvement in building envelope performance) of existing buildings also continues to be sluggish, particularly in OECD countries. The buildings sector comprised roughly 230 billion m^2 in 2015, the majority of which will still be standing in 2050. Improvement measures typically pursued today (e.g. window replacements and modest levels of insulation) are a missed opportunity to achieve deep energy savings with cost-effective investments. The rate of annual building energy renovations also needs to improve considerably, from rates of 1% to 2% of existing stock per year today to more than 2% to 3% per year by 2025.

Tracking progress

Global progress in achieving high-efficiency new buildings is slow, particularly in non-OECD countries where the greatest floor area additions are expected to 2050. Much greater effort is needed to support adoption and enforcement of mandatory building energy codes in developing countries, starting first with rapidly emerging economies that risk locking in inefficient building envelope investments over the next decade.

Some notable advancement in 2015 and 2016 includes the ongoing development of building energy codes in several sub-Saharan African countries. Progress in India has also been made to shift from a voluntary national code to locally adopted mandatory codes for non-residential buildings in most Indian states.

Additional progress includes introduction of a low-carbon building label in France in 2016 as well as the introduction of building energy performance certificates in Russia and South Africa. As of 2016, nearly 40 countries had mandatory certification programmes, and as many as 80 countries had voluntary programmes.²

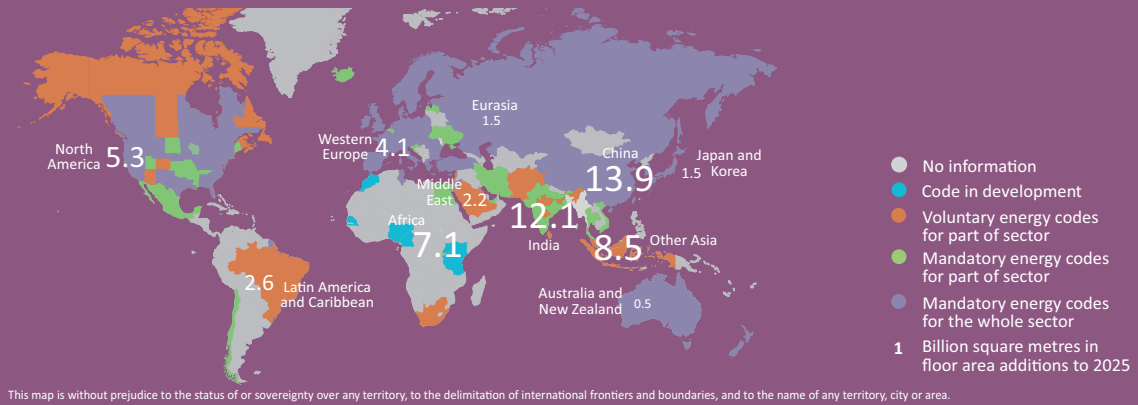
Recommended actions

Clear and consistent signals on building energy performance, along with improved access to finance for high-performance building envelope construction and renovations, are needed to move markets to energy-efficient and low-carbon building envelope investments. Significant effort is needed to quickly adopt and enforce aggressive building energy codes and performance standards in line with 2DS ambitions across all countries. Additional effort is also needed to update many existing building energy codes (both voluntary and mandatory).

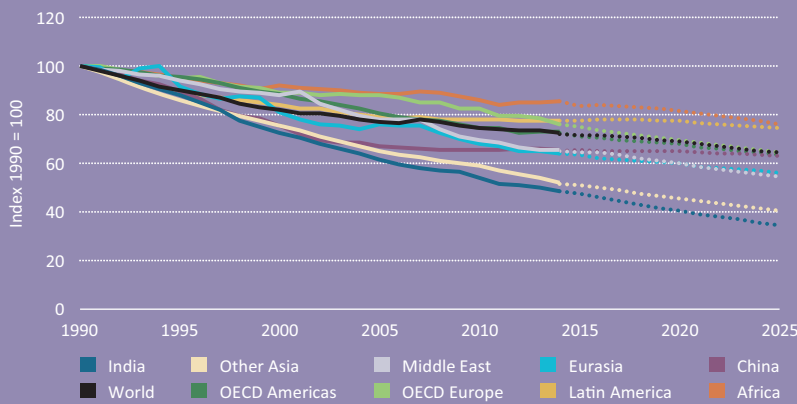
Policy makers should also support development and demonstration of advanced and integrated envelope solutions and building practices. Co-operation among governments, especially on harmonisation and improvement of building energy performance standards, can help to provide an assertive signal to markets in line with 2DS building envelope expectations.

1–2. Refer to Technology overview notes on page 109.

2.49 Building energy codes



2.50 Change in building envelope performance

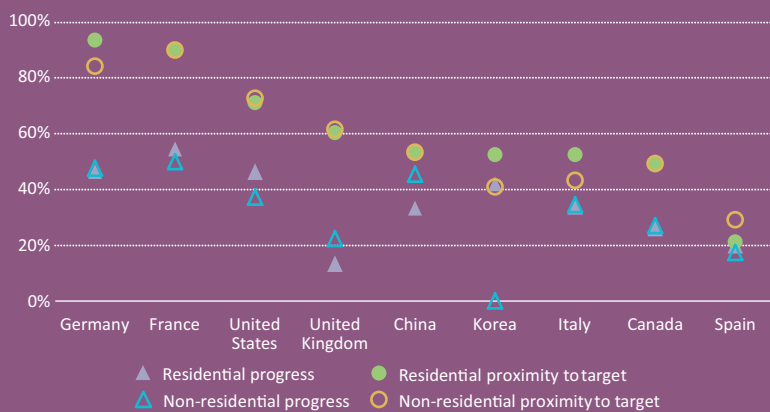


ONLY
1/3
OF COUNTRIES
HAVE
MANDATORY
ENERGY
CODES FOR
THE ENTIRE
BUILDINGS
SECTOR

2/3

OF NEW
BUILDINGS NEED
TO BE COVERED
BY MANDATORY
BUILDING
ENERGY CODES
BY 2025

2.51 Efficiency policy progress, 2005-15



For sources and notes see page 109

Lighting, appliances and equipment

● Not on track
 ↗ Positive developments

The global energy efficiency potential from lighting, appliances and equipment in buildings represents 100 EJ of energy savings potential to 2025. Action is needed to expand energy efficiency standards and labelling (S&L) programmes across all countries and the vast majority of products. S&L programmes also need to evolve with technology developments to ensure continual energy efficiency improvements.

Recent trends

Global energy use for lighting, appliances and equipment¹ in buildings grew steadily at 1% per year since 2010. In non-OECD countries, where demand for energy services and thermal comfort is growing rapidly, the energy use grew at twice that rate.

Energy demand for lighting and space cooling in buildings grew considerably over the last decade, particularly as improved access to electricity, increasing household wealth and demand for thermal comfort all drove greater energy demand in developing countries. Globally, cooling and lighting demand both grew by roughly 2% per year since 2005, while in non-OECD countries the average annual growth rate was more than 5%.

Increasing ownership of household appliances (e.g. refrigerators and televisions) and changes in consumer preferences (e.g. appliance size) also continued to drive greater energy use in buildings. Despite considerable progress on S&L policies for household appliances in many countries, when population growth, decreasing household size² and growing access to electricity in developing countries are taken into account, the net effect is that major appliance energy demand globally grew by 50% between 1990 and 2016.

By contrast, space heating and hot water energy demand grew at a slower pace of less than 0.5% per year since 2010. This lesser rate is due in part to shifts away from traditional use of biomass in non-OECD countries, while energy efficiency progress (e.g. condensing boiler and heat pump adoption in many OECD countries) also helped to improve energy demand in those end uses.

Tracking progress

Coverage of S&L programmes continues to expand across more countries and an increasing number of products, but assertive policy across all countries is needed to expand and strengthen S&L across the vast majority of building end uses. Effort is also needed to address energy efficiency

and product labelling for networked devices and other electrical plug loads (e.g. portable electronics and small appliances), which grew on average by 3.5% per year since 2010. “Smart” appliances and networked devices may represent a major energy efficiency opportunity, but work is still needed to ensure those technologies are used smartly and to their energy-saving potential.

Much greater effort is also needed to address cooling energy demand growth globally. Despite minimum performance standards and availability of high-efficiency products, the average energy performance of cooling equipment is still very similar across most countries and continues to underperform. Much greater effort is needed to capture the energy efficiency potential, especially in rapidly growing markets such as India, Mexico and Indonesia, where cooling demand could increase by 5% or more per year over the next decade.

On a positive note, lighting sales, despite earlier shifts from inefficient incandescent lamps to equally inefficient halogen lighting, started to shift to high-efficiency LEDs, which represented 15% of total residential lamp sales in 2015 (expected to have grown to nearly 30% in 2016). Recent market trends also suggest that average television energy use started to peak in 2015, with energy efficiency improvements moving faster than increases in television sizes.

Recommended actions

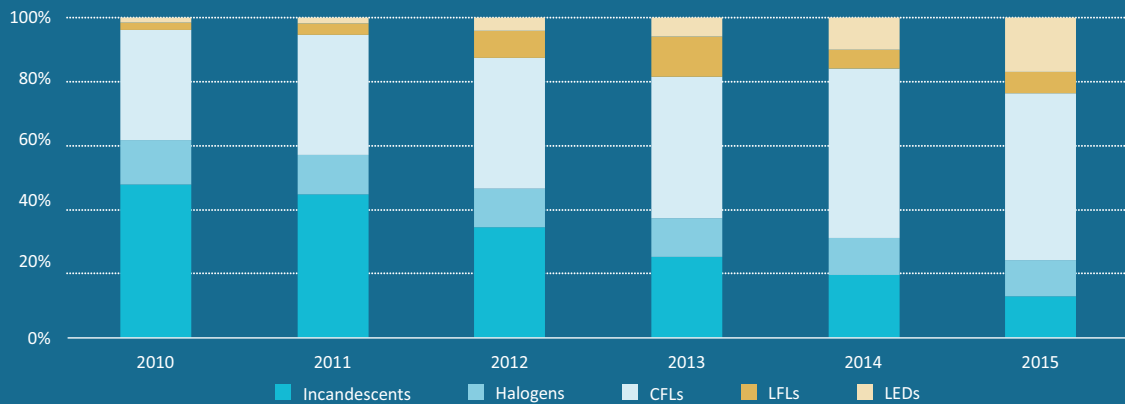
Global building electricity consumption needs to be halved from the current 3% increase per year over the last decade to a 1.5% annual increase under the 2DS. S&L programmes need to be expanded and strengthened across all countries and the vast majority of end-use products. They also need regular review to ensure that efficiency requirements keep up with changes in technology and are in line with 2DS objectives. This review includes monitoring and enforcement of existing S&L. Last, S&L programmes should seek to account for changing consumer preferences (e.g. greater image resolution) that can have a significant influence on final energy demand.

1–2. Refer to Technology overview notes on page 110.

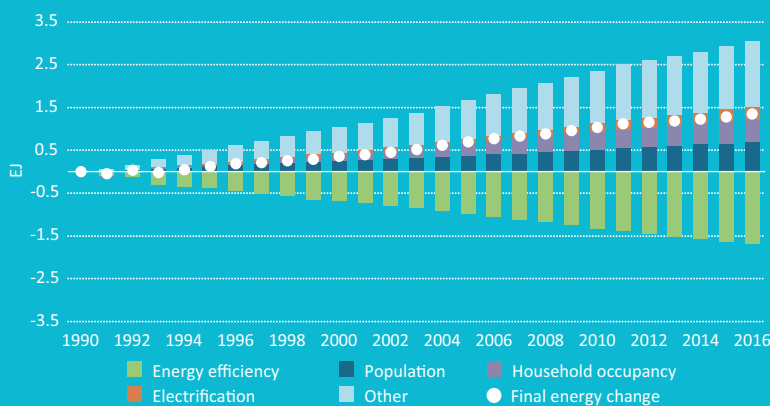
2.52 Efficiency ratios of split-package air conditioners, 2015



2.53 Global lighting sale share estimates in the residential sub-sector



2.54 Final energy decomposition of major appliances



50%

REDUCTION IN
AVERAGE ANNUAL
ELECTRICITY
DEMAND GROWTH FOR LIGHTING,
APPLIANCES
AND EQUIPMENT
NEEDED BY 2025

For sources and notes see page 110

Renewable heat

● Not on track
~ Limited developments

Heat accounts for more than 50% of final energy consumption and remains largely fossil fuel-based. Growth in renewable heat has been steady but slow, and an increase of 32% would be needed between 2014 and 2025 to meet 2DS goals. Solar thermal heating would need to see the largest increase, but if its recent slowdown in growth continues, it will not be on track.

Recent trends

The direct use of renewables for heat (modern biomass, solar thermal and geothermal) increased by 8%, from 13.2 EJ in 2010 to 14.2 EJ in 2014.¹ More than one-third of this increase was due to the consumption of renewable heat in China, mostly through the rapid growth of solar thermal installations. Currently, the European Union is the largest consumer of renewables for heat, with almost 15% of its heat demand met by renewables. In the emerging economies, Brazil has one of the highest shares of renewables used for heat (37%), due to using biomass in industries such as food, paper and pulp, and ethanol.

Biomass (excluding the traditional use of biomass) accounts for 90% of renewables used for heat, with a variety of heat applications in the buildings and industry sectors. Biomass use for heating in the European Union has grown steadily and accounted for over 60% of all wood pellet demand in the European Union in 2015. However, some evidence indicates that low heating oil and LPG prices have constrained the growth of biomass heating in some countries, especially in the off-the-gas-grid segment where biomass tends to be most competitive.

Solar thermal (mainly used for water heating) has increased more rapidly than renewable heat as a whole. However, the rate of new installations has slowed in the last two years due to a slowdown in China and sluggish growth in the European Union. In 2015, the total newly installed capacity was 40 gigawatts thermal capacity (GW_{th}), 15% lower than in 2014. In countries with high levels of insolation, solar thermal systems can be very cost-competitive with electric or fossil fuel alternatives. Elsewhere, large installations can provide economies of scale. The world's largest solar thermal plant entered operation in Silkeborg in Denmark at the end of 2016 and is expected to produce 80 000 MWh for use in the local district heating network.

Electric heat pumps also play an important role in heat decarbonisation, through the use of renewable heat stored in the ground, air and water

and the rising share of renewables in electricity supply. Heat consumption from heat pumps is estimated to have increased by 7% since 2010, with the fastest growth (50%) in China.

Tracking progress

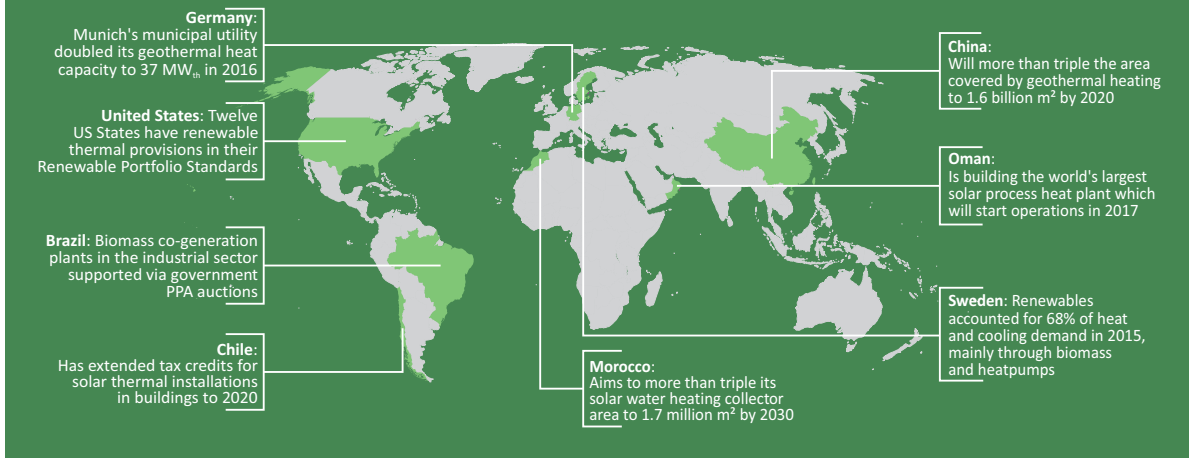
Good potential exists globally for renewable heat, but remains largely unexploited. Growth in renewable heat has not matched that of renewable electricity. The direct use of renewables for heat would have to increase 32% between 2014 and 2025 to meet the 2DS target, with faster growth needed in the non-biomass segments.^{2,3} For example, solar thermal heat consumption would have to almost triple by 2025. This growth would require an annual deployment rate more than twice that of current levels. Achieving that level is unlikely unless deployment in key countries, including China and India, picks up. Heat pump use would also have to increase more rapidly than in recent years, coupled with rapid deployment of renewable electricity.

Recommended actions

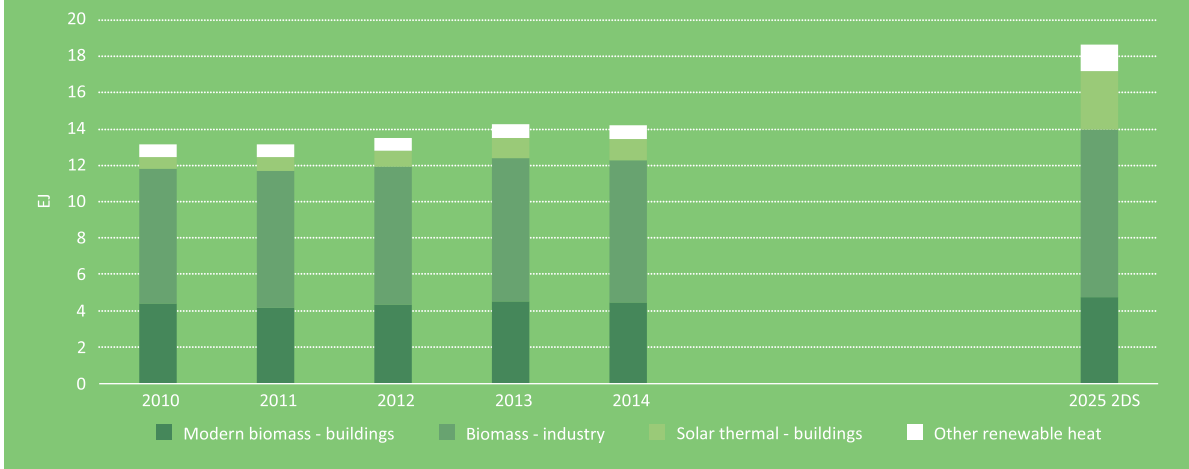
Renewable heat continues to face numerous economic (e.g. high capital costs, split incentives, and fossil fuel subsidies) and non-economic (e.g. lack of awareness, lack of confidence, and suitability issues) barriers. To address these barriers, increased policy support and policy consistency are needed. Governments should set targets and develop strategies for heat decarbonisation. To be effective, these need to cover all sectors and consider the appropriate balance between renewable heat deployment, heat electrification and energy efficiency improvement. An expansion of district heating networks can also play a role, allowing economies of scale to be exploited, as well as better control of air pollutants in the case of biomass. Due to the fragmented and decentralised nature of heat supply, heat planning at the local level can make an important contribution. Other policy instruments that have been shown to be effective include carbon taxes, building codes that require renewable heat installations in new buildings, and financial support mechanism.

1–3. Refer to Technology overview notes on page 110.

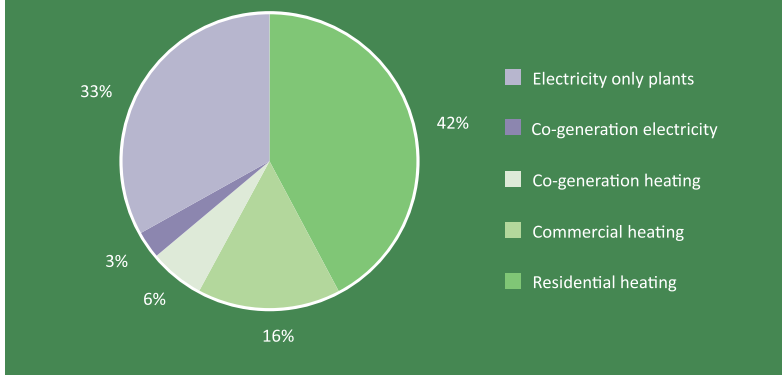
2.55 Renewable heat



2.56 Renewable heat by technology 2010-14 versus 2025 2DS target



2.57 Share of EU wood pellet consumption (2015)



SOLAR THERMAL
CAPACITY REACHED

436
GWth

IN 2015

For sources and notes see page 110

● On track
 ↗ Positive developments

Energy storage

Strong deployment of storage technologies continued to be driven by policy, technological developments and a better appreciation by regulators of the value of storage. Lithium-ion batteries are positioned as the main storage technology due to cost reductions and rapid scale-up of manufacturing capacities. Storage is on track with 2DS due to positive market and policy trends, but an additional 21 GW of capacity is needed by 2025. Further policy action is, therefore, required to tackle challenges to deployment.

Recent trends

With the rise of renewables in much of the world, understanding and managing flexibility is becoming a cornerstone of energy markets. Energy storage played a much greater role in providing flexibility in 2016, with important deployments in both short-term and long-term balancing markets, particularly in Europe and the United States.

While the total capacity additions of non-pumped hydro utility-scale energy storage grew to slightly over 500 MW in 2016 (below the 2015 growth rate), nearly 1GW of new capacity was announced in the second half of 2016. The vast majority of utility-scale stationary energy storage capacity in 2016 was lithium-ion batteries. Other batteries (e.g. redox flow or lead-acid) amounted to an estimated 5% of capacity additions, with all other storage technologies combined accounting for the remaining 5%. A key defining trend during 2016 was the concerted action of integrated energy companies, manufacturers and equipment providers to expand their storage activities, leading to a more concentrated market.¹

Energy storage in the United States experienced a slight growth contraction relative to 2015, with activity largely sustained by state policy. In Europe, growth continued at historic rates, with a capacity market auction in the United Kingdom delivering half a gigawatt of winning bids. Countries with significant solar PV capacity (France, Germany, Australia and Italy) led growth in the nascent market for behind-the-meter storage installations.

In China, the 13th FYP, the trend toward high-voltage transmission capacity and the lack of specific policy support weaken the outlook for battery storage and strengthen that of large-scale pumped hydro projects. Commissioned storage installations in the ASEAN region, however, almost doubled, largely driven by small-scale and island systems.

Beyond the technologies themselves, innovative business models that capitalise on the benefits of storage have seen timid growth in some regions. While there are positive moves by regulators in Europe and in the United States to create enabling environments for aggregators, virtual power plants and other platforms, it is still early to evaluate their impact on 2DS projections.

Tracking progress

The 2DS envisions 21 GW aggregate energy storage capacity by 2025. The key area of uncertainty remains behind-the-meter storage. Growth in this area was significant in 2016, albeit from a very low base of 20 MW and regulatory uncertainty subduing outlook.

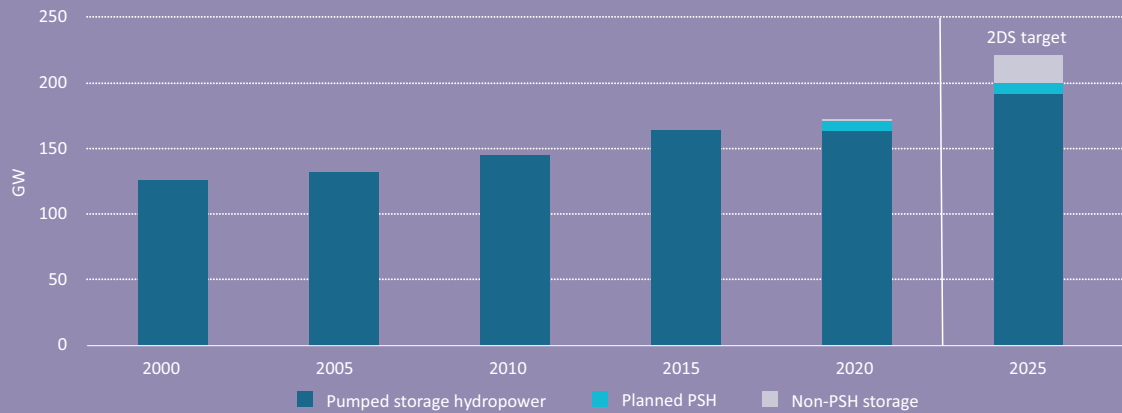
Remaining on track with the 2DS targets will require the technology growth to continue at the current growth trajectory over the next decade. While evolutionary improvements to the technology appear to be sufficient to meet short-term deployment needs, advanced technologies, particularly those decreasing material requirements and increasing energy density, will be required to stay on track. In 2016, larger players began to acquire start-ups that are developing these next-generation technologies.

Recommended actions

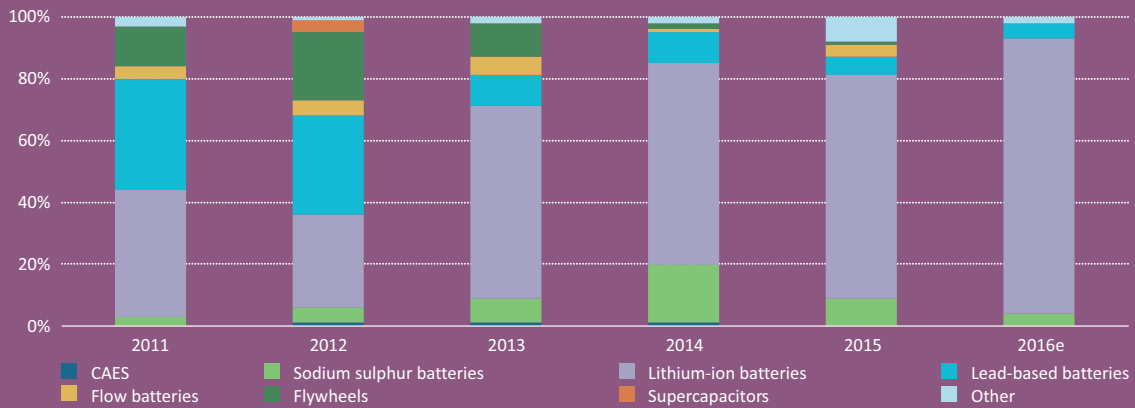
Coherent policies need to complement promising technological developments to fully realise the potential of energy storage. The use of storage by grid operators is limited at present, largely due to the lack of clarity and transparency in market rules and regulations, the lack of markets for flexibility and ancillary services, and the low penetration of new business models. While net metering and other incentives can have a positive impact on behind-the-meter storage, policy assessments are required in each jurisdiction to assess the impact of prosumer-generated electricity and storage. This includes an appreciation of the impact of such developments on traditional grid and utility business models.

1. Refer to Technology overview notes on page 111.

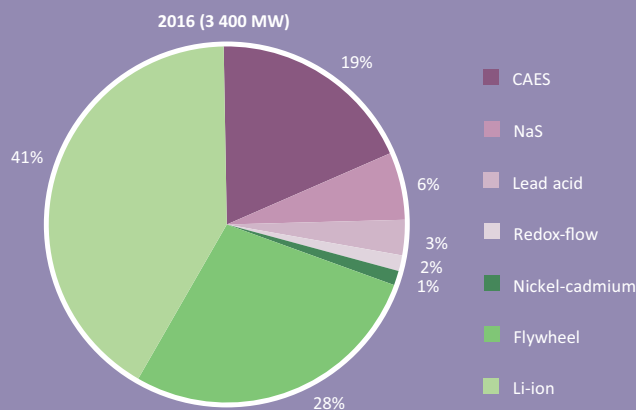
2.58 Globally installed electricity storage (GW)



2.59 Shares in annual non pumped hydro storage technology additions



2.60 Installed non-pumped hydro storage, 2016



For sources and notes see page 111

Technology overview notes

Unless otherwise noted, data in this report derive from IEA statistics and *ETP* analysis. The *TCEP* dataset for up to 2014 is derived from official IEA statistics, with 2014 the latest year that a full dataset was available. The year 2014 is taken as a base year for estimates and forecasts. Sources for data after 2014 vary by technology type or market. They can be a product of capacity investment analysis or collected sales data, or in some cases are provisional estimates based on forecasts and market trends.

The notes in this section provide additional sources and details related to data and methodologies. Throughout the report, annual averages are calculated as compound average growth rates.

Renewable power (page 64)

Figures 2.1, 2.2, 2.3 and 2.4 sources: data from IEA (2016c), Medium-term Renewable Energy Market Report and 2°C Scenario (2DS) targets from 2017 ETP model.

Nuclear power (page 68)

Note 1: This effect is evident elsewhere, but it seems to be most acute in the United States. However, two states facing eminent closures – Illinois and New York – took action to allow nuclear to receive low-carbon financial incentives to maintain existing capacity.

Note 2: A documentation and quality control issue reported to the French regulator by Areva concerning its Creusot foundry prompted safety reviews at reactors using the facility's components in France and in several other countries. So far, French and other national regulators have not found any issues that pose a safety risk in their opinion, but the issue caused significant disruptions to the operation of the French fleet, in particular.

Note 3: To bridge this gap using wind and solar, for instance, would require 200 gigawatts electrical (GW_e) to 250 GW_e of additional capacity.

Coal-fired power (page 72)

Note 1: Coal generation in China is estimated to have rebounded again in 2016.

CCS (page 74)

Note 1: CO₂ is captured, compressed and transported for injection into onshore oilfields for injection for EOR. EOR is a closed-cycle process that involves injecting carbon dioxide (CO₂) into older oil reservoirs to increase or prolong production. The CO₂ is injected into the reservoir, recovered from the produced oil and re-injected. CO₂ is retained and eventually stored through injection for EOR, though additional monitoring and planning is needed to verify the CO₂ is stored effectively and accounted for.

Note 2: The captured CO₂ is transported by pipeline 82 miles and injected into depleted fields for EOR purposes. See Note 1.

Note 3: This three-year CO₂ injection programme is scheduled for 2016–18, with monitoring continuing for another two years until 2020.

Note 4: These two projects, the Kemper Project in the United States and the Gorgon CO₂ Injection Project in Australia, will be capable of capturing up to 6.5 MtCO₂ per year.

Note 5: In 2016 the government completed a feasibility study on three industrial emission sources and the associated transport and storage options. They also announced a three-year extension to the Technology Center Mongstad (TCM) test facility, a joint venture between the Norwegian state, Statoil, Shell and Sasol.

Note 6: Only 9.3 million tonnes of the captured CO₂ is being stored with appropriate monitoring and verification focussed on verifying the long term retention of CO₂. Such monitoring and verification is not always the case for EOR projects. See Note 1.

Figure 2.14 and 15: Source: GCCSI (2015), *The Global Status of CCS 2015*. Note: large-scale projects are defined in accordance with the Global Carbon Capture and Storage

Institute (GCCSI), i.e. projects involving the annual capture, transport and storage of CO₂ at a scale of at least 800 000 tonnes of CO₂ (tCO₂) for a coal-based power plant, or at least 400 000 tCO₂ for other emissions-intensive industrial facilities (including natural gas-based power generation). Advanced stage of planning implies that projects have reached at least the “Define stage” in accordance with the GCCSI Asset Lifecycle Model.

Figure 2.16: Note: Data are in USD 2015 prices and purchasing price parity (PPP).

Figure 2.17: Source: IEA analysis based on BNEF (2015), Funds Committed (private database). Note that total project investment is in nominal USD and is recorded at the point of final investment decision.

Industry (page 76)

Note 1: Including process and feedstock-related emissions.

Note 2: Unless otherwise noted, all numbers are derived from the IEA, 2017a.

Note 3: Industry includes International Standard Industrial Classification (ISIC) divisions 7, 8, 10–18, 20–32, and 41–43, and Group 099, covering mining and quarrying (excluding mining and extraction), construction and manufacturing. Petrochemical feedstock energy use and blast furnace and coke oven energy use are also included.

Note 4: World Steel (2016).

Note 5: Calculated based on the Cement Sustainability Initiative (CSI) Getting the Numbers Right database, in combination with estimates from national associations for regions with less coverage. Source: Cement Sustainability Initiative (CSI), 2017.

Note 6: IAI (2017), World Aluminium Statistics, The International Aluminium Institute, London, www.world-aluminium.org/statistics/.

Note 7: IAI (2016), Global Mass Flow Model, The International Aluminium Institute, London, www.world-aluminium.org/publications/.

This represents the share of production based on new and old scrap. Internal scrap has been excluded for consistency with published statistics.

Figure 2.18: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included.

Figure 2.19: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included, as well as process and feedstock-related emissions.

Figure 2.20: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included. “Heat” refers to commercial heat purchased from heat networks. Heat generated on site is included in fuel terms. “Electricity” includes all electricity consumption, including the electricity generated on site. Generation from black liquor in recovery boilers is included in “heat” and “electricity”.

Figure 2.21: Process CO₂ emissions from lime kilns in the pulp and paper sector are considered carbon-neutral because they are from biogenic sources of lime from the sector’s raw materials, and thus they are not included in this figure. Other sources of process CO₂ emissions exist in the industrial sector; this includes only process CO₂ from the five energy-intensive sectors.

Textbox 1: Chemicals and petrochemicals, iron and steel, non-ferrous metals, non-metallic minerals, and pulp, paper and printing. Included here are energy use in blast furnaces and coke ovens and as petrochemical feedstock.

Textbox 2: Based on IEA estimates from energy-intensive industrial sector modelling.

Chemicals and petrochemicals (page 80)

Note 1: “Primary chemicals” includes: ethylene, propylene, benzene, toluene and xylenes, ammonia and methanol. These chemicals form the basis of the modelling for the sector.

Note 2: HVCs include: light olefins (ethylene and propylene) and BTX aromatics (benzene, toluene and xylenes).

Note 3: The weight of feedstocks is determined by the length of their constituent hydrocarbon chains. Lighter feedstocks include natural gas, ethane and LPG. Heavier feedstocks include naphtha and fuel oil.

Note 4: SEC: process energy consumption per tonne of primary chemical(s) in GJ/t.

Note 5: IEA estimates based on regional modelling results. SEC values for HVCs include the methanol-to-olefins route. The large ranges of SEC for a given chemical can be primarily attributed to the range of feedstocks used in different regions. Processes fed by heavier feedstocks generally incur a process energy penalty per unit of chemical produced, compared with a process producing the same chemical with a lighter feedstock.

Note 6: Final energy consumption includes both process energy and fuel use as feedstock. Emissions are calculated based on fuel combustion and stoichiometric calculations to compare carbon content of feedstocks and products. Emissions from oxidised chemicals-based products, such as plastics used in waste-to-energy facilities, are accounted for in other sectors.

Figure 2.25: “Other” feedstock shares for HVCs include gas oil for steam cracking, ethanol dehydration, and methanol to olefins. “Naphtha” includes both feedstock for steam cracking and catalytic cracking. For methanol, coke oven gas constitutes the “Other” category.

Figure 2.26: Production volumes for HVCs only include those produced in the chemical and petrochemical sector. Both the propylene and BTX aromatics components of HVCs have significant shares sourced from the refining sector. The energy intensities shown do not cover these quantities.

Pulp and paper (page 82)

Note 1: IEA analysis focuses on pulp and paper manufacturing, which makes up the majority of pulp, paper and printing sector energy use.

Note 2: This share of wood pulp in total fibre furnish does not include fillers.

Note 3: Pulp and paper amounts are referred to in air-dried tonnes, with 10% moisture content. Kraft pulping (or sulphate pulping) is the conversion of wood into pulp, breaking the bonds between lignin, hemicellulose and cellulose with a solution of sodium hydroxide and sodium sulphide.

Note 4: Black liquor is a by-product from kraft pulping. It is an aqueous solution of sulphate chemicals used in the pulping process and lignin and hemicellulose residues extracted from wood.

Figure 2.29: FAO (2016). SEC ranges are indicative of the scale of national average energy intensity. They are based on IEA analysis, not reported data. SEC includes energy for paper machines and for pulpers. Chemical recovery, pulp drying, wood processing, and other energy use are not included.

Transport (page 84)

Note 1: In high-income countries, which account for 20% of the mitigation measures proposed in NDCs, nearly 50% of mitigation strategies target fuel efficiency improvements or decarbonising fuels. Low- and middle-income countries often opt for import restrictions based on vehicle age and fuel efficiency measures.

Note 2: Progress on HDVs has been encouraging, with indications of efforts to draft legislation to address the energy efficiency of trucks in Europe, India and Korea. However, only Canada, China, Japan and the United States have actually put in place HDV fuel economy standards to date.

Note 3: Offset mechanisms include both carbon credits and carbon allowances from emissions trading systems.

Note 4: Implications of this decision for the maritime fuel mix and prospects for low-carbon alternative fuels are discussed in the “International shipping” section.

Note 5: Continued CO₂ emissions growth in non-OECD countries is commensurate with increasing transport activity, driven mainly by rising incomes and population growth.

Note 6: The CO₂ emissions cited here are evaluated on a tank-to-wheel basis, under a framework that includes combustion emissions of biofuels (and wherein well-to-tank GHG intensity of biofuels may offset combustion emissions).

Note 7: Vehicle efficiency (or fuel economy) regulations should first and foremost target the most energy-intensive modes of passenger and freight transportation (namely, passenger cars and heavy-duty trucks).

Note 8: A sizeable potential to reduce specific CO₂ emissions in international shipping comes from considerable scope within the sector for efficiency improvements, as well as the availability of renewable solutions such as wind assistance.

Electric vehicles (page 86)

Note 1: The term “EV market share” refers in this section to the share of electric car sales in total PLDV sales.

Note 2: In this section, electric cars refer to plug-in electric passenger light-duty vehicles (PLDVs), and comprise full BEVs and PHEVs. “Electric cars” are also commonly referred to as EVs.

International shipping (page 88)

Note 1: Expressed in constant PPP-adjusted USD.

Note 2: International shipping energy demand reached 8.2 EJ in 2014, up from 6.5 EJ in 2000.

Note 3: The global fleet size grew between 2010 and 2015; the most significant growth took place for container ships. The average container ship size grew at an annual rate of 18.2% between 2010 and 2015, compared with 1.9% between 2001 and 2009 (UNCTAD, 2016), allowing for fewer ships to satisfy global freight demand.

Note 4: It mandates a minimum improvement in the energy efficiency per tonne kilometre of new ship designs of 10% by 2015, 20% by 2020, and 30% by 2025, benchmarked against the average efficiency of ships built between 1999 and 2009.

Note 5: In 2014, HFO accounted for 84% of the marine bunkers fuel mix. HFO has an average sulphur content of 2.5%.

Note 6: This effect is measured in megajoules per vehicle kilometre, rather than tonne kilometre, to exclude the effect of increasing average ship size. The 1% fuel efficiency increase excludes the effect of projected growth of average ship size and freight capacity. The assumption underlying this calculation is that each ship abides by the efficiency standard as prescribed: 10% more fuel efficient between 2015 and 2020, 20% more efficient between 2020 and 2025, and 30% more efficient between 2025 and 2030.

Note 7: Most of the reduction took place after 2010 and can most likely be attributed to an unexpected issue of overcapacity in the wake of the financial crisis, which pushed numerous older and less efficient ships into an early retirement.

Note 8: Possible exceptions, where low-SO_x technologies may also contribute to GHG mitigation, include advanced biofuels, low-carbon synthetic fuels and, to a much lesser extent, LNG.

Note 9: Other low-carbon energy carriers, such as low-carbon synthetic fuels or hydrogen, could also complement these solutions.

Note 10: To stay on track with the 2DS, the emissions from the sector must remain below 800 MtCO₂ in 2025.

Note 11: IMO is the United Nations (UN) agency responsible for regulating international shipping.

Note 12: For example, switching to LNG and scrubbers could help to reduce local air pollution, but these measures would be inadequate to bring the sector's carbon emissions trajectory in line with the 2DS. On the other hand, energy efficiency, wind assistance, advanced biofuels, low-carbon synthetic fuels and hydrogen could help to meet both the needs of pollutant emissions mitigation requirements and to achieve significant GHG emissions reduction.

Fuel economy of LDVs (page 90)

Note 1: The values used here are expressed on the basis of a normalisation of regional test procedures to the Worldwide Harmonized Test Cycle, based on the conversion factors developed by ICCT (2014).

Note 2: The widening gap between on-road and tested fuel economy is especially relevant for vehicles being tested according to the European test cycle, also used in the UN framework and now migrating towards the Worldwide Harmonized Test Cycle, partly with the aim to address this gap.

Note 3: This is largely attributable to the greater weight, footprint and power rating of LDVs sold in these markets, and matches the lower price of fuel in comparison with other OECD countries.

Note 4: This correlates with tightened fuel economy policies in non-OECD markets enacted over the past few years (such as China and Brazil), and with China's increasing share of the LDV market (GFEI, 2017). The slowdown in global fuel economy improvement rates also matches falling oil prices in the second half of 2014 and 2015.

Transport biofuels (page 92)

Note 1: Sustainably produced biofuels offer a lower-carbon-intensity alternative to petroleum-derived fuels. Conventional biofuels include sugar- and starch-based ethanol and oil crop-based biodiesel. Advanced biofuels are sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

There is currently no globally recognised definition for advanced biofuels, with different interpretations of the term, as well as alternative terminology such as second-generation biofuels in use. Classification as "advanced" does not necessarily infer greater sustainability versus all conventional biofuels per se, as biofuel sustainability must be judged on the individual characteristics specific to each production pathway. However, where waste and residue feedstocks are used, GHG emissions associated with land-use change are avoided.

The United States and Brazil combined accounted for over 70% of global conventional biofuel production in 2016. In the US Renewable Fuel Standard, total renewable fuel volumes for 2017 indicate that the limit for corn-based ethanol of 15 billion gallons will be reached. Structural challenges relate to availability of suitable vehicles and fuel distribution infrastructure. Flexible-fuel vehicles have suitable engine modifications to use higher ethanol blends (e.g. E85), or as is commonly found in Brazil, pure hydrous ethanol (E100). Brazil's NDC for the Paris Agreement outlines that the share of sustainable biofuels in its energy mix will be increased to approximately 18% by 2030. Examples of markets where biofuels mandates and supportive policies have been strengthened since the downturn in global crude oil prices include Argentina, Brazil, India, Indonesia, Spain and Thailand.

While emissions from aviation do not sit within the Paris Agreement, the International Air Transport Association (IATA) has adopted its own set of ambitious targets to reduce the climate impact from air transport, including carbon-neutral growth from 2020 and a reduction in net aviation CO₂ emissions of 50% (on 2005 levels) by 2050.

Examples of ambitious and long-term transport sector targets include Finland's aim for a 30% biofuels contribution in transport and Sweden's ambition of a vehicle stock independent of fossil fuels, both by 2030. Examples of policies to establish defined reductions in the life-cycle carbon intensity of transportation fuels include the Low Carbon Fuel Standard in California and Climate Protection Quota in Germany. Several EU member states have recently established advanced biofuels mandates, including Denmark (from 2020) and France (from 2018). These complement policies already established in Italy (from 2018) and the United States.

The Biofuture Platform aims to facilitate international policy dialogue and collaboration to facilitate the deployment of sustainable low-carbon alternatives to fossil fuels in transport. The Below50 collaboration initiative from the World Business Council for Sustainable Development, in partnership with Sustainable Energy for All and the Roundtable on Sustainable Biofuels, has been established to work with the biofuels industry to promote sustainable fuels that are a minimum of 50% less carbon-intensive than conventional fossil

fuels. Examples of sustainability indicators include those developed by the Global Bioenergy Partnership, while an example of a strong governance framework is the EU sustainability criteria for biofuels.

Note 2: Y-o-y growth 2015–16 from IEA (2017b).

Buildings (page 94)

Note 1: More information can be found in the *Global Status Report 2016* of the Global Alliance for Buildings and Construction at www.globalabc.org.

Figure 2.46: Source: derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics. Notes: CO₂ = carbon dioxide; TJ = terajoule (1 012 joules); EJ = exajoule (1 018 joules); building carbon intensities represent emissions from direct energy consumption as well as indirect emissions from final energy consumption of electricity and commercial heat; other renewables include modern biofuels and solar thermal energy; this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Figure 2.47: Sources: population: UN DESA (2015), *World Population Prospects: The 2015 Revision, Medium-Fertility Variant*; energy decomposition calculations derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics. Notes: EJ = exajoule (1 018 joules); the energy decomposition represents the influence of each factor (e.g. population) on changes in total final energy demand since 1990; household occupancy reflects the decreasing average number of persons per household; other represents energy demand factors, including improved access to commercial fuels (in developing countries), changes in climate (i.e. annual average heating and cooling degree days) and changes in energy service provision (e.g. greater demand in total luminous flux per square metre); energy efficiency includes both increases in product performance (i.e. technical efficiency) as well as shifts from less efficient equipment to more efficiency technology (e.g. gas boiler to heat pump); final energy change is the annual change in final energy consumption relative to 1990.

Figure 2.48: Source: historical energy derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics. Notes: MWh = megawatt-hour; other renewables include modern biofuels and solar thermal energy; building energy per person represents total final energy per capita (not climate-corrected).

Building envelopes (page 96)

Note 1: Average building envelope performance represents the physical performance of the building envelope (the parts of a building that form the primary thermal barrier between the conditioned interior and exterior) with respect to how much energy is needed to heat and cool a building.

Note 2: More information can be found in the *Global Status Report 2016* of the Global Alliance for Buildings and Construction at www.globalabc.org.

Figure 2.49: Notes: Floor area additions represent the expected number of square metres to be added to the 2015 building stock by key region to 2025; further work on building energy code country inclusion and distinction by level of code is ongoing, and feedback is welcome; this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area. Source: IEA building code analysis and IEA (2015), *IEA Building Energy Efficiency Policies (BEEP) Database*, www.iea.org/beep/.

Figure 2.50: Notes: Average building envelope performance represents the physical performance of the building envelope (the parts of a building that form the primary thermal barrier between the conditioned interior and exterior) with respect to how much energy is needed to heat and cool a building; the evolution of average building envelope performance is compared to 1990, where annual global average building envelope performance (in useful energy per square metre [m²], climate corrected) was roughly 155 kilowatt-hours per m² in 1990. Source: historical energy derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Figure 2.51: Notes: progress is shown as the percent improvement in building envelope thermal resistance requirements from 2005 to 2015 weighted (using building energy use, envelope area and thermal resistance) by building end-use and envelope components; the proximity to target shows the percent achieved toward requiring a nearly zero-energy building envelope; policy progress shown here for the United States, Canada and China only considers the cold climate zones of those countries. Source: IEA building code analysis and IEA (2015), *IEA Building Energy Efficiency Policies (BEEP) Database*, www.iea.org/beep/.

Lighting, appliances and equipment (page 98)

Note 1: Building equipment includes energy-consuming technologies for heating, cooling and ventilation; cooking; hot water; and other electrical plug loads and equipment (e.g. office equipment, medical devices, information technology networks and electric motors) used in buildings. It does not include traditional use of biomass.

Note 2: Household size represents the decreasing average number of persons per household (and, therefore, more households).

Figure 2.52: Notes: Co-efficient of performance (COP) represents the energy efficiency ratio (watts in cooling equivalent per watt of electricity consumption): the higher the COP, the greater the energy-efficiency. Annual average growth in space cooling demand represents the expected change in useful cooling energy demand between 2015 and 2025 under the 2DS.

Figure 2.53: Notes: LED = light-emitting diode; LFL = linear fluorescent lamp; CFL = compact fluorescent lamp. Source: IEA estimates based on on-going data discussions with lighting partners, including the United Nations Environment En.lighten programme and Philips and Osram lighting.

Figure 2.54: Notes: EJ = exajoule (1 018 joules); the energy decomposition represents the influence of each factor (e.g. population) on changes in total final energy demand since 1990; household occupancy reflects the decreasing average number of persons per household; other represents other energy demand factors, including improved access to electricity (in developing countries), increases in appliance ownership and changes in technology choice (e.g. larger refrigerators and televisions); energy efficiency represents increases in product performance (i.e. technical efficiency) which can include shifts to more efficiency technology (e.g. televisions using light-emitting diodes); final energy change is the annual change in final energy consumption relative to 1990.

Renewable heat (page 100)

Note 1: The figures for renewable heat are based on renewables reported in IEA statistics under TFEC. Direct use excludes renewables used in commercial heat (i.e. heat sold and delivered to end users, for example through district heating) and renewable electricity used for heating. In 2014, renewables in district heating accounted for around 1 EJ. The figure for the European Union does not match the share reported under the progress reporting for the Renewable Energy Directive, which applies a different methodology (e.g. it includes heat pumps).

Note 2: This tracking excludes the traditional use of biomass, which continues to play a major role in sub-Saharan Africa and parts of Asia, especially in rural areas where it is used mainly for cooking. The analysis focuses on “modern” biomass used for space and water heating in residential and commercial buildings, as well as all biomass used for process heat applications in industry and agriculture. Biomass use for heat can vary significantly from year to year depending on winter weather. For example, across much of Western Europe, average winter temperatures in 2014 were higher than in 2013, thus resulting in a 11% decrease in residential biomass use.

Note 3: Data for total installed global solar thermal collector capacity are estimated based on data from several sources including *Solar Heat Worldwide* published by the IEA Solar Heating and Cooling Programme, www.iea-shc.org/solar-heat-worldwide.

Figure 2.55: Note: this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Figure 2.56: “Other renewable heat” includes geothermal heat across all sectors, solar heat in industry and all renewable heat sources in agriculture.

Figure 2.57: Source: AEBIOM (2016), *AEBIOM Statistical Report 2016*, AEBIOM, Brussels.

Energy storage (page 102)

Note 1: From the integrated energy companies, Total agreed to acquire French battery manufacturer and storage–project developer Saft Groupe for 950 million euros (USD 1.1 billion), while Engie acquired an 80% stake in Green Charge Networks. Large equipment providers also invested, including an estimated USD 50 million investment by GE Ventures in German behind–the–meter storage provider Sonnen. The trend also solidified on the manufacturing side, as large diversified energy storage companies including LG Chem, Samsung SDI and NGK Insulators accounted for 70% of total installed capacity.

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Catalysing energy technology transformations

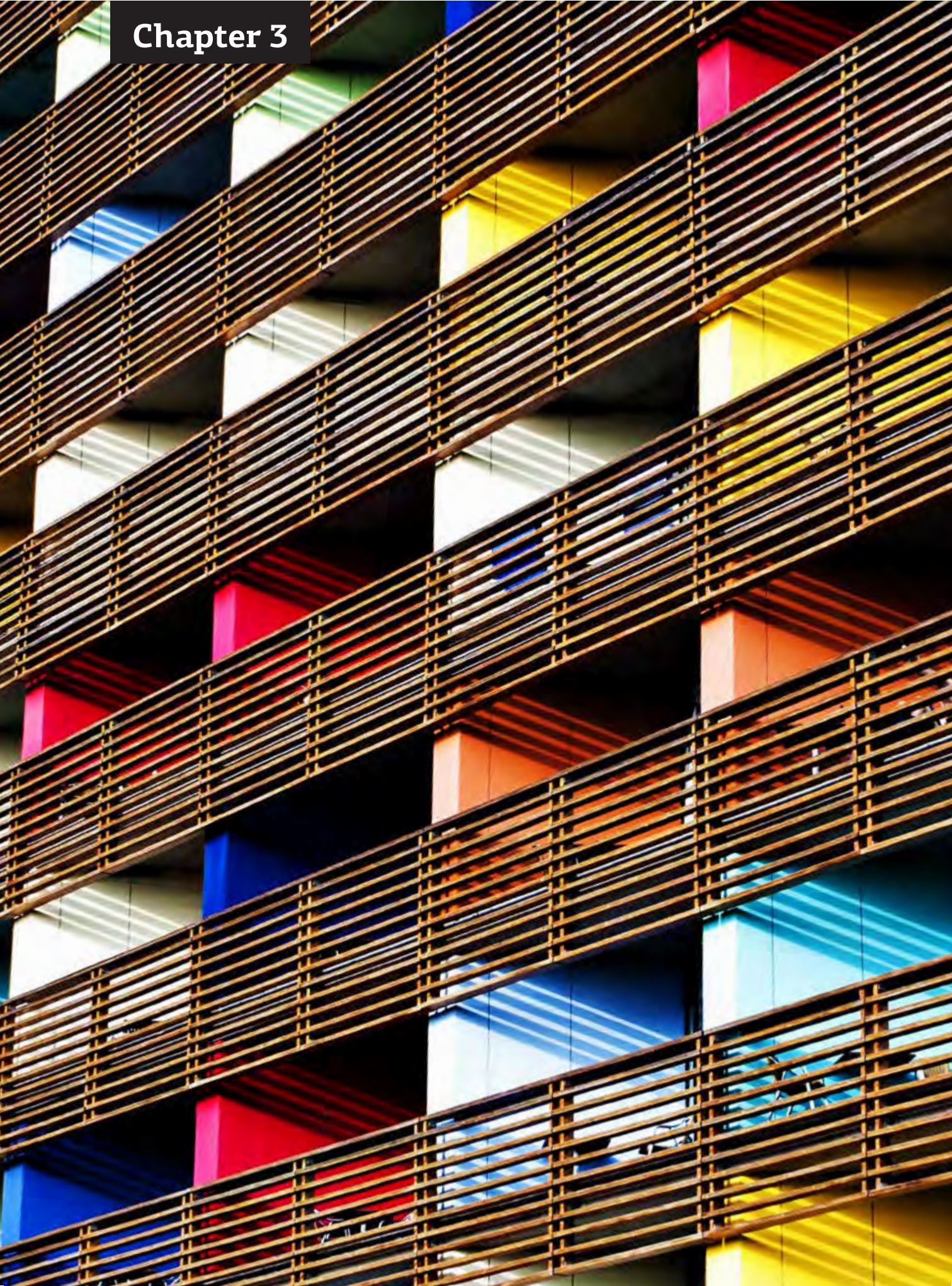
Energy Technology Perspectives 2017 focuses on the prospects to put the energy sector on a trajectory of accelerated and scaled-up deployment of clean energy technologies. It examines whether a rapid and broad uptake of available technologies and those in the innovation pipeline can advance the energy sector beyond an already very challenging 2°C pathway in order to achieve the internationally agreed long-term climate targets in a manageable transition.

Our findings show that a pathway that is more ambitious than 2°C could reduce energy sector CO₂ emissions to net zero by 2060 and limit the average temperature increase to 1.75°C by 2100. Such an outcome, however, is a long way from the trajectory of today's energy system and would demand a fundamental and immediate shift in the current level of technology and policy ambition.

The chapters in Part 2 look at how the various energy sectors contribute to an ambitious clean energy transition. They analyse the needs for energy technology innovation and accelerated deployment of best available technologies and practices in the buildings, industry, transport and power sectors. The opportunities for and challenges of significant contributions from sustainable bioenergy and carbon capture and storage are evaluated in cross-sectoral chapters.

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Chapter 3



Accelerating the transition to sustainable buildings

The energy savings potential in the buildings sector remains largely untapped due to continued use of less efficient technologies. Rapid deployment of energy-efficient and low-carbon measures can drastically reduce buildings energy demand and emissions to 2060, while also supporting power sector decarbonisation. Greater effort is needed to implement strategic policies and market incentives to encourage broad uptake of sustainable energy solutions in buildings.

Key findings

- **The global buildings sector consumed over 30% of global final energy consumption in 2014, or nearly 125 exajoules (EJ), and 55% of final electricity demand.** When upstream power generation is taken into account, buildings are responsible for more than one-quarter of global energy-related carbon dioxide (CO₂) emissions today.
- **Building energy efficiency measures contributed to more than 450 EJ in cumulative energy savings over the last 25 years.** Yet, despite some progress, the potential for energy efficiency improvements in buildings still remains largely untapped.
- **Around two-thirds of energy-consuming equipment in buildings is still not covered by mandatory energy efficiency standards.** Even more alarmingly, half of floor area additions to 2060 – more than 100 billion square metres (m²) – are expected to occur in countries that currently have no mandatory building energy codes in place.
- **Global buildings energy demand could increase to more than 160 EJ in 2060 under the Reference Technology Scenario (RTS) if assertive action is not taken to improve the energy performance of buildings.** Practically all new growth in energy demand occurs in developing countries, where floor area is expected to more than double by 2060.
- **More than half of new buildings additions to 2060 will be built over the next 20 years, and by 2035 nearly two-thirds of the global buildings stock to 2060 will already be standing.** Immediate steps must be taken to avoid lock-in of inefficient buildings and address energy demand from long-lived buildings assets.
- **Buildings-related CO₂ emissions in the RTS grow to 10 gigatonnes of CO₂ (GtCO₂) in 2060.** Three-quarters of emissions are related to upstream power generation, in spite of a near halving in power sector CO₂ intensity, as buildings electricity demand in the RTS more than doubles by 2060.
- **In the 2°C Scenario (2DS), buildings energy demand only increases marginally, thanks to more ambitious energy efficiency measures, to 130 EJ in 2060.** Buildings-related emissions are 85% lower in 2060 compared with the RTS, and direct emissions from fossil fuel use in buildings to 2060 are halved over the next 40 years.

- **Enabling rapid efficiency measures in the Beyond 2°C Scenario (B2DS) would reduce global buildings energy demand by an additional 12% below the 2DS in 2060, or one-third beyond the RTS.** Major shifts away from coal, oil and natural gas amount to more than 23 billion tonnes of oil equivalent (Gtoe) (965 EJ) in cumulative fossil fuel reductions to 2060 compared with the RTS.
- **Rapid deployment of high-efficiency lighting, cooling and appliances in the B2DS would save 50 EJ in electricity demand between now and 2030 – or nearly three-quarters of global electricity demand today.** Those savings would allow greater shifts to electricity without additional burden to the power sector.
- **Buildings-related emissions reduction in the B2DS represents more than 275 GtCO₂ in cumulative savings compared to the RTS – more than all the CO₂ emissions produced by the global energy sector from 2006 to 2014.** Shifts away from fossil fuels account for 21% of the reductions, while aggressive uptake of efficiency measures supports power sector decarbonisation in the face of rapidly growing electricity demand.
- **Natural gas demand in buildings in the B2DS could be reduced by as much as 80% by 2060 compared to today.** A strategic vision would be necessary to: avoid growth in gas demand; shift demand to efficient, renewable and integrated solutions (e.g. heat pumps and district energy); and decarbonise remaining gas supply (e.g. by switching to biogas).

Opportunities for policy action

- **National and local authorities across all countries should urgently establish and enforce mandatory building energy codes that apply progressively tighter energy performance standards for both new and existing buildings.** A sound balance among regulatory instruments, incentives (e.g. tax credits) and financing tools, capacity-building initiatives, and technological innovation is needed to accelerate widespread adoption of low-carbon, high-efficiency buildings practices and technology solutions.
- **Significant action is needed to expand existing policies and regulations for energy-consuming equipment and buildings technology (e.g. window performance).** Labelling and minimum energy performance standards (MEPS) should be expanded to cover the vast majority of buildings end uses, while existing MEPS should be strengthened.
- **Governments can advance uptake of energy-efficient, low-carbon buildings technologies through appropriate policy packages and market incentives.** Those programmes, including research, development and deployment strategies to improve buildings performance at affordable prices, should seek to bring to market widespread adoption of high-performance buildings technologies and services.
- **The ambitious B2DS would require swift, unprecedented policy action, including suitable pricing signals, to drive innovation and move markets quickly to low-carbon, high-efficiency technologies and best buildings practices.** Clear, consistent and long-term signals to consumers and manufacturers are needed to maximise energy efficiency investments and avoid locking in inefficient, carbon-intensive assets.
- **Transitions away from fossil fuel use in buildings would require long-term strategic thinking and co-ordination.** Governments would need to set forth clear expectations on buildings energy performance and carbon intensity, especially given the long life of buildings and energy distribution assets (e.g. gas networks).

Overview

This chapter outlines opportunities for energy efficiency measures and CO₂ emissions reduction in the buildings sector. It examines technology trends and their CO₂ emissions implications and identifies policy actions that could support the achievement of global climate ambitions. It does this in the context of three scenarios that look to 2060 with varying levels of ambition to achieve climate change goals:

- the RTS, which takes into account existing or expected buildings energy policies that would improve the energy efficiency of end-use technologies but that would not sufficiently address uptake of highly efficient and advanced buildings technologies across the world's buildings stock
- the 2DS, which is consistent with the goal of limiting the global average increase in temperature to 2°C and includes an increasingly aggressive deployment of highly efficient buildings technologies to 2060, along with rigorous application of building energy codes and deep energy renovations across the global buildings stock
- the B2DS, which seeks to limit the global average increase in temperature to below 2°C and includes a rapid and aggressive deployment of energy efficiency opportunities in the global buildings sector, along with the rigorous application of building energy codes and deep energy renovations across the global buildings stock and a strategic shift away from fossil fuel use in buildings by 2060.

The global buildings sector consumed more than 123 EJ in 2014, or over 30% of global final energy consumption.¹ The residential subsector alone accounted for nearly three-quarters of buildings energy use, where final energy demand in residential buildings globally increased by 30% between 1990 and 2014. In certain rapidly emerging economies, such as India and Indonesia, residential energy consumption increased by more than 50% during that period. In Africa, it nearly doubled, although the average buildings energy consumption per person in Africa was still 25% less than the global average in 2014.

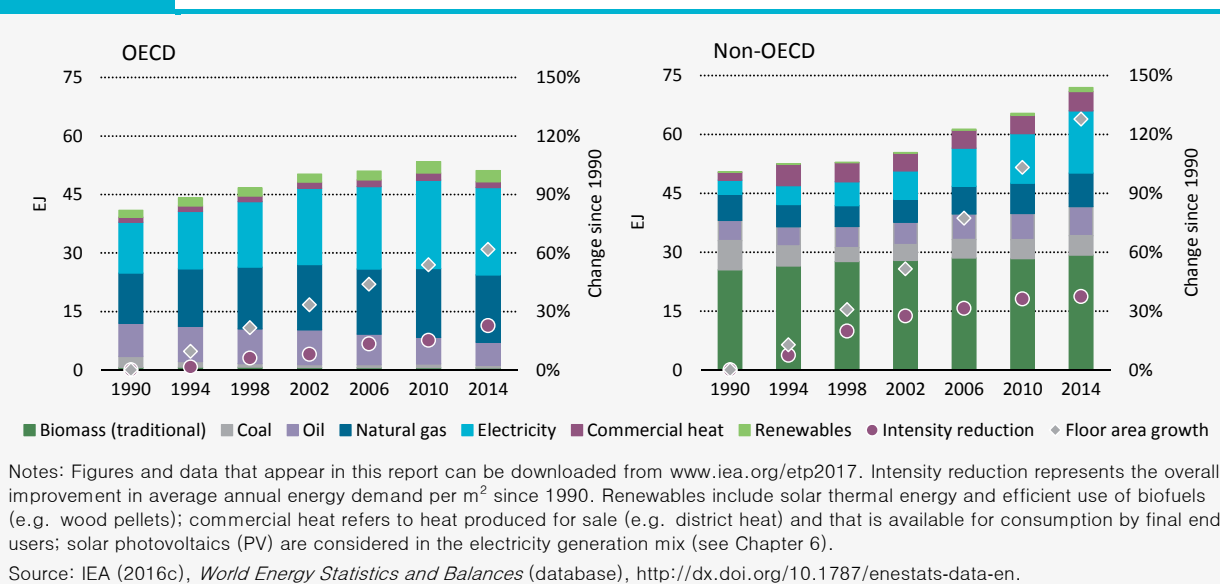
Traditional use of solid biomass² in residential buildings, particularly in developing countries, accounted for one-quarter of total buildings final energy consumption in 2014 and one-third of final energy use in the residential subsector. On a positive note, average use of solid biomass per person in non-Organisation for Economic Co-operation and Development (OECD) countries declined steadily by around 1% per year from 1990, due to a combination of factors, including urbanisation, increasing income per household and greater access to commercial fuels³ in developing countries. Still, that improvement was not enough to offset strong population growth in those countries, which increased on average by 1.5% per year during the same period. As a result, total traditional use of solid biomass in non-OECD countries increased by 15% between 1990 and 2014.

The global buildings sector accounted for 55% of total final electricity demand in 2014 – up from 48% in 1990 – with electricity accounting for nearly 70% of the total growth in final energy demand in buildings since 1990 and representing one-third of total energy use in buildings today (Figure 3.1). In some rapidly emerging economies, such as the People's Republic of China (hereafter, "China") and India, electricity demand in buildings grew on average by more than 8% per year over the last decade. As a whole, non-OECD buildings electricity consumption increased by a multiple of 4.5 between 1990 and 2014. By contrast, buildings electricity demand in OECD countries has remained relatively stable in recent years, largely due to energy efficiency improvements, although it still was up 25% since 2000 and nearly 75% since 1990.

1. The IEA is working closely with the National Bureau of Statistics in the People's Republic of China (hereafter, "China") and the Tsinghua University Building Energy Research Center to improve assessments on traditional use of solid biomass in the residential subsector in China. Total final energy in buildings shown here reflects anticipated revisions in the 2017 IEA *World Energy Statistics and Balances*.

2. Traditional use of solid biomass refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys. Solid biomass includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

3. Commercial fuels used in buildings include liquid fuels (i.e. liquefied petroleum gas [LPG] and fuel oil), gaseous fuels (i.e. natural gas and methane), solid fuels (wood pellets, coal and charcoal) and commercial heat (i.e. heat produced for sale). Information on modern energy access can be found at www.worldenergyoutlook.org/resources/energydevelopment/.

Figure 3.1. Buildings energy use and intensity per m² since 1990


Key point *Global buildings energy intensity per m² improved at roughly 1.5% per year since 1990, but this was not enough to offset growth in buildings sector floor area, at nearly 3% per year.*

The net effect, globally, is that buildings continue to place a growing demand on the power sector, whose average efficiency was 43% in 2014.⁴ When upstream power generation is taken into account, buildings are therefore responsible for 26% of global energy-related CO₂ emissions, or 9.4 GtCO₂ in 2014. One-third of those total buildings-related emissions, or roughly 8% of global energy-related CO₂ emissions in 2014, were from direct fossil fuel consumption in buildings.

The overall energy performance of the buildings sector (in terms of average global energy demand per m²) continued to improve in 2014, in line with the average annual improvement of roughly 1.5% per year since 1990. Continued development and enforcement of multiple buildings energy policies and energy efficiency measures in recent years helped to offset growth in total energy consumption, and both mandatory and voluntary building energy codes now exist in more than 60 countries (GABC, 2016). However, effective enforcement continues to be an issue in many regions, and existing codes in many countries need to be expanded and updated to cover all buildings types to improve their energy performance.

Roughly one-third of total final consumption by energy-consuming equipment in buildings globally is also now covered by mandatory energy efficiency standards or policies, in comparison with only 15% in 2005 (IEA, 2016a). As a result of those measures and growing coverage of building energy codes, the average energy intensity of the global buildings stock decreased by nearly 33% from 225 kilowatt hours per m² (kWh/m²) in 1990 to roughly 150 kWh/m² in 2014, despite the doubling of total floor area since 1990 and growing ownership of energy-consuming equipment. Buildings energy intensity improvements in non-OECD countries have been around 60% greater than in OECD countries since 1990, where rapid growth in China, paired with greater coverage of building energy codes and standards, helped to drive the improvement in average non-OECD buildings energy intensity per m².

At the same time, energy demand per person globally has remained practically constant since 1990, at nearly 5 megawatt hours (MWh) per person. There are considerable differences across regions, countries and even areas within countries (e.g. urban and non-urban distinctions [IEA, 2016b]), due to a variety of factors such as climate, energy

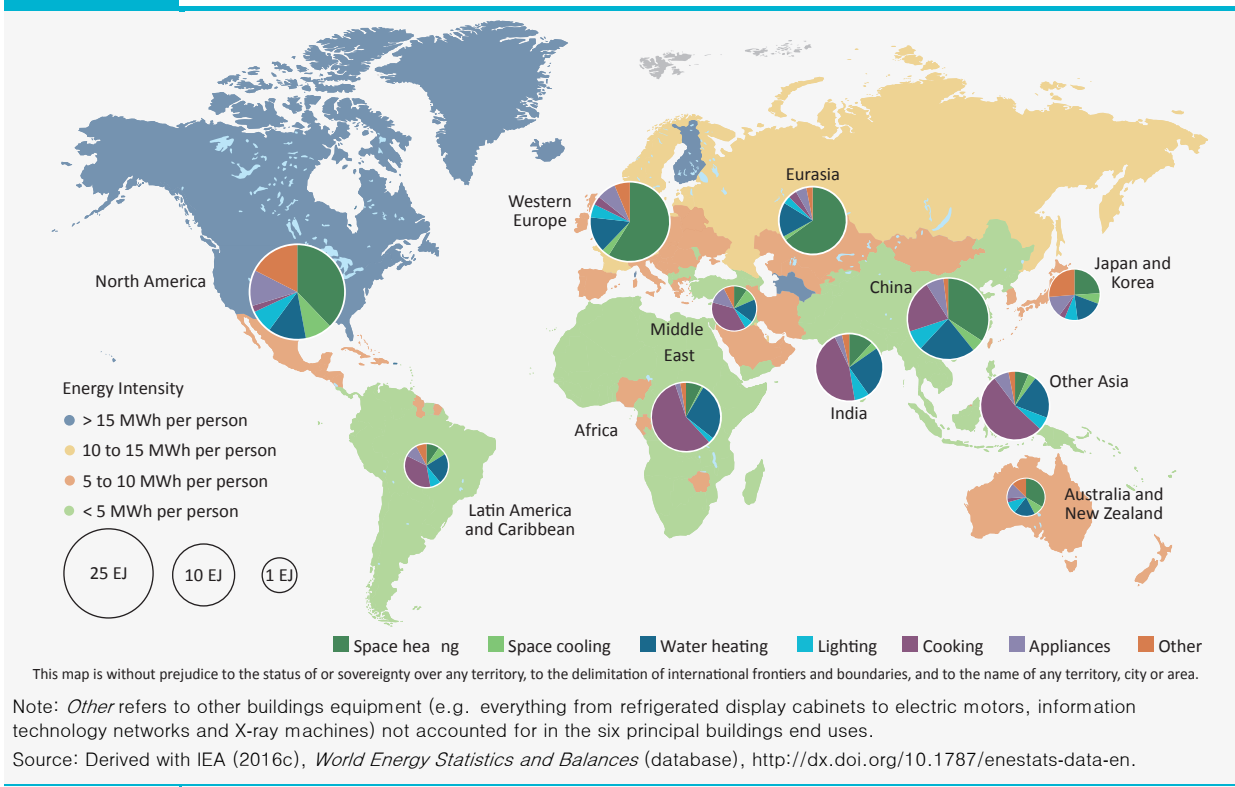
4. This excludes electricity produced by co-generation (the combined production of heat and power), which accounted for roughly 9% of total global electricity production in 2014 and had an average global efficiency (main activity producers) of 60%.

access, household income and ownership of energy-consuming products. Globally, a clear divide is still evident between OECD countries and developing regions (Figure 3.2). In OECD countries, average energy demand increased slightly from 10.5 MWh per person in 1990 to roughly 12 MWh per person in 2005, although it then decreased back to around 11 MWh per person in 2014. That reduction may be partly explained by warmer winters in recent years, as space heating accounts for 45% of OECD buildings final energy use.

By contrast, buildings sector energy demand in non-OECD countries decreased from around 3.3 MWh per person in 1990 to 3 MWh per person in 2002, largely due to decreased use of biomass (traditional) per capita. Since 2002, however, energy demand per person consistently rose to more than 3.3 MWh per person in 2014, as increasing living standards and growing demand for energy services and thermal comfort continued to drive demand for commercial fuels (including, in particular, electricity consumption) in those regions.

Figure

3.2. Buildings energy intensity per capita and final energy end use by key regions, 2014



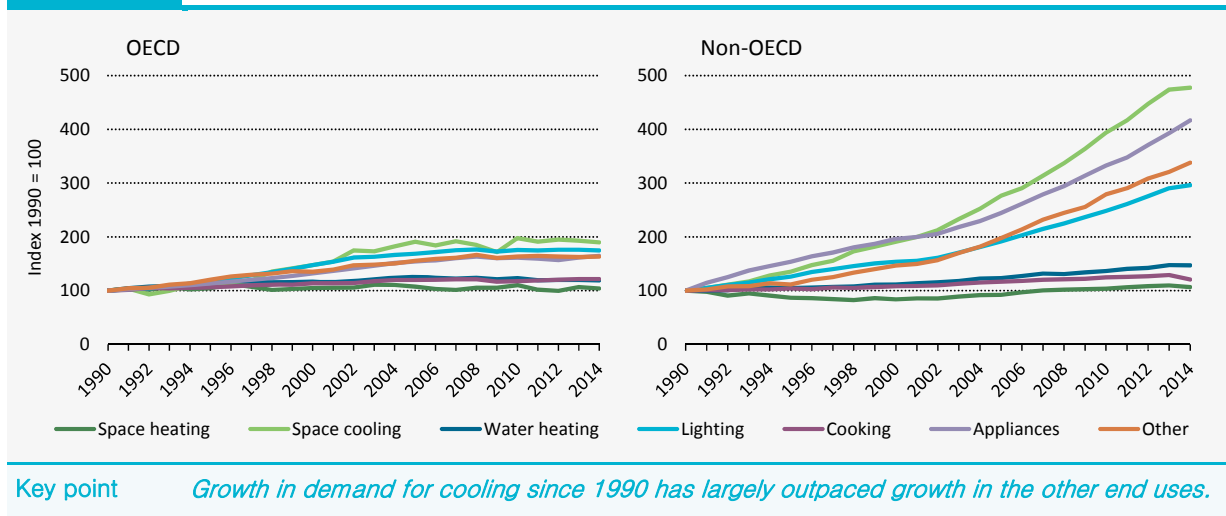
Key point

Global buildings energy use per person has remained relatively constant since 1990, with considerable differences across regions and countries.

Globally, space and water heating demand continue to account for the lion's share of energy consumption in buildings, representing nearly 65% of buildings final energy use in OECD countries and roughly 50% in non-OECD countries (largely based on traditional use of solid biomass for water heating purposes). Even when traditional use of solid biomass is excluded, space and water heating demand still represent the largest buildings end uses in non-OECD countries, due mainly to large space heating demand in the Russian Federation (hereafter Russia) and China. This is changing, however, as improved standards of living are contributing to rapid growth in demand for lighting, household appliances and increasingly for space cooling in buildings, especially in developing regions in warm and hot climates where space heating needs are typically minor. Space cooling energy demand, in particular, grew by an average of 7% per year between 1990 and 2014 in non-OECD

countries, or nearly five times the average annual growth rate of total final energy demand in non-OECD buildings (Figure 3.3). Even in OECD countries, cooling demand grew by 2.5 times the average annual growth rate of total buildings energy demand during that period.

Figure 3.3. Changes in energy demand by end use, 1990-2014



Key point *Growth in demand for cooling since 1990 has largely outpaced growth in the other end uses.*

Adoption of energy-efficient technologies (e.g. condensing boilers, heat pumps and more recently solid-state lighting [SSL], such as light-emitting diodes [LEDs]) has helped to curtail energy growth in the buildings sector in recent years. A growing number of policy measures, including building energy codes and standards and labelling programmes for energy-consuming equipment, have helped improve buildings energy performance in many countries. Perhaps most notable is progress in 2015 and 2016 on building energy code development across several countries in Africa, where the vast majority of the continent still does not have in place either voluntary or mandatory building energy codes (see Chapter 2, “Tracking clean energy progress”). In India, similar progress has been made in shifting from a voluntary national code to locally adopted mandatory building energy codes (mostly for non-residential buildings) in most states. Additional effort is needed to expand those mandatory building energy codes to the rapidly expanding residential subsector, whose floor area could more than double by 2030.

Despite positive developments, progress to date has not kept up with energy technology potential or the increasing demand that a growing and more prosperous global population is having on buildings sector energy use. For instance, room air conditioner (RAC) sales in many markets often have an average coefficient of performance (COP) of 2.5 to 3.0 (Shah et al., 2015).⁵ However, readily available RACs in those same markets frequently have a COP of 3.5 and higher. In some markets, such as China and Japan, best available technologies (BATs) already have COPs as high as 6 or greater (see Chapter 2).

5. COP refers to equipment energy performance. For example, a COP of 2.0 indicates that two units of useful heat are produced (or extracted) for one unit of energy input. Another common performance indicator is the seasonal energy efficiency ratio, which represents overall energy performance across a range of operating temperatures rather than at an average annual temperature.

Forging a pathway to sustainable buildings

The energy efficiency potential in the global buildings sector is enormous: around two-thirds of global buildings energy use (roughly 80 EJ) is still not subject to MEPS (IEA, 2016a). Even more alarmingly, half of global buildings floor area additions to 2060 – more than 100 billion m², or the equivalent of all the floor area in China, India and the United States today – are expected to occur in countries that currently do not have in place mandatory building energy codes.

Coverage of mandatory energy standards and regulations varies across countries and buildings end uses. It is particularly weak in many non-OECD countries (typically covering less than 20% of buildings final energy demand), where the bulk of new energy demand to 2060 will occur. Existing MEPS also need to be strengthened in many countries (including OECD countries) to narrow the gap between minimum energy performance and BAT.

While progress is being made – for instance, more than 75 countries now have some level of voluntary or mandatory standards for refrigerators – significant scope still exists to tap into the buildings sector's energy efficiency potential. For example, had average global standards been implemented across all countries for space heating and cooling, water heating and lighting equipment, the global energy savings in 2015 would have been in the order of 6 EJ, or 8% of the total energy demand for those respective end uses that year (IEA, 2016a). Implementing the highest current MEPS across all countries would have saved nearly 20% of that respective energy consumption (13 EJ). If BAT had been installed, the savings would have resulted in more than two-thirds reduction in energy demand by those end uses (45 EJ).

The need for swift and assertive energy efficiency measures across the global buildings sector is of the essence, especially given the long life of buildings sector assets, which will place significant constraint on achieving ambitious CO₂ emissions reduction without costly changes (e.g. early retirement of equipment) once those investments have been made. While some energy-consuming equipment (e.g. incandescent light bulbs) have shorter life spans and can be replaced relatively quickly with more efficient technologies, the typical lifetime of core buildings energy services (e.g. heating, cooling and ventilation systems) can last as much as 20 years or more. Even more important is the building envelope and building design (e.g. orientation), which can last for decades or even centuries and have a major influence on heating, cooling and ventilation needs in buildings (IEA, 2013a).

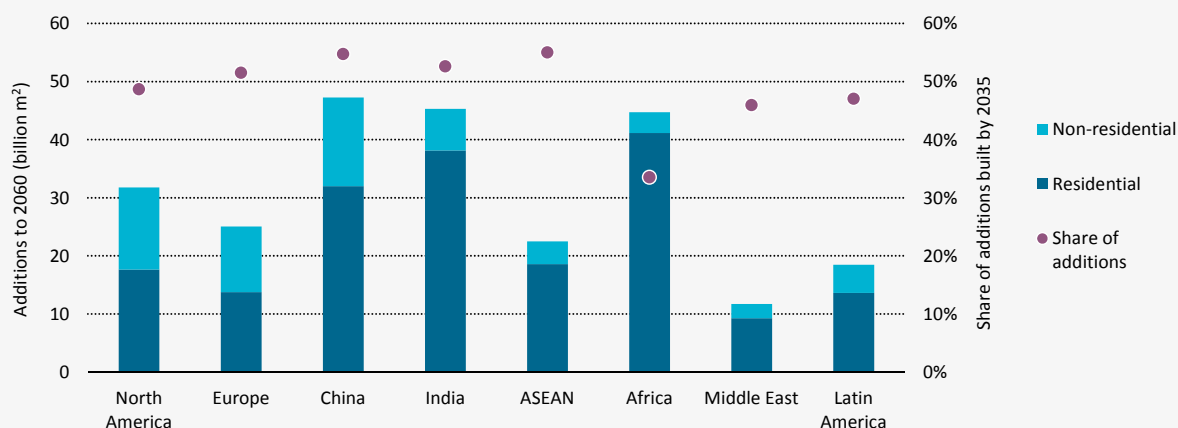
There is an increasing urgency to avoid the lock-in of inefficient buildings (both through new construction and weak energy renovations) and equipment if global ambitions for a 2°C world (or below) are to be achieved. More importantly, the window of opportunity is rapidly closing (Figure 3.4). Over the next 20 years, more than half of expected buildings additions to 2060 will be completed, and by 2035, nearly two-thirds of the global buildings stock anticipated in 2060 will already be standing. More than 80% of those buildings additions will be in non-OECD countries, which will account for roughly 70% of global buildings floor area in 2035.

Additionally, deep energy renovations (e.g. 30% to 50% energy intensity improvement or greater, with the objective of moving towards near-zero energy buildings [nZEBs])⁶ will be a key priority over the coming decades. This is particularly the case in OECD countries, where roughly 65% of the total expected buildings stock in 2060 is already standing today. Under 2DS (or B2DS) ambitions, more than 2% of existing stock would need to be renovated every year over the next 40 years across OECD countries. This is equivalent to around 1.8 billion m² per year, or roughly eight times the buildings construction market in the United States in 2015 (USCB, 2016), and compares to an estimated 850 million m² renovated globally in 2015. This would require a considerable scaling up of buildings energy renovations across OECD countries, including the likely need for additional skilled labour, to achieve effective deep energy renovations of existing buildings. The risk of locking in less-than-optimal energy renovation measures (typically achieving 10% to 15% energy intensity improvement today) is just as critical as the risk of inefficient new construction.

6. nZEBs have nearly zero or very low annual heating and cooling loads, typically in the range of 30 kWh/m² to 15 kWh/m² or better.

Figure

3.4. Floor area additions to 2060 and share of additions built by 2035 for selected regions



Note: ASEAN = Association of Southeast Asian Nations.

Key point

Swift action is needed to address buildings envelope performance over the next 20 years to avoid the lock-in of energy-intensive buildings investments, especially in developing regions.

The significant energy efficiency potential of the buildings sector and the critical call to action for buildings has not gone unrecognised. In 2015, a first-ever “buildings day” was held at COP21 in Paris as a dedicated event to present how the buildings and construction sectors are able to tackle climate change through low-carbon and energy-efficient solutions. A Global Alliance for Buildings and Construction (GABC)⁷ was also launched by partners, including the International Energy Agency (IEA), at COP21 to mobilise stakeholders, scale up climate actions in the buildings sector and accelerate the transition to sustainable buildings.

Since the Paris Agreement, nearly 90 countries (including the European Union [EU]) have put forward buildings-related actions in their intended or now registered nationally determined contributions (NDCs). Those actions include commitments to reduce emissions from buildings and construction supply chains, to increase buildings-integrated renewables,⁸ and to adopt or strengthen building energy codes and policies, such as rating and disclosure programmes. A few countries, such as Afghanistan, Bangladesh, Jordan and South Sudan, have mentioned specific actions to encourage financing or investment in energy-efficient buildings, renewables or buildings energy renovation programmes. A number of other countries, such as Morocco, India and Mongolia, also set forth more detailed goals and actions for achieving emissions mitigation in the buildings sector.⁹ However, to date most NDCs with buildings-related measures have referenced rather general actions without detailing how those ambitions would be achieved.

Greater clarity is needed on specific buildings-related actions to be taken under the Paris Agreement. To achieve progress, effort is required to scale up actions across the entire sector, including applying a sound balance of regulatory instruments (e.g. building energy codes and standards), incentives (e.g. financing schemes), information and capacity building (e.g. information campaigns and training), and support for research and development (R&D) of high-performance solutions for buildings. Policy packages will also need to encourage the application of successful business models (e.g. energy service

7. Further information about the GABC and its work areas can be found at www.globalabc.org.

8. Renewables may include solar thermal energy, solar PV or other renewable energy, such as efficient use of biofuels; solar PV is not addressed explicitly in this chapter and is considered in the electricity generation mix (see Chapter 6).

9. Further information on buildings-related actions and ambitions can be found in the GABC Global Status Report 2016 (GABC, 2016).

companies), involving utilities and attracting private-sector finance, to drive the transformation of the buildings sector towards high levels of energy efficiency and renewables.

Future impact of current ambitions: buildings sector in the RTS

If no action beyond current commitments is taken to improve the uptake of energy efficiency measures in the buildings sector, energy demand could increase by another 30% to reach nearly 160 EJ in 2060 under the RTS. Non-OECD countries would account for nearly 90% of that growth, as access to electricity and commercial fuels, household wealth, living standards, and the size of the buildings sector (i.e. floor area and total number of households) would all continue to increase at a rapid pace. Asian countries, and in particular China and India, account for nearly 45% of total energy demand growth in the RTS, while rapid increases in energy demand in Africa account for another quarter of net buildings energy demand additions to 2060. Demand in OECD countries increases only slightly, as consistent with recent trends, with North America (including Mexico) driving the bulk of energy additions as population and the size of the buildings sector continue to grow. In a few OECD countries, such as Japan, Germany and Italy, energy demand in the RTS even declines by as much as 15%, in part due to expected population decline to 2060.

Energy consumption for space heating in the RTS continues to represent an important share of final energy demand, accounting for slightly more than 20% of global buildings energy use in 2060 (in comparison with 32% today). The decreasing share, reflecting a gradual decline of about 15% in total global space heating energy use in 2060 compared with 2014, is due partly to improved buildings energy performance in colder climates. This includes marginal energy renovations of existing buildings and continued trends in improved heating equipment efficiency. At the same time, a major shift is expected in buildings additions in warmer climates, where demand for cooling services increases considerably. Ownership of energy-consuming equipment (e.g. household appliances) also grows rapidly in non-OECD countries. As a result, the share of total buildings energy demand for space cooling and appliances each more than doubles by 2060, together accounting for nearly 30% of buildings energy consumption in 2060 (compared with 13% today).

Coal and oil use in buildings under the RTS are both expected to decline significantly over the coming decades, continuing the steady global trend since the early 1990s of buildings shifting to natural gas and electricity. Traditional use of solid biomass in buildings similarly declines by 45% by 2060, as developing regions continue to shift towards commercial fuels. By contrast, natural gas use increases by 15%, while buildings sector electricity demand more than doubles by 2060. As a result, indirect emissions from the power sector related to electricity consumption in buildings increase by more than 20% in the RTS, in spite of a halving of the average global carbon intensity of electricity production by 2060.

When direct emissions from fossil fuel consumption in buildings to 2060 are included (a 25% reduction compared with 2014, despite increases in natural gas consumption), total buildings-related CO₂ emissions slowly increase to 10 GtCO₂ under the RTS. Direct and indirect buildings emissions therefore account for one-quarter (or 430 GtCO₂) of cumulative CO₂ emissions from the global energy sector to 2060 – the equivalent of all the CO₂ emissions from the entire energy sector since 2000. This clearly is not in line with global ambitions set forth at the 21st Conference of the Parties (COP21) in Paris in 2015, and will require much more aggressive deployment of energy-efficient and low-carbon solutions in the global buildings sector if those aspirations are to be achieved.

Moving beyond the RTS to accelerate the transition to sustainable buildings and achieve ambitions for a 2°C world or below would require a more effective design of energy policies and more assertive technology ambitions in the buildings sector, some of which may be unprecedented. This chapter considers an accelerated transition towards more sustainable energy consumption in buildings. It examines the chief energy technology and policy priorities that would be needed to realise the significant energy savings and emissions reduction potential from buildings. This includes a focus on the large potential electricity savings from a rapid and aggressive roll out of energy-efficient lighting, cooling and appliances in buildings over the coming decade. It then looks at the energy savings and emissions reduction potential across the global buildings sector from a strategic phase-out of inefficient, carbon-intensive assets by 2060 in tandem with the rigorous and widespread

uptake of energy-efficient, renewable and integrated technology opportunities in buildings. Finally, it discusses the market conditions and policy actions that would be needed to put the global buildings sector on a B2DS pathway, including practical information and market examples to demonstrate how energy-efficient, low-carbon technology deployment in a B2DS world can be achieved.

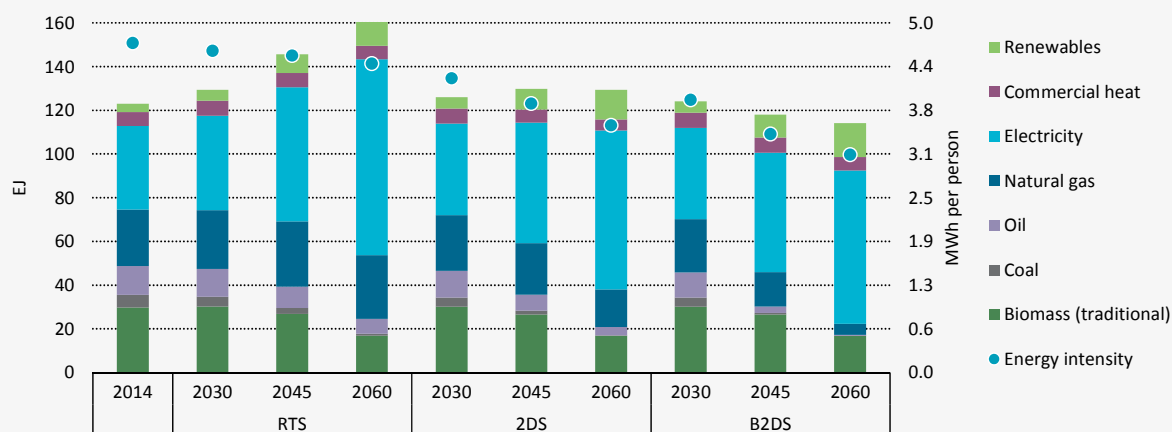
Outlook for an energy-efficient, low-carbon buildings sector

The B2DS considers a buildings sector pathway to 2060 that comprises a rapid and aggressive deployment of energy efficiency opportunities across the global buildings stock, alongside a long-term, strategic shift away from carbon-intensive energy technologies in buildings. Whereas the 2DS considers a progressively assertive roll-out of energy-efficient, low-carbon technologies over the coming decades, the B2DS goes one step further to advocate a disruptive (i.e. radically faster) adoption of high-performance buildings technologies and low-carbon solutions, starting as quickly as possible with best-performing products already available in most markets today. This would require considerable effort to drive markets to adopt best buildings practices and high-efficiency, low-carbon technologies over the coming decade, setting forth the necessary policy frameworks and market measures to drive technological innovation and the widespread deployment of sustainable, energy-efficient buildings solutions in the decades to come.

In the B2DS, final energy demand in the buildings sector decreases to 114 EJ by 2060, or 30% below the RTS and 12% below the 2DS, while providing the same level of energy service as in the RTS and 2DS (Figure 3.5). Cumulatively, this represents 1 275 EJ – more than 30 Gtoe – in total energy savings compared with the RTS, or more than two times the total global primary energy supply in 2014. Shifts away from fossil fuel use in buildings represent 76% (965 EJ) of those reductions, where natural gas demand in particular could be reduced by as much as 80% by 2060 compared with today. At the same time, solar thermal use increases ninefold over 2014 levels, while heat pump technologies (in terms of final energy) increase by a multiple of 3.5 compared with today.

Figure

3.5. Buildings final energy consumption by scenario and fuel type



Key point

Buildings energy savings in the B2DS (compared with the RTS) represent more than twice global energy production in 2014, while shifts to high-efficiency technologies allow the sector to electrify and still consume less electricity than in the RTS in 2060.

Unlike the 2DS, in which buildings energy demand continues to increase to 130 EJ in 2045 and then remains roughly constant to 2060, the B2DS would implement measures that allow global buildings energy demand to peak almost immediately by 2020, thanks to a rapid scaling up of energy efficiency. The B2DS then sees a steady decline in demand, by an average annual rate of around 0.2% to 2060. As a result, the global buildings sector

consumes nearly 490 EJ less energy (cumulatively) compared with the 2DS, or slightly more than the total final energy consumption (TFEC) by the EU buildings sector over the last 25 years.

The additional savings beyond the 2DS reflect much faster deployment of energy efficiency measures, such as LED lighting and high-performance household appliances, over the next two decades. Further savings are attributable to the long-term, strategic shift away from carbon-intensive assets (e.g. gas boilers) to high-performance, renewable and integrated technologies (e.g. heat pumps, solar thermal and energy-efficient district energy solutions). This contributes to more than 340 EJ (or 8 Gtoe) in cumulative fossil fuel reductions in the buildings sector between 2040 and 2060 in comparison with the 2DS. While technically feasible, those shifts would need to be planned and properly staged within the context of the broader energy sector to avoid unnecessary costs or early retirement of existing capital (e.g. natural gas networks and recent installations of gas equipment in buildings).

The accelerated uptake of high-efficiency products in the B2DS would require strong “push” (e.g. mandatory performance targets) and “pull” (e.g. upfront incentives such as consumer rebates) policies to overcome barriers (e.g. higher upfront costs and availability of less efficient products) and drive global market transformation towards energy efficiency in the coming years. For instance, LEDs still represented only around 15% of global residential lighting sales in 2015 (see Chapter 2),¹⁰ despite the fact that the cost of LED A-type lamps (i.e. traditional pear-shaped bulbs typical in residential applications) have decreased by nearly 90% since 2008 (US DOE, 2015). Despite some progress and continued improvements in LED energy performance (resulting in even lower life-cycle costs compared with traditional lighting technologies such as incandescent and halogen lamps), higher upfront costs and continued availability of less efficient, less expensive lighting technologies on the market continue to shape consumer preferences and investment choices. Product reliability (particularly with respect to LED lifetimes) and consumer perceptions (e.g. of brightness and light colour) have also influenced uptake of energy-efficient LED technologies, although global efforts, such as the Clean Energy Ministerial Global Lighting Challenge,¹¹ have been working across governments and with industry to deliver high-quality and high-efficiency lighting products.

The rapid energy efficiency drive required to move markets to BATs over the coming decade may be unprecedented at a global scale, but the energy savings would be substantial. The aggressive deployment of energy-efficient lighting, cooling and household appliances under the B2DS would save as much as 50 EJ of electricity between now and 2030. Those savings – the equivalent of roughly 330 coal power plants or a third of global annual nuclear production today¹² – would reduce pressure caused by rapidly growing electricity demand in buildings, while also allowing a greater shift from fossil fuels to electrical end uses (e.g. from electrification of heat and growth in electric vehicles) and reducing the additional burden to the power grid and generation capacity.

The largest energy savings potential under the B2DS, unsurprisingly, is in heating and cooling demand. Aside from the effect of building envelope measures, the vast majority of heating and cooling systems in buildings are far from the technical efficiencies possible using technologies that are already on the market and cost-effective. For instance, a significant proportion of systems for space and water heating demand in buildings globally uses inefficient oil and gas boilers (e.g. less than 70% to 80% for typical conventional boilers) or electric resistance technology (less than 100% when storage and distribution losses are included). Condensing boilers would minimally improve equipment performance above 90% to 95% or higher, whereas shifts to high-efficiency equipment, such as electric heat pump technologies, would achieve energy performance typically above 250% to 400%

10. The LED share of global residential lighting sales may have reached as much as 30% in 2016.

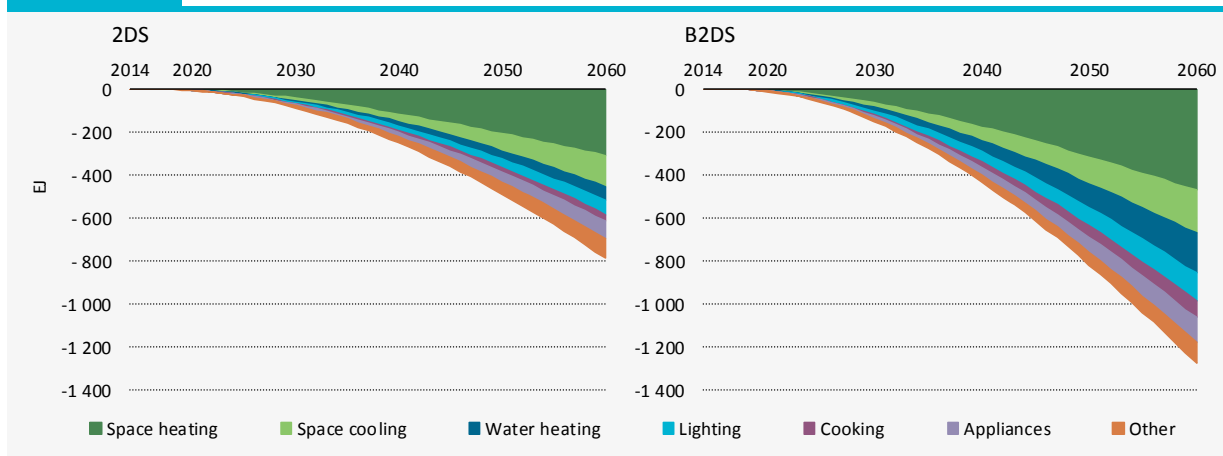
11. Further information on the Global Lighting Challenge can be found at: www.globallightingchallenge.org.

12. The global energy savings from upfront energy efficiency measures in buildings under the B2DS represent an average of roughly 925 terawatt hours (TWh) of annual electricity savings over the next 15 years. A typical 500 megawatt coal power plant produces roughly 2.8 TWh of electricity annually (average full-load hours of 5 600 hours). A large (1 gigawatt) nuclear power reactor produces roughly 7.5 TWh per year (average full-load hours of 7 500 hours). The energy savings equivalents described here represent annual energy demand and power generation averages, and therefore do not represent peak power generation capacity (typically using fossil fuels).

or higher for space heating, and as much as 200% to 300% or greater for water heating.¹³ Integrated energy solutions, such as high-performance and low-carbon district energy systems, could similarly improve energy and carbon intensities for heating and cooling in buildings, while also enabling flexible synergies across the broader energy system.¹⁴

Under the B2DS, energy demand for space heating and cooling is 45% lower (21 EJ) in 2060 than under the RTS (or 6 EJ lower than the 2DS), representing more than half of global cumulative buildings energy savings to 2060 (Figure 3.6). Building envelope improvements represent nearly 320 EJ (or nearly half) of the cumulative space heating and cooling energy savings to 2060, through assertive implementation and enforcement of building energy codes for new construction across all countries, and an aggressive scaling up of deep building energy renovations of the existing global stock.

Figure 3.6. Cumulative energy savings by end use relative to the RTS



Key point

Rapid energy efficiency deployment, alongside a long-term, strategic shift from fossil fuels to high-performance, renewable and integrated energy technologies, leads to cumulative energy savings of 1 275 EJ under the B2DS, or 60% greater reductions than in the 2DS.

Adoption of high-efficiency and renewable heating and cooling equipment represents a further 350 EJ of cumulative energy savings compared with the RTS, or nearly 220 EJ of savings beyond the 2DS. Those additional reductions are largely due to shifts away from gas equipment (e.g. condensing boilers in the 2DS) to high-efficiency and renewable technologies (e.g. heat pumps and solar thermal) and to efficient and low-carbon district energy (e.g. for replacement of existing hot-water distribution systems for space heating in buildings using gas boilers). The space heating and cooling energy reductions in the B2DS also reflect anticipated improvements in equipment performance (e.g. increased COPs in heat pump technologies), as uptake of efficient technologies and consequent market growth would incentivise additional R&D for more efficient products at lower cost due to improved returns on investment for manufacturers. Policies that value energy efficiency can also help to drive development of equipment with even higher performance.

Energy savings from shifts to high-performance lighting, appliances and water heating equipment account for a further 35% (430 EJ) of the cumulative energy savings under the B2DS. This is nearly 220 EJ more than the energy savings from those end uses in the 2DS,

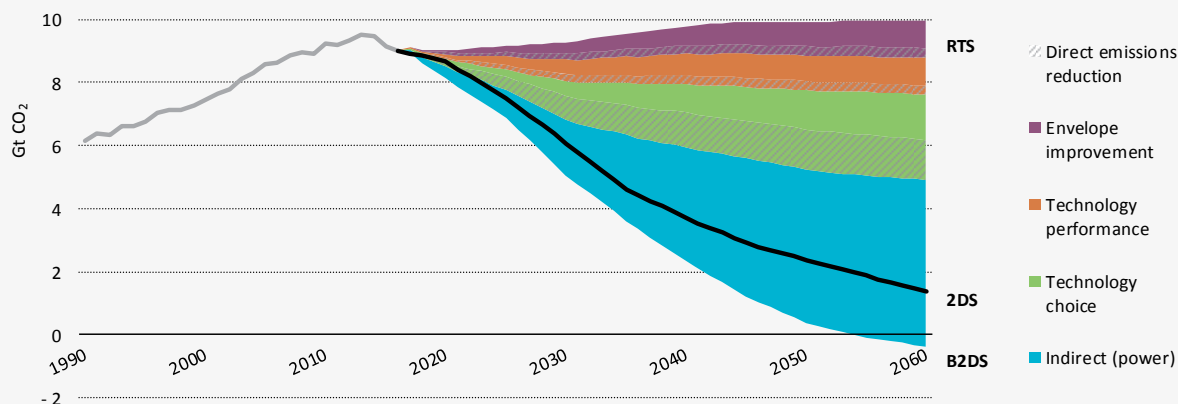
13. For further information on building equipment performance and technology opportunities, see *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013b).

14. Integrated and enabling technologies, such as modern, efficient district energy networks and thermal energy storage, can take advantage of multiple energy resources (e.g. available excess heat from industrial processes and variable renewable power generation) in combination with other energy technologies, such as heat pumps and adsorption chillers, to meet heating and cooling demand in buildings. Those integrated network solutions can also enable flexible synergies across energy supply and demand, raising the net efficiency of the energy system, reducing peak energy loads and supporting deep decarbonisation of the entire energy sector.

notably because of rapid shifts to high-performance lighting and appliances in the coming decade. Water heating savings account for more than half (or nearly 120 EJ) of those cumulative energy savings to 2060 beyond the 2DS. These stem from progressive shifts away from fossil fuels to more efficient, integrated and renewable technologies, such as heat pumps, solar thermal technologies, and modern and low-carbon district energy. Solar thermal use, in particular, increases nearly tenfold compared with today in the B2DS.

The long-term, strategic shift away from fossil fuel use in buildings, alongside the rapid uptake of energy-efficient, integrated and renewable energy technologies (with clean power generation), leads to a drastic reduction in buildings-related CO₂ emissions in the B2DS (Figure 3.7). While total emissions in the 2DS already see an 85% reduction compared with the RTS in 2060, continued use of natural gas in buildings in the 2DS means that buildings-related emissions still remain around 1.4 GtCO₂ in 2060, including 1.2 GtCO₂ in direct emissions. Under the B2DS, buildings-related emissions are 56 GtCO₂ (cumulative) lower than in the 2DS to 2060, including 32 GtCO₂ of additional reductions in direct emissions from fossil fuel use in buildings. In addition, uptake of high-efficiency equipment (e.g. heat pump water heaters and high-performance cooling equipment), renewables and integrated energy solutions, and improved buildings energy management (e.g. smart controls), all help to reduce peak energy loads in buildings through load shifting (temporal shifts) and load shedding (energy demand reduction). Those measures help to support net-negative emissions in power generation, despite increasing electrification of the buildings sector.

Figure 3.7. Key contributions to CO₂ emissions reduction in buildings



Notes: Indirect emissions reduction attributable to buildings represents a decrease in upstream emissions from reductions in electricity demand related to energy efficiency improvements in the buildings sector; the remaining indirect (power) emissions reduction is from improved carbon intensities of power generation, where negative emissions are the result of bioenergy carbon capture and storage (CCS) technologies (see Chapter 6). Technology choice represents shifts from one type of equipment to another technology and/or fuel, such as incandescent lamps to LEDs or gas boilers to electric heat pumps. Technology performance represents energy technology improvements over time (e.g. higher COPs for heat pumps). Envelope improvements account for any buildings measures (including deep energy renovations) that improve the energy intensity of the building envelope beyond the marginal improvements anticipated in the RTS.

Key point *More than 50% of cumulative CO₂ emissions reduction in buildings to 2060 under the B2DS results from shifts to low-carbon and high-performance technologies, which also support investment in net-negative carbon power generation.*

In total, the B2DS represents more than 275 GtCO₂ of cumulative emissions reduction to 2060 compared with the RTS – more than all the CO₂ emissions produced by the global energy sector from 2006 to 2014. Shifts away from fossil fuels in the B2DS, alongside building envelope measures, technology choice (e.g. condensing boiler technology) and continued improvements in product performance for fossil fuel equipment (e.g. higher COPs from gas heat pumps), all contribute to nearly 60 GtCO₂ of total direct emissions reduction in buildings to 2060 compared with the RTS, or more than 20% of cumulative emissions reduction in the buildings sector. The remaining savings result from indirect

emissions reduction related to improved carbon intensities in the power sector, where aggressive uptake of energy efficiency measures in buildings supports less expensive decarbonisation of power generation in the face of rapidly growing electricity demand. On the whole, roughly 40% of the indirect emissions reduction, or more than 80 GtCO₂ of cumulative emissions savings to 2060, is attributable to energy efficiency measures (including more efficient technology choices) in buildings, meaning that more than half of total cumulative CO₂ emissions reduction in the global buildings sector under the B2DS results from the large-scale adoption of low-carbon, renewable and high-performance technology solutions.

Energy technology strategies for sustainable buildings

Capturing the enormous energy savings potential in the global buildings sector would deliver a broad range of benefits, including significant reductions in CO₂ emissions and other pollutants that pose a threat to human health. Achieving the 2DS already requires an unprecedented effort to develop and deploy energy-efficient and low-carbon technologies over the next 40 years, using a broad range of policy measures and market incentives. Going beyond the 2DS would require even swifter and more assertive policy action to drive innovation and move markets as quickly as possible over the next decade to best buildings practices and low-carbon, high-efficiency technology solutions. A strategic vision and subsequent policy framework would also be necessary to shift buildings away from fossil fuels, as those investments would require long-term planning and policy support to ensure that buildings measures are co-ordinated with investments in energy supply and distribution.

Locking in better buildings for tomorrow

Over the next 40 years, global buildings floor area is expected to grow by 230 billion m². When building demolition (typically less than 1% per year) is taken into account, this means that an average of 6.5 billion m² will be constructed every year over the next 40 years – the equivalent of adding the total buildings floor area of Japan to the planet every year to 2060.

Building envelope improvements, through high-performance construction of new buildings and deep energy renovations of existing buildings, will play a critical role in achieving the 2DS and B2DS ambitions for an energy-efficient and low-carbon buildings sector.¹⁵ Under both scenarios,¹⁶ global average building envelope performance improves by 50% by 2060 (compared with 30% in the RTS), which would require a doubling of global average annual improvement rates from around 0.75% in the RTS to more than 1.5% per year in the 2DS and B2DS. This would require enormous effort (including financing for building envelope performance measures) to ensure markets adopt best practices and high-performance envelope technology solutions, especially in rapidly emerging economies where new construction risks locking in less-than-optimal building envelope performance. Yet global progress to date in implementing, strengthening and enforcing building energy codes for high-efficiency new buildings continues to be sluggish (see Chapter 2).

Advancement of deep energy renovations also continues to be slow, largely due to the upfront costs of deep envelope improvements and the lack of incentive (or obligation) to improve buildings energy performance. Improvement measures typically pursued today (e.g. occasional window replacements and modest levels of insulation) do not achieve the deep energy savings needed to meet 2DS and B2DS objectives. This is despite numerous analyses, such as the work by the IEA Technology Collaboration Programme (TCP) on

15. Further information on building envelope technologies, priorities and R&D strategies to 2050 can be found in the IEA Technology Roadmap: *Energy Efficient Building Envelopes* (IEA, 2013a) at www.iea.org/publications/freepublications/publication/technology-roadmap-energy-efficient-building-envelopes.html.

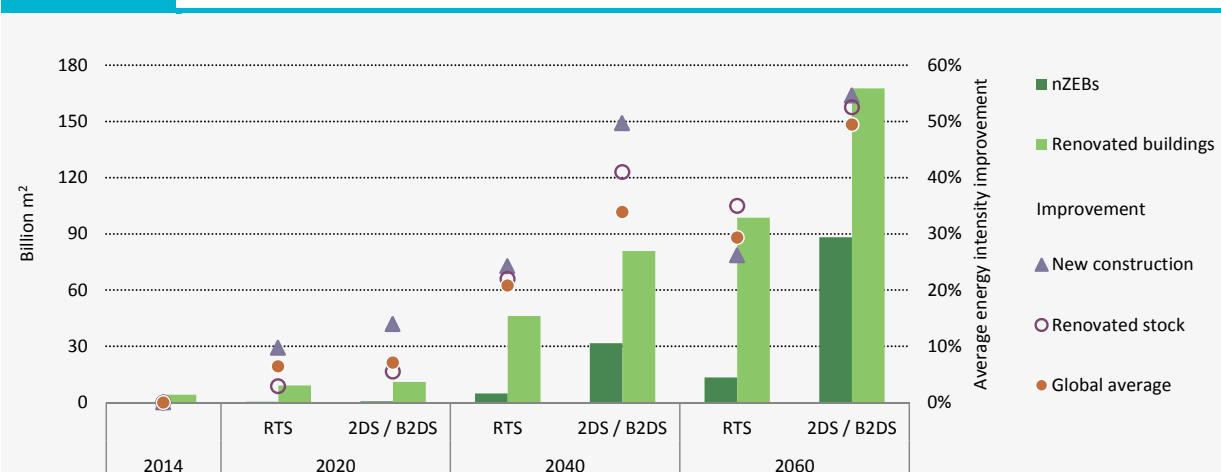
16. Building envelope improvements in the 2DS require an unprecedented global uptake of high-performance new building construction and deep energy renovation of existing buildings (Figure 3.8). While further or faster improvement of the global building stock may be possible, the B2DS does not consider additional measures beyond the 2DS for building envelopes, given the already immense scale of effort needed relative to existing and historical trends.

Energy in Buildings and Communities (EBC),¹⁷ that have demonstrated the long-term cost-effectiveness of deep energy renovation (IEA, 2016b).

Rapid progress is needed to achieve high-performance buildings construction and deep energy renovations in order to meet 2DS and B2DS targets, requiring rates of improvement in energy intensity of 30% or more for 2% to 3% of the existing stock per year by 2025 and beyond. For instance, the number of nZEBs in the global buildings stock increases nearly sixfold in the 2DS and B2DS compared with the RTS, representing one-quarter of residential floor area in 2060, compared with only 4% in the RTS (Figure 3.8). The amount of existing floor area that is renovated by 2060 is similarly 65% greater than in the RTS (or more than twice estimated annual buildings energy renovations in 2014), while the average energy intensity of the renovated buildings stock (in terms of building envelope performance) is 55% better than RTS improvements to 2060. Likewise, the energy intensity of new buildings, thanks to widespread adoption of nZEBs and high-performance new construction, sees twice the energy performance improvement of the RTS in 2030, or a 50% net improvement over the global average energy intensity of new building envelopes constructed today.

Figure

3.8. Changes in global residential buildings stock and improvements in average energy intensity to 2060



Note: Changes in energy intensity represent improvement in average building envelope performance (in kWh/m²) relative to 2014.

Key point

High-performance buildings construction and deep energy renovations of existing buildings play a critical role in reducing residential buildings energy demand.

The consequences of delaying action to address global buildings envelope performance are considerable: a ten-year delay in achieving B2DS building envelope measures would result in around three years of additional energy consumption to 2060 (or 127 EJ) for heating and cooling in buildings due to those less-than-optimal buildings investments. That is equivalent to total buildings final energy consumption in India over the last 15 years (Figure 3.9). Delaying envelope improvements would be particularly significant in China, which accounts for one-third of the total potential losses due to continued delay over the next decade.

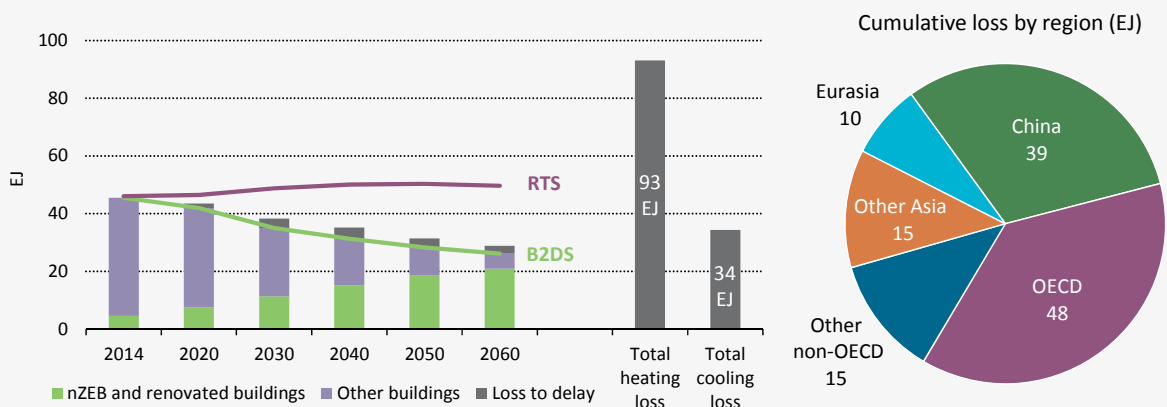
The risks of inaction go beyond energy demand and buildings sector decarbonisation. Building energy codes and energy performance standards have other important implications, including thermal comfort, health and safety within buildings, and improved air quality in cities. In urban northern China, for example, heat demand contributes to significant air pollution during winter months, as district heat covers about 90% of space

17. Information on the EBC TCP, including research for cost-effective district-level building energy renovation strategies (Annex 75), business and technical concepts for deep energy retrofits of public buildings (Annex 61), and other projects on cost-effective measures for low-energy buildings, can be found at www.iea-ebc.org.

heating needs and coal accounts for more than 80% of district heat generation in China (IEA, 2015). Continued delay in achieving high-performance envelopes (including deep energy renovations of existing buildings), and the consequent continued high demand for district heat, would therefore have important consequences for meeting China's ambitions to improve national air quality, where nearly 1 million premature deaths annually can be attributed to indoor and outdoor air pollution (IEA, 2016e). The Chinese government has identified buildings energy consumption and emissions related to district heat as key priorities and has developed a plan to proactively improve buildings energy performance and accelerate the refurbishment of the district heat network (IEA, 2016b).

Figure

3.9. Consequences of a ten-year delay in achieving B2DS building envelope measures



Note: Total heating and cooling losses represent the cumulative energy loss to 2060 from a ten-year delay in building energy code implementation and enforcement.

Key point

Delaying implementation and enforcement of B2DS buildings measures would result in around three years of additional energy consumption for heating and cooling in the buildings sector.

Building envelope energy performance also has important implications for countries with hot and humid climates, such as India and Indonesia, where cooling demand is growing rapidly. Cooling equipment typically ejects heat into the local atmosphere,¹⁸ which can increase local ambient temperatures alongside heat from reflective surfaces and other sources (e.g. transport), thereby perpetuating the need for mechanical cooling. This “heat island effect” can be sizeable, with temperatures in urban areas as much as 2°C to 4°C higher than surrounding areas (LBNL, 2013; Taha et al., 1988). Building envelope measures, such as “cool roofs” and exterior shading, and building design, such as placement of windows, building orientation and use of natural ventilation, can drastically reduce the need for space cooling, while also contributing to reduced heat island effects in urban areas (IEA, 2013a).

Multiple actions can be taken to improve the energy performance of building envelopes. These range from simple measures, such as air sealing, window attachments (e.g. shutters and shades) and reflective surfaces (e.g. cool roofs that reflect visible and near-infrared light), to highly insulating windows, advanced insulation (e.g. aerogels) and whole-building renovation packages.¹⁹ First and foremost, national and local governments across all countries should urgently establish and strengthen energy codes for both new *and* existing buildings, accompanied by appropriate enforcement infrastructure and capacity. This

18. Heat can also be ejected via other media (e.g. water) or recovered for other purposes (e.g. in district energy networks that can exchange or store heat from cooling for district heating purposes).

19. Further information on building envelope technologies and strategies can be found in *Technology Roadmap: Energy Efficient Building Envelopes* (IEA, 2013a) at www.iea.org/publications/freepublications/publication/technology-roadmap-energy-efficient-building-envelopes.html.

includes establishing a comprehensive policy framework that assists the various actors and stakeholders across the buildings and construction sectors to overcome barriers, including market failures (e.g. in supply chains), hidden and high upfront costs, and other behavioural and informational barriers (including misinformation about energy efficiency measures). Public awareness is also critical to ensure market change: the multiple benefits of energy efficiency investments are often overshadowed by the upfront costs, even when they are cost-effective over the lifetime of the measure (IEA, 2014a).

Typically, no single policy instrument is able to drive buildings sector transformation towards high levels of energy-efficient and low-carbon energy technology. Rather, a combination of policy instruments, often working with a broad range of stakeholders and authorities, is required to deliver the full spectrum of change needed (see Box 3.1 on how the Mexican government is using such an integrated approach to support change). Effective policy packages routinely provide a balanced mixture of both mandatory and voluntary regulatory tools (e.g. building energy codes and certifications), alongside market incentives and capacity-building initiatives, such as training for builders and product installers, who represent a key interface for decision making. Pricing signals, including elimination of fossil fuel subsidies and other perverse incentives that discourage adoption of energy efficiency and low-carbon measures in buildings, should also be considered as part of a comprehensive policy package to drive markets towards sustainable buildings technologies.

Scaling up high-performance buildings construction and deep energy renovations of existing buildings will require considerable effort to shift the massive global buildings market. To ensure action occurs in the coming years and avoid locking in inefficient buildings for decades to come, governments can enable the transition to sustainable buildings by:

- Setting clear and consistent objectives on building energy and emissions performance (for both new and existing buildings) to provide a signal to markets on long-term expectations for investment in building energy efficiency.
- Working with key authorities (e.g. energy, construction and finance ministries) and buildings stakeholders, including urban planning authorities, to ensure alignment in buildings energy policy design and enforcement.
- Collaborating with manufacturers and buildings supply chains to foster and accelerate diffusion of high-performance technology and best buildings practices.
- Working with other governments to share experiences and best practices, with a particular emphasis on knowledge transfer, capacity building and technology leapfrogging in developing countries, where the vast majority of new buildings additions will occur.
- Increasing access to finance, including direct financing and related support schemes, through appropriate national and regional mechanisms that stimulate capital flows, while also increasing investor confidence in sustainable buildings measures.²⁰
- Supporting and participating in R&D efforts (e.g. the IEA TCPs²¹ and the Affordable Heating and Cooling of Buildings Challenge²²) to advance and demonstrate cost-effective, high-efficiency products and solutions for the buildings sector, including improved solutions for zero-energy buildings and net-zero energy communities.

20. Examples of such initiatives include the De-Risking Energy Efficiency Platform (<https://deep.eefig.eu/>) and the Investor Confidence Project (www.eepformance.org).

21. Further information on 40 years of technology collaboration at the IEA can be found at www.iea.org/tcp/.

22. Further information on Mission Innovation challenges can be found at <http://mission-innovation.net/>.

Box

3.1. A new energy programme for sustainable housing in Mexico

In August 2016, the Mexican government launched a comprehensive, sustainable improvement programme for housing that aims to reduce energy consumption in low-income households through energy efficiency and renewable energy measures, such as improved thermal insulation and glazing, energy-efficient air conditioners and solar water heaters. The programme builds on efforts to improve financing for sustainable buildings measures, as well as the success of a similar green mortgage programme available to federal civil servants.*

The sustainable housing programme is operated by the Trust Fund for Electricity Savings (*Fideicomiso para el Ahorro de Energía Eléctrica*, FIDE) with technical support from the Federal Electricity Commission (*Comisión Federal de Electricidad*, CFE) and financial support from the Mexican National Development Bank (*Nacional Financiera*). CFE is responsible for carrying out a building diagnosis and evaluating the best combination of technology solutions, while FIDE approves the technologies and then both organisations approve the installers. The programme also has a component on capacity building and information for home users.

The Mexican government expects to start implementation of the programme in 2017, and FIDE is evaluating the eligibility of households that have shown interest in the programme. Loans of up to 2 300 United States dollars (USD) will be provided to households with monthly average salaries of up to approximately USD 550, with a payment period of up to five years. Payments will be collected through the household's monthly electricity bill.

Overall, the government expects to achieve energy savings of approximately USD 230 per year per household (roughly 5% or more of household income). The National Housing Commission, with the Ministry of Energy through its Fund for Energy Transition and Sustainable Energy Use, is also providing a subsidy for up to 40% reduction in the cost of energy-efficient technologies.

The new programme, while limited to low-income households, is an important step forward to increase the adoption of energy efficiency and renewable energy measures in Mexico's buildings. It is also a good example of cross-cutting collaboration, which will be critical in the future as Mexico makes large-scale efforts to improve building energy performance.

The IEA has been supporting the Ministry of Energy in Mexico in its work to improve building energy performance, under the IEA Energy Efficiency in Emerging Economies Programme, with a strong focus on the adoption and enforcement of building energy codes by local government. The IEA is also supporting a respective roadmap for action, which aims to reduce the need and energy used for space cooling in Mexico.

* Further information on policies and programmes in support of Mexico's Sustainable Energy Transition can be found in Chapter 8 of *Energy Technology Perspectives (ETP) 2016* (IEA, 2016b).

In the immediate term, governments can also identify key buildings segments (e.g. social housing, public buildings and large commercial buildings) that have critical mass to engage in energy efficiency action straight away, thereby fostering the market scale needed to help drive down the cost of building energy efficiency solutions. For instance, the Dutch government initiated an innovative buildings refurbishment programme (*Energiesprong*) in 2010 that convened multiple buildings stakeholders (e.g. public housing associations, builders and financiers) to establish a large-scale refurbishment proposition that achieves deep energy renovations within ten days, using off-site prefabrication and providing a 30-year energy performance warranty. By working at an appropriate scale (initially 111 000 homes) and creating a regulatory and finance package that reduces investment risks, the programme has eliminated upfront investment costs for consumers, who see no increase in their monthly energy bills (which are instead paid to an energy service provider rather than a traditional energy utility).²³

23. Further information about the Dutch *Energiesprong* programme can be found at <http://energiesprong.nl>.

Other actions governments can take in the immediate term include information and awareness campaigns, such as energy efficiency drives to engage consumers, and training and capacity-building programmes that disseminate critical knowledge and information to those working in or with the buildings and construction trades. This includes simple measures that can have considerable impact, such as training on effective air sealing of buildings and proper use of buildings controls and energy management systems (see Box 3.2 on the energy efficiency potential of better controls for heating and cooling in buildings).

Box

3.2. Energy savings through improved controls for heating and cooling

Optimisation of heating and cooling energy demand in buildings through improved controls offers considerable potential to save large quantities of energy. Energy efficiency policy has historically targeted equipment performance (e.g. energy performance standards for boilers), while optimisation of heating and cooling systems (including distribution) is often neglected.

System optimisation, including improved controls, can deliver significant energy savings beyond (and complementary to) energy reductions from improvements in building envelopes and heating and cooling equipment. Examples of improved controls include smart thermostats that are programmable, and connected (i.e. networked) devices that monitor and regulate heating and cooling loads. Savings can range between 15% and 50%, depending on the building and control technology (Grözinger et al., 2017).

One basic optimisation technique in buildings is automatic temperature controls for individual equipment (e.g. radiators or cooling vents in a room). Individual room or unit temperature control is often missing in buildings, which can not only lead to occupant discomfort, but also result in additional energy demand (e.g. from use of additional space heaters and cooling fans). Poor control also often requires oversizing in heating and cooling system design to distribute the same thermal load across an entire building's occupied space. Better controls can therefore have considerable impact on both occupant comfort and efficient operation of the heating and cooling system, including pumps and ventilation equipment.

Another optimisation technique is dynamic balancing of energy flows in pipes, valves and distribution equipment within a building. Dynamic balancing is uncommon in most buildings today, but together with automatic temperature controls for heating and cooling equipment, it can ensure the right amount of energy is delivered to all parts of a building at all times and conditions. More advanced, intelligent and remotely connected functionalities also enable occupants to adapt energy use to individual needs and behaviour (e.g. by control of temperatures via smartphone applications that are connected to thermostats). Automatic control functionalities can also be paired to building energy management systems to continuously monitor and better manage heating and cooling loads relative to dynamic feedback from users and the building. They can similarly be used in district energy networks to adjust supply conditions (e.g. pressure and distribution temperatures) for better balancing and energy management across the network (Danfoss, 2016).

Energy savings depend, of course, on user behaviour and building characteristics. Energy savings from replacing simple radiator valves (or lack thereof) with automatic thermostats can be in the range of about 15% to 35% (von Manteuffel, Offermann and Bettgenhäuser, 2015; Hirschberg, 2016). Depending on circumstances, dynamic balancing can deliver around 10% to 25% in additional relative savings beyond automatic thermostats. Investments are typically capital-light with short payback periods.

Beyond better energy management, controls for heating and cooling in buildings can have important social and health-related implications. For instance, around 11% of the population in the EU is not able to adequately heat their households at an affordable cost (Pye and Dobbins, 2015). Optimisation of heating and cooling loads (with appropriate financing tools and support schemes for low-income households) can help to reduce buildings energy demand, while also allowing healthy temperatures and reducing energy expenses.

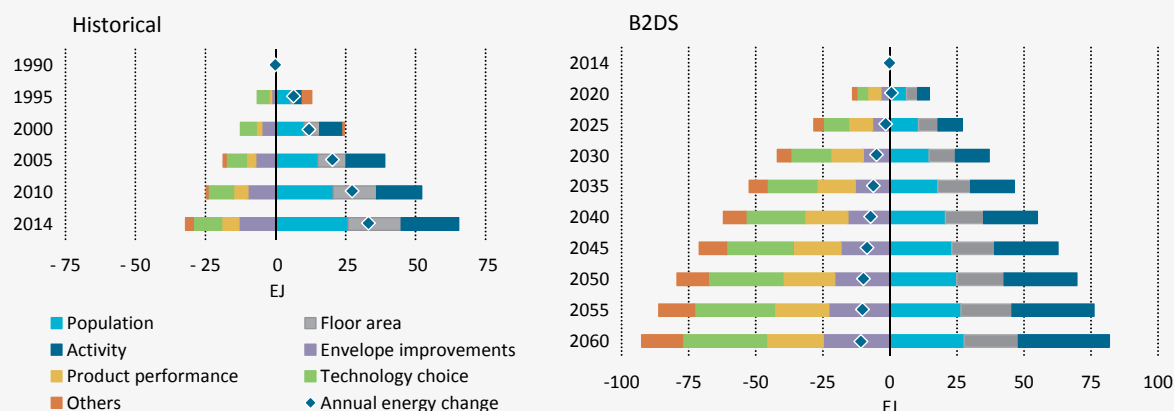
Note: Stephan Kolb (Danfoss) provided substantive input into Box 3.2.

Capturing the energy efficiency potential for a B2DS world

Over the last 25 years, energy efficiency measures have contributed 450 EJ in cumulative energy savings – equivalent to all of global final energy demand in 2014 – including nearly 90 EJ of energy savings from shifts away from traditional use of solid biomass in developing countries to more efficient end-use technologies, due to improved energy access. Other notable measures include the growing shift from conventional boilers to condensing boiler technology, and the global effort to phase out incandescent lighting for more efficient technologies (e.g. compact fluorescent lamps [CFLs] and more recently LEDs). These helped offset a rapidly growing buildings sector, where growth in population, floor area and buildings sector activity (e.g. greater ownership of appliances) continued to drive greater demand for energy services and consumption in buildings. Energy demand in 2014 would certainly have been far greater without those energy efficiency investments, although improvements to date were still insufficient to actually reduce total energy demand in buildings, which was 35% higher in 2014 than in 1990 (Figure 3.10).

Figure

3.10. Decomposition of global final energy demand in buildings by key contribution



Notes: The energy composition represents the influence of each indicator on changes in total final energy demand from 1990 (historical) and from 2014 to 2060 (B2DS). *Activity* represents the decreasing average number of persons per household, increases in average household income and ownership of energy-consuming equipment, and growth in services value added. *Envelope improvements* account for buildings measures that improve the energy intensity of the building envelope. *Product performance* represents energy technology improvements over time (e.g. from continued R&D). Technology and fuel switching represent shifts from one type of equipment to another technology and/or fuel. *Others* includes greater access to electricity (in developing countries), changes in energy demand influences (e.g. annual heating and cooling degree days) and any residuals from the decomposition analysis.

Sources: Population: UN DESA (2015), *World Population Prospects: The 2015 Revision, Medium-Fertility Variant*; services value added: calculations derived with IMF (2016), *World Economic Outlook Database: April 2016*; energy decomposition calculations derived with IEA (2016c), *World Energy Statistics and Balances* (database), <http://dx.doi.org/10.1787/enestats-data-en>.

Key point

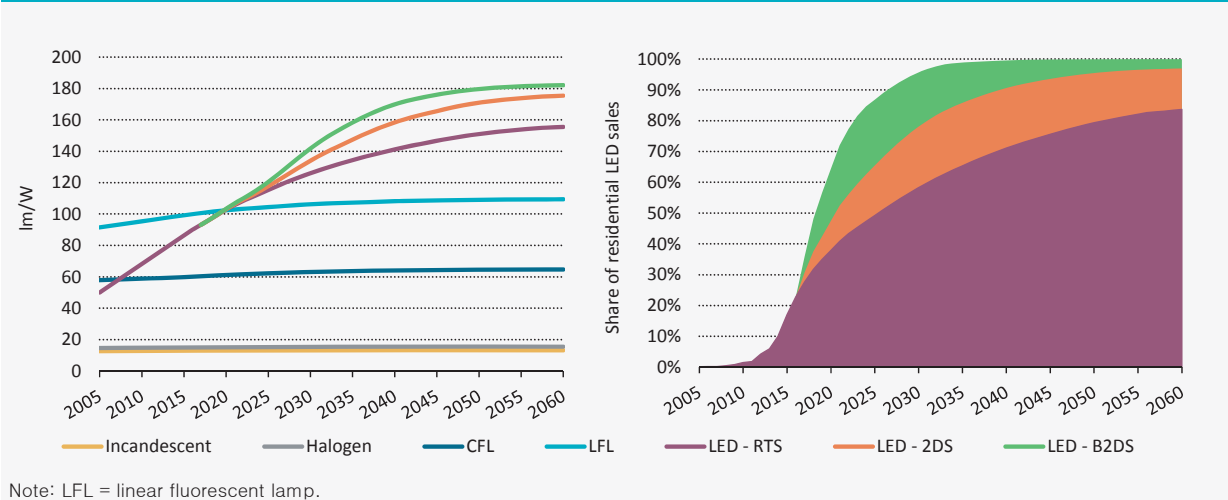
Energy efficiency measures under the B2DS reverse historical trends, offsetting the effect of an increasing global population, buildings activity drivers and growing floor area in buildings.

While the energy efficiency potential of the global buildings sector still remains largely untapped, the good news is that high-efficiency and low-carbon energy technology solutions (e.g. heat pumps, high-efficiency appliances and solar thermal technologies) already exist in most markets. Significant improvements can be achieved if existing policies and regulations for energy-consuming equipment are implemented and strengthened across all countries to cover the vast majority of end-use equipment in buildings. This would drive the demand for and adoption of efficient technology solutions, while also possibly helping to drive down costs and make those products more affordable, supporting a reversal in historical trends and reducing buildings energy consumption, despite expected growth in global population and buildings sector activity.

Under the B2DS, energy efficiency measures, including building envelope improvements, represent nearly 2 400 EJ in cumulative energy offsets to 2060 relative to 2014 – more than all the final energy consumed by the buildings sector over the last 20 years. Nearly 70% of those reductions come from the adoption of high-performance equipment in buildings, where slightly less than one-third (or 610 EJ in cumulative savings to 2060) are due to enhanced technology performance (e.g. improvements in very high-efficiency heat pump technologies). Market scale, continued R&D and greater value for energy efficiency (e.g. return on investment) all incentivise further development of even higher performance in buildings technology solutions. When growing population, floor area and buildings activity are all taken into account, the total impact of energy efficiency measures across the global buildings sector in the B2DS contributes to a net cumulative energy reduction potential of 270 EJ in effective energy savings to 2060, equivalent to the last two years of TFEC across IEA member countries.

Figure

3.11. Lighting equipment performance and residential LED market share to 2060



Note: LFL = linear fluorescent lamp.

Key point

Rapid deployment of energy-efficient LED technologies in the B2DS creates critical mass in the market, helping to drive R&D for improved energy performance.

Rapid adoption of the most efficient buildings end-use technologies, including best available lighting, cooling and household appliances today, underpins the energy savings and emissions reduction potential in the B2DS. Unlike the 2DS, in which those technologies are progressively deployed over the next 10 to 20 years, the B2DS requires a speedy uptake of energy efficiency measures, starting first with off-the-shelf products that can already be adopted in most markets today, such as LED lighting products and solutions (Figure 3.11). This would require significant policy action, including wide-ranging MEPS to address continued availability of less efficient products, and market incentives to help address the traditional consumer decision-making process, which often considers upfront costs over life-cycle cost-effectiveness. Those wide-ranging measures may be unprecedented in many countries, yet the energy offsets available from rapid deployment of high-efficiency lighting, cooling and appliances alone are more than 80 EJ (cumulative) over the next 15 years, and the life-cycle costs for those high-performance technologies are already economically viable in many markets (aside from the other benefits of energy efficiency measures).

A “race to the moon” for high-performance technologies over the next decade would also help to bring forward more efficient products and technology solutions (e.g. advanced lighting controls), in the same way that past R&D programmes and market incentives helped to bring to market current BATs. For example, LED lighting efficacy (measured in lumens per watt [lm/W]) is expected to increase to around 150 lm/W in the RTS (in line

with anticipated product development), where continued availability of less efficient products (e.g. halogen lighting) influences the adoption of high-efficiency LEDs and lessens the motivation to invest in R&D for greater LED performance. In the 2DS, LED efficacy nearly doubles, leading to global energy savings of 65 EJ to 2060 compared with the RTS. This is thanks to LEDs commanding a higher share of sales due to greater effort to move markets away from inefficient lighting, and the subsequent incentive for manufacturers to improve energy performance and product choices by improving returns on investment for continued R&D. In the B2DS, the energy savings from lighting demand in buildings nearly double to 128 EJ compared with the RTS, thanks to even more immediate adoption of high-efficiency lighting (through assertive push and pull policies over the next decade). This would provoke yet faster improvement in lighting performance and possibly even higher efficiencies in the future from innovative products and energy services (see Box 3.3 on advancing lighting solutions).

Box

3.3. Intelligent lighting solutions for sustainable buildings

SSL, including semiconductor, organic and polymer LEDs, has the potential to provide high-quality, energy-efficient lighting that surpasses traditional lighting technologies (e.g. halogen lamps and CFLs) at decreasing life-cycle costs. In recent years, typical LED performance has improved from around 60 lm/W to as much as 100 lm/W or higher, in comparison with halogen lamps at less than 15 lm/W or CFLs at roughly 60 lm/W. Purchase costs have also come down by as much as 90% since 2008 (US DOE, 2015).

More efficient SSL technologies are expected to come to market in coming years, including recent product developments that would allow for improved lighting services in buildings (e.g. changes in colour temperature to replicate natural lighting). Some of the newest SSL products coming to market are also efficient enough to run directly on the local Ethernet due to very low electricity consumption, thereby removing the need for connection to an electrical cable. This will allow the SSL to interact directly with buildings controls and energy management systems. Not only could these “smart” products improve the overall operating efficiency of lighting in buildings, they could also provide improved management of lighting and energy services (e.g. detection of presence for lighting, heating and cooling needs).

The IEA TCP on Energy-Efficient End-Use Equipment (4E) has an SSL annex that is working to address product performance, quality, lifetimes and other common challenges with SSL technologies. This includes work across nine countries looking at global harmonisation of product quality and performance, as well as collaboration on the development of performance tiers across a wide range of product attributes (e.g. colour, lifetime and efficacy). Governments could use these when designing lighting programmes and policies.

Note: Further information on the 4E SSL annex can be found at <http://ssl.iea-4e.org/>.

Governments can encourage rapid adoption of energy efficiency measures in the coming years by creating market conditions, including consumer awareness, that favour energy efficiency and engage the entire buildings sector energy chain, from suppliers to product installers and final energy consumers, in the transition to sustainable buildings.

Governments can do this with:

- Upfront incentives, such as rebates and financing schemes, for both consumers and product manufacturers
- Regulatory tools, including MEPS, that discourage inefficient technologies
- Support for development of appropriate market scale (e.g. through bulk procurement).

Governments can also collaborate with industry and product manufacturers to identify market failures, known technology issues, such as product performance and quality, and other common obstacles, such as lack of appropriate financing mechanisms, which hinder

diffusion of high-performance technologies. Co-operation through international platforms, such as the IEA 4E TCP and the Clean Energy Ministerial's Super-Efficient Equipment and Appliance Deployment initiative,²⁴ can similarly help bring forward energy-efficient technologies by allowing information, experiences and best practices to be shared across governments. It can also help identify common challenges and ways to facilitate greater uptake of energy efficiency measures, for example through harmonisation of standards and testing procedures.

Greater international collaboration, including co-operation at the subnational level, will be equally important in coming years to improve upon already successful energy efficiency policies and technology programmes, particularly in rapidly emerging economies and developing countries. Initiatives such as United for Efficiency²⁵ and the IEA Energy Efficiency in Emerging Economies²⁶ programme can help to scale up adoption of energy-efficient technologies by working with policy makers and relevant stakeholders in developing countries to implement effective policies to drive sustainable market transformation.

Concerted effort is also needed to ensure energy efficiency programmes and policies evolve with technological development and consumer choice. For instance, energy efficiency gains in the global market for televisions over the last decade were largely offset by consumer preference for larger television screens. Only in the last year or two did market trends finally start to suggest that average television energy consumption had peaked (see Chapter 2), although increasing resolution quality (e.g. 4K [4 000 pixels] and ultra-high-definition televisions) may equally influence the prevailing trend in coming years to greater energy consumption.

Networked devices, including the increasing share of smart appliances and connected equipment in buildings, have similarly added considerable new demand for electricity over the last decade, mainly because everything that is connected is always "on" (IEA, 2014c). Substantial energy savings, as well as better management of peak load in buildings,²⁷ are possible if smart devices are used more effectively. For example, plug loads could be reduced by as much as 50% if smart plugs or advanced power strips were used (King and Perry, 2017). However, energy efficiency policies first need to include these technologies within the wider purview of efforts to limit energy consumption in end-use equipment (e.g. the global one-watt initiative to reduce standby power).

Finally, to ensure the long-term transition to sustainable energy in buildings, government support for R&D programmes and other collaborative platforms, such as the global initiative on Mission Innovation,²⁸ will be critical to accelerate the development of high-efficiency, low-carbon buildings technology solutions in the future. Considerable effort is needed to generate technological leaps that move beyond existing or expected BATs and at lower cost. For example, while energy performance improvements of major household appliances (e.g. refrigerators) have been substantial in the last two decades, due to R&D, MEPS, labelling programmes and related energy policies, significant gains in the future may require advanced technical solutions (e.g. vacuum insulated panels) or alternative technologies, such as thermoelectric cooling using heat pumps (see Box 3.4 on international collaboration to bring forward advanced heat pump technology solutions for multiple applications). Greater support for accelerated R&D will be necessary to develop those products (and others) and bring them to market at affordable prices as quickly as possible, especially given the anticipated rapid expansion of the built environment and energy-consuming equipment in buildings over the coming decades.

24. See www.cleanenergyministerial.org/Our-Work/Initiatives/Appliances.

25. See <http://united4efficiency.org/>.

26. See www.iea.org/topics/energyefficiency/e4/.

27. See Chapter 6 on smart grids and demand-side management.

28. See <http://mission-innovation.net/>.

Box

3.4. Advances in heat pump technologies for multiple applications

Heat pump technologies will play a vital role in meeting B2DS objectives, given the critical importance of drastically improving product performance for heating and cooling services in buildings, including water heating, refrigeration and other related applications (e.g. clothes washing and drying). Progress in deploying heat pump solutions in buildings is improving – for instance, heat pump sales in Europe doubled in the last decade (EHPA, 2016) – but faster adoption of heat pump technologies is needed across the global buildings sector.

The IEA TCP on heat pumping technologies (HPT TCP) is a collaborative research and information platform across 16 countries looking at heat pumping technologies, applications and markets. It seeks to develop high-quality, high-performance heat pumps for multiple applications and operating conditions (e.g. cold and hot/humid climates).

The HPT TCP has several ongoing initiatives (called annexes) to advance heat pump technology performance, quality and reliability for various applications. These include research activities on hybrid and fuel-driven sorption heat pumps, cold-climate and industrial heat pumps, heat pumps for water heating, and heat pump technologies for district energy systems. The programme is also considering the application of heat pumps in multifamily residential buildings and for nZEB applications. A recent annex, announced in 2016, will look at the acoustic signature of heat pumps, to minimise noise and increase acceptance of heat pumps in buildings.

The IEA is currently working with multiple partners, including HPT TCP, the European Heat Pump Association and the Heat Pump and Thermal Storage Technology Center of Japan, to collect improved global data on heat pump technologies and energy performance. The collaboration seeks to shine light on global heat pump markets and to identify opportunities for increased deployment and adoption of efficient, low-carbon heat pumps.

Note: Further information on the HPT TCP can be found at <http://heatpumpingtechnologies.org/>.

Transitions to low-carbon buildings and net-zero energy communities

Building envelope improvements and rapid deployment of energy efficiency measures across the global buildings sector are essential to meeting B2DS objectives, but these alone are insufficient to achieve the energy transition to low-carbon buildings by 2060. The B2DS also requires a critical shift away from fossil fuels, moving beyond the measures prescribed in the 2DS (e.g. mandatory condensing boiler technology) to cut fossil fuel consumption in buildings by an additional 75% by 2060. This effectively means that nearly all coal and oil use in buildings would be eliminated over the next 40 years, while natural gas use in the B2DS would be reduced by an additional 70% compared with the 2DS in 2060.

For this to happen, a long-term strategic vision and comprehensive policy framework would be necessary to progressively decarbonise energy demand in buildings. Achieving the transition to low-carbon buildings would also need to be carefully planned within the context of the broader energy sector, to avoid unnecessary costs or early retirement of existing capital (e.g. natural gas networks and recent installations of gas equipment in buildings). This would require a combination of policy packages, market frameworks (including financing mechanisms) and planning tools, such as heat mapping and urban planning, to facilitate a smooth shift away from fossil fuels over the coming decades (see Box 3.5 on the Heat Roadmap Europe project to develop low-carbon heating and cooling strategies for the European Union).

The transition away from fossil fuel use in buildings is also likely to require thinking about building energy communities, rather than individual building applications, to achieve critical mass for fossil fuel phase-out and the subsequent phase-in of high-efficiency, renewable and integrated technology solutions. For instance, technical limitations may constrain certain technology choices to replace existing fossil fuel equipment in buildings (IEA, 2016b), such as lack of adequate rooftop area in dense urban areas for large-scale solar

thermal applications, or inadequate exterior space in multifamily residential buildings for heat pump equipment. Near-zero or net-zero energy communities may therefore be a more realistic goal, in some instances, for achieving a carbon-neutral buildings sector, using integrated solutions to ensure the best possible economic efficiency for the community.²⁹ Integrated energy systems could also take advantage of cost-effective synergies that would allow for greater energy system flexibility, for example combinations of high-performance buildings with advanced district energy, heat pumps, renewables and other carbon-neutral power generation, including excess heat recovery.

Box

3.5. Mapping heating and cooling strategies for Europe

Heat Roadmap Europe is a collaborative project across various universities, consultancies and industries to develop low-carbon heating and cooling strategies in the European Union, where fossil fuels (and in particular natural gas) account for roughly half of TFECE in buildings. The roadmap project combines advanced computer models of the EU energy system with detailed expertise within industry to create robust, evidence-based recommendations for the decarbonisation of heating and cooling across the European Union.

One of the major outputs of Heat Roadmap Europe is the Pan-European Thermal Atlas, which includes detailed mapping of heat demand in the European Union to assess the feasibility of large-scale energy projects, such as district energy systems, by determining appropriate heat densities. The project has shown that around 50% of EU heat demand is located in urban areas that have heat densities similar to those served by existing district heating networks (where only 10% of EU heat demand is currently supplied with district heat) (Connolly et al., 2014).

Heat Roadmap Europe has also investigated different supply options (e.g. excess and renewable heat) that could be used for potential district energy networks. For instance, the city of Middlesbrough in the United Kingdom (UK) has a heat demand around 2.8 TWh per year for a population of roughly 350 000 people, which is primarily supplied using natural gas today. Roughly 14 TWh per year of excess heat is available from a neighbouring mix of power plants, industries and waste incinerators (Persson, Möller and Werner, 2014). District heating solutions could therefore supply heat to a large proportion of the city, if not all buildings, while the use of currently available excess heat in a district heat network would also support future shifts to other flexible energy sources in the future.

Heat Roadmap Europe has simulated the impact of an energy transition for heating and cooling in the European Union by estimating the corresponding costs and carbon abatement potential. The conclusions indicate that district energy networks (e.g. using excess heat) could meet a large proportion of heating and cooling demand in buildings. They would also allow for greater integration of renewables (including renewable electricity generation) using technologies such as large-scale heat pumps and thermal storage. This would require considerable upfront investment, although such solutions would reduce the cost of supplying heat in the long term while also drastically reducing energy demand and carbon emissions.

Work on the Heat Roadmap project is ongoing, with continued research under the EU Horizon 2020 programme. Further information can be found at www.heatroadmap.eu.

Note: David Connolly (Aalborg University) provided substantive input into Box 3.5.

Shifting buildings away from fossil fuel consumption would also require more targeted energy policies and strategies for developing countries in order to improve access to affordable, low-carbon and energy-efficient technologies. In many developing countries today, fossil fuel use in buildings is in fact growing, particularly as households shift away

29. Further information on integrated and multidisciplinary approaches to energy-efficient communities can be found in the analysis by the EBC TCP (Annex 51), available at www.iea-ebc.org/projects/completed-projects/ebc-annex-51/.

from traditional use of solid biomass to low-cost and readily accessible fossil fuels (e.g. LPG). Global initiatives, such as the Clean Energy Ministerial Global Lighting and Energy Access Partnership (LEAP)³⁰ and the Efficiency for Access coalition,³¹ can help developing countries leapfrog existing technologies to bring affordable and sustainable energy access (e.g. shifting traditional use of solid biomass to solar cookers or solar thermal systems) and ensure a clean and efficient energy transition.

Avoid, shift and improve: Strategies for reducing fossil fuel use in buildings

Just over one-third (35% or 45 EJ) of final energy consumption in the global buildings sector in 2014 was from direct fossil fuel use, and three-quarters of that was for heating purposes (excluding cooking). When traditional use of solid biomass is excluded, more than two-thirds of final energy demand for space and water heating in buildings was provided by fossil fuels, and if average operating efficiencies (e.g. 80% to 90% for gas boilers) are taken into account, this means that roughly 60% of heating equipment in the global building stock today is fed by coal, oil or natural gas (Figure 3.12).

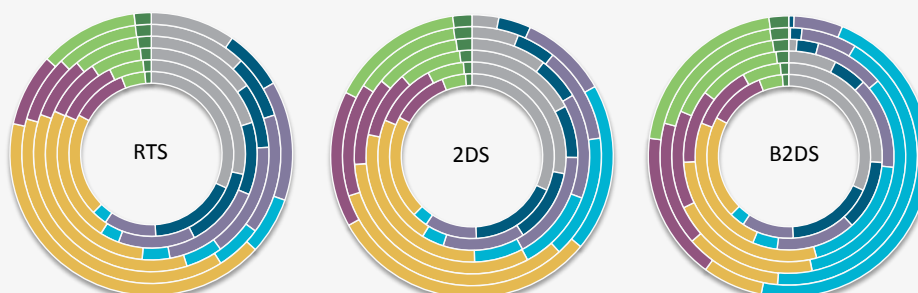
Coal and oil boilers, while still common in certain regions, such as China, Eastern Europe and certain parts of the United States, have increasingly been phased out over the last two decades, as many buildings have shifted to gas boilers (providing around one-third of final energy demand for heating in 2014) and electricity (providing around 10% of final energy demand for heating in 2014). Less common have been shifts to renewable technologies, such as efficient biomass³² (e.g. pellet stoves) and solar thermal heating, although some regions have made exceptional progress in recent years. For instance, use of solar thermal equipment in buildings has doubled in China since 2010.³³

Figure

3.12. Evolution of heating equipment in buildings to 2060

Inner to outer ring

2014
2020
2030
2040
2050
2060



■ Coal and oil boilers ■ Gas boilers ■ Efficient gas technologies ■ Heat pumps
■ Electric resistance ■ District heat ■ Solar thermal ■ Efficient biomass

Notes: Heating in buildings represents space and water heating; it excludes cooking and other end uses. Efficient gas technologies include gas condensing boilers, gas instantaneous equipment and gas heat pumps. Traditional use of solid biomass is not included.

Key point

The B2DS represents a strategic shift away from fossil fuel equipment to high-efficiency and renewable technologies, such as heat pumps, solar thermal and modern district energy.

30. Further information can be found at www.cleanenergyministerial.org/Our-Work/Initiatives/Energy-Access.

31. Further information can be found at www.efficiency4access.org/about/.

32. Efficient biomass heaters, such as high-performance fireplaces, masonry stoves and pellet stoves, can achieve burn efficiencies of as much as 90% or more, while maintaining high temperatures over long periods of time (IEA, 2013b).

33. Despite significant growth over the last decade, the rate of new installations of solar thermal technology in buildings has slowed down in the last two years due to less rapid growth in China. See Chapter 2, "Tracking clean energy progress".

Gas condensing boilers are also increasingly common in many regions, representing an estimated 10% of global equipment stock for heating purposes in 2014. MEPS, including policies mandating condensing boilers for gas equipment in some countries, and various market incentives have helped to shift demand away from less efficient conventional boilers over the last decade to much higher efficiency gas condensing technologies. These trends, particularly towards gas-driven heating equipment in critical heat markets such as Europe, the United States, Canada, Russia and the Caspian region, are likely to continue to 2060 in the RTS. Under this scenario, gas-based equipment still accounts for 40% of global final energy demand for heat in 2060 (or 30% of installed heating equipment when product efficiencies are taken into account). Even in the 2DS, fossil fuel use, notably including gas condensing boilers for heating in buildings, still represents one-quarter of final energy demand (or 17% of total installed equipment) for space and water heating in 2060.

By contrast, fossil fuel use in buildings under the B2DS effectively decreases to around 10% of total final energy demand for heating purposes (or 6% of installed equipment) in 2060, where very high-efficiency gas technologies (e.g. gas heat pumps) account for nearly all of remaining fossil fuel heating technologies in the buildings stock by 2060. Similarly, nearly all electric resistance heating under the B2DS to 2060 shifts to high-performance technologies, including in particular electric heat pumps, as well as some instantaneous water heaters where applicable (notably avoiding storage losses).³⁴ Electric heat pumps increase from roughly 3% of installed heating equipment in buildings today to nearly 50% of the total heating stock in 2060. At the same time, the average energy performance of heat pumps in buildings, with COPs of around 2 to 2.5 today, doubles by 2060 to achieve average COPs of 4 to 4.5 or greater.

The share of demand for heat provided by district energy and renewables also increases significantly by 2060 under the B2DS. While the share of commercial heat for heating purposes in buildings increases only marginally to 2060 in the 2DS (due to a lack of incentives to develop markets and a shift away from natural gas), it increases by 50% under the B2DS, thanks to favourable market conditions (e.g. incentives for excess heat recovery and energy balancing with variable renewable energy) that encourage the development of energy-efficient, renewable and integrated district energy solutions. The shift to integrated district energy solutions in the B2DS also allows for greater flexibility across the broader energy system, including better demand-side management (e.g. dynamic control of heat demand, network pressure and distribution temperatures), which subsequently support clear power generation and the inclusion of multiple energy-efficient and renewable heat sources in the energy system.

At the same time, solar thermal markets, including increased deployment of solar cooling solutions,³⁵ also surge under the B2DS, accounting for one-quarter of final energy consumption for heating purposes in 2060 (compared with 2% today and only 16% in the 2DS), or roughly 21% of total installed heating equipment. In particular, uptake of solar thermal solutions for water heating demand in buildings increases sixfold under the B2DS to 2060, where technology leaps directly to solar thermal technology as households gain greater access to modern energy in developing countries. This helps to avoid nearly 65 EJ of fossil fuel and electricity demand growth (cumulative) compared with the RTS. For this to happen, the cost of solar thermal systems (including, in particular, installation and maintenance costs) would need to come down by as much as 40% or more (IEA, 2016d).³⁶

Several challenges stand in the way of a shift away from fossil fuel equipment in buildings, including the need for affordable access to energy in developing countries and the global need to simultaneously improve building envelope performance with properly sized heating and cooling equipment (IEA, 2013b). Capital expense is also a common barrier, with oil

34. Instantaneous water heaters can reduce storage losses compared with traditional water heaters with a storage tank (e.g. for small bathrooms or kitchen sinks); however, widespread use of instantaneous water heaters can also place greater stress on the electricity grid and power generation during peak demand hours (e.g. showering in the early morning). Heat pump water heaters with storage tanks can not only significantly improve the operational efficiency of hot water production, but also allow for demand-side response with respect to electricity production (e.g. from variable renewable electricity).

35. Solar cooling represents 3% of TFECS for space cooling in 2060 under the B2DS (a 75% increase compared with the RTS), or roughly 15% of total installed cooling equipment in 2060.

36. Task 54 of the Solar Heating and Cooling (SHC) TCP is looking at ways to drive down the cost of solar thermal systems by as much as 40%. For further information, see <http://task54.iea-shc.org/>.

and gas boilers being some of the least expensive heating equipment choices (excluding electric resistance heaters) from an upfront investment perspective. Distributive infrastructure (e.g. piping and radiators), space limitations (especially in dense urban environments) and building attributes (e.g. solar exposure) can also be challenges to shifting away from fossil fuels. Efficient, renewable technologies (e.g. air-to-water and water-to-water heat pumps for water heating and distribution) may be technically viable alternatives to replace fossil fuel equipment, but those solutions are often more expensive (in upfront costs) and can require investment beyond equipment replacement (e.g. retrofitting piping and radiators to allow for lower temperature heat distribution).

R&D can help to bring forward high-performance, low-carbon technology solutions as replacements for fossil fuel equipment in buildings at lower upfront and life-cycle costs. Relevant initiatives include efforts led by the IEA HPT TCP on heat pump technologies for multifamily residential buildings, and the IEA SHC TCP on building-integrated solar envelope systems.³⁷ At the same time, R&D and energy policy strategies to shift buildings away from fossil fuel use should also take into account consumer preference (e.g. the desire for instantaneous heat)³⁸ and familiarity with products, which can have considerable influence on technology choice. This would entail not only looking at the performance of target technology, such as improved response to instantaneous heat demand, but also providing better insight into end-user decision-making processes and consumer familiarity with, and comfort using, alternative energy technology solutions as replacements for well-known fossil fuel equipment in buildings.

To achieve a deep decarbonisation strategy in the global buildings sector, the B2DS proposes a long-term strategy to shift away from fossil fuels by 2060, in particular including transitions away from natural gas demand in buildings in comparison with the 2DS. This three-pronged approach – to avoid first, then shift and finally improve fossil fuel use in buildings – centres around investment decisions that can be taken over the next 20 to 30 years to progressively move the global buildings sector away from coal, oil and natural gas. It also takes into account the simultaneous need to properly co-ordinate and facilitate investments in energy supply (e.g. natural gas and district energy networks) to avoid stranded assets and unnecessary or costly investments, including those targeted towards energy access in developing countries.

Avoiding growth in new demand: energy planning and policies to avoid growth in fossil fuel demand should be vigorously pursued to avoid locking in new carbon-intensive assets, especially in markets where costly capital infrastructure (e.g. natural gas networks) have not already been built. For new buildings additions, and in emerging markets in particular, effort should be placed on deploying high-efficiency, renewable and integrated energy solutions such as heat pumps, solar thermal technologies and efficient, low-carbon district energy, to avoid development of long-lived capital investments in gas networks and fossil fuel equipment in buildings. Particular support, such as the Global LEAP and efforts under Sustainable Energy for All,³⁹ would be needed to provide inexpensive, energy-efficient and renewable technologies in developing countries, where affordable access to clean energy will be crucial to ensure a carbon-neutral transition away from traditional use of solid biomass. Potentially suitable technologies include solar PV with LED lighting and high-efficiency cooling equipment.

In markets with existing large gas infrastructure, new capital investments should be avoided when possible to prevent lock-in or stranding of long-lived assets. Any existing capital measures, such as network replacement, should be co-ordinated with long-term strategies and integrated solutions to significantly reduce demand for natural gas by 2060. This could entail the use of heat mapping and energy community planning, and the sustainable local production of biogas or hydrogen. This would require instituting a clear vision for fossil fuel use in buildings and across the broader energy sector,

37. Further information on the SHC TCP and ongoing tasks can be found at www.iea-shc.org.

38. Historically, one market hurdle for heat pumping and solar thermal technologies has been limited ability to meet calls for large quantities of immediate heat, where boiler technologies are able to burn fuel to instantaneously produce additional heat. Technology solutions, such as heat pump pairing with small electric resistance units to meet short-term heat demand, do exist, and R&D focusing on improved product solutions for heat pumps and solar thermal is ongoing.

39. Further information can be found at www.se4all.org.

including strong engagement of stakeholders from both the energy supply and demand industries to ensure that actions and investments continue to meet energy needs in buildings, including demand for thermal comfort and affordable heat.

Shifting existing demand over time: large potential exists to shift existing heat demand away from fossil fuels to district energy networks, heat pumps and solar water heating, as carbon-intensive assets in buildings come to the natural end of their product life cycle. In order for this to happen smoothly, strategic co-ordination of actors and technology solutions would be needed to ensure that policies and market frameworks are in place when fossil fuel assets are replaced (see Box 3.6 on strategic plans to shift buildings away from natural gas in the Netherlands). This would most likely necessitate planning across larger energy communities, where effective, affordable solutions for shifting buildings energy demand away from gas may have implications beyond a single building. For instance, it may be more competitive, in terms of cost-effectiveness and total energy and emissions reduction, to convert entire neighbourhoods to district heat to meet necessary heat densities and avoid expensive gas delivery to a few remaining buildings.

Box

3.6. Strategic plans to shift away from natural gas in Dutch buildings

Natural gas is a major part of the Dutch energy economy, representing nearly a third of final energy consumption in the Netherlands and more than 60% of final energy use in buildings. In December 2016, the Ministry of Economic Affairs issued an energy agenda that outlined the main features of future energy policy in the Netherlands to 2050, including the objective to reduce CO₂ emissions by 80% to 95% by 2050 (MEA, 2016).

In the buildings sector, government efforts to reduce CO₂ emissions from gas consumption have focused on two key pillars: energy conservation in buildings (e.g. improved envelope) and a drastic reduction in natural gas demand by stimulating and accommodating low-carbon electricity and heat solutions, including district heat. In principle, no new gas infrastructure will be constructed (the Gas Act will be amended accordingly) and ambitious plans in several Dutch cities, such as Amsterdam, Rotterdam and Utrecht, have already proposed measures to roll out district heat solutions to shift buildings away from gas.

The city of Amsterdam, which has set an ambitious target to be natural gas-free by 2050, already has several large and small district heat networks, which are connected to various heat sources, such as a waste-to-energy facility. The municipality aims to build out the heat network and increase the number of connected buildings from 72 000 (2015) to 230 000 in 2040 (Municipality of Amsterdam, 2015, 2016). This includes a strategic roll-out plan that is engaging various stakeholders, such as companies, tenants, energy producers and network operators, to ensure the network is affordable, sustainable and accessible to different heat producers, including renewable energy sources such as geothermal and large-scale thermal solar energy. Additional measures include agreements with housing associations to improve the energy efficiency of the buildings stock – a critical element in achieving high-efficiency, low-carbon district heat using low distribution temperatures.

The transition to a natural gas-free city in Amsterdam is estimated to cost 5 billion euros (EUR) to EUR 6 billion. This includes investment in buildings installations, modifications to energy networks, and measures to produce sustainable heat and to capture excess and renewable heat. Most investment will be borne by property owners, network owners and operators, and energy companies. The city will also contribute through subsidies and network development.

Improving equipment efficiency and gas supply: in instances where gas-based equipment makes sense with respect to long-term energy planning and decarbonisation strategies, energy efficiency measures should be a first-order priority, moving minimally in the coming decade to gas condensing boilers, if not higher-performance gas heat pump technology.

Under long-term decarbonisation strategies, R&D efforts and strategic plans for remaining gas infrastructure should focus on bringing to market very high-performance gas or gas-replacing technologies, including higher performance and more affordable gas heat pump technologies, micro co-generation, and hydrogen and fuel cell technologies.⁴⁰ The latter would require greater R&D and considerable market support, such as the large-scale fuel cell demonstration and commercialisation programme in Japan (ENE-FARM),⁴¹ to bring to market efficient and affordable fuel cell technologies for buildings applications. The first fuel cell system in a residential application was introduced in 2009, and under the ENE-FARM initiative (with government subsidies) as many as 196 000 units have been deployed since then, including around 40 000 units sold in 2016 (Maruta, 2016).

Under an “improve” strategy, additional efforts would also be needed to improve the carbon intensity of gas supply to buildings, including the use of biogas and even eventually sources such as hydrogen using methanation with CCS. Demonstration projects already exist today – for instance, injection of hydrogen in natural gas in northern France (Engie, 2016) – but greater planning and development strategies would be needed for similar solutions, particularly as the transition away from natural gas may require additional investment in energy supply and distribution infrastructure (see Box 3.7 on hydrogen deployment potential in the United Kingdom). Such investment should also be considered with respect to long-term energy planning and decarbonisation strategies to ensure they are economically viable and fit within the needs of the broader energy economy.

Within a B2DS framework to decarbonise energy demand in buildings, improve strategies would need to appropriately consider interim measures and the effect that short- to medium-term investment and technology choice would have on achieving a long-term transition away from fossil fuels. For example, natural gas networks in many regions still have a long useful life, so investment in gas-based equipment in those areas may be warranted with respect to demand densities and energy supply planning. While energy efficiency should be a first-order priority, decisions should also assess the compromises between greater investment in the efficiency of the gas equipment as against a lesser efficiency improvement at smaller investment cost that could be retired or replaced earlier with a low-carbon solution.

As transitions away from fossil fuel use in buildings would require long-term strategic thinking and co-ordination, governments should set forth clear expectations on buildings energy performance and carbon intensity to engage stakeholders on a B2DS pathway, especially given the long life of buildings sector and energy distribution assets. In the short term, energy mapping, carbon targets and local technology demonstrations such as the H21 project in the United Kingdom can help to identify and bring forward effective and affordable solutions for decarbonised heat in buildings.

Yet far larger market scale for high-performance technologies and buildings solutions is needed to shift the massive buildings market away from fossil fuel consumption. This would require setting clear policies for future investment (e.g. prohibiting fossil fuel equipment in new construction), establishing assertive market frameworks (e.g. upfront incentives and long-term performance thresholds) to shift buildings investment away from fossil fuel, and finally working across buildings stakeholders (e.g. natural gas and district heat networks) to find appropriate solutions to meeting low-carbon heat demand in buildings.

Buildings energy performance should also be addressed at the forefront of strategic thinking for a low-carbon energy economy, as building energy efficiency measures and long-lived buildings assets will influence the effectiveness and affordability of energy supply investment. Greater importance should be placed on buildings as part of broader energy communities, and national policies should seek to enable local planning and policy design that support widespread development of high-efficiency, renewable and integrated energy solutions (IEA, 2016b).

40. *Co-generation* refers to the combined production of heat and power.

41. Further information on ENE-FARM can be found at www.j-lpgas.gr.jp/en/appliances/; information on Japan’s strategic roadmap for hydrogen and fuel cells can be found at www.meti.go.jp/english/press/2016/0322_05.html.

Box

3.7. Hydrogen energy deployment demonstration in Leeds (United Kingdom)

Natural gas accounts for nearly 60% of TFEC in buildings in the United Kingdom and nearly 75% of buildings energy consumption for space and water heating. Significant effort will be needed to shift buildings away from natural gas use if the country is to meet its 2050 targets to reduce emissions by at least 80% from 1990 levels by 2050 (CCC, 2015).

The H21 project in Leeds is one initiative looking to demonstrate the potential for hydrogen to reduce the CO₂ intensity of heat demand in buildings, where around 95% of households in the region use natural gas for space and water heating and cooking (BEIS, 2015). Globally, a number of technological, cost and infrastructural barriers have deterred the deployment of hydrogen as a low-carbon energy solution, and the H21 project looks to address those challenges using market-ready hydrogen techniques (steam methane reformers) with CCS. The recovered steam from hydrogen production and CCS could reduce the CO₂ intensity of heat from 184 grammes per kilowatt hour (g/kWh) for natural gas to 27 g/kWh for hydrogen (NGN, 2016).*

The H21 project will require a suitable transmission grid. The gas distribution industry in the United Kingdom is already upgrading gas mains from ageing cast-iron pipes to polyethylene replacements (which are hydrogen-suitable). The project proposal also includes connection to geological hydrogen storage, using salt caverns in the region. This will provide flexibility to meet peak demand and to offset seasonal fluctuation in heat demand.

Several additional steps are needed to achieve the objectives of the H21 project, including hydrogen-ready designs and standards for buildings equipment. This will add cost and complexity to conversion of gas equipment, where the average cost per building is estimated at around 3 000 British pounds. The technical and environmental effectiveness of the H21 project will also depend on the UK government's decision to support CCS. Additional business risks include other low-carbon energy sources (e.g. biogas), if they can gain access to the hydrogen infrastructure at competitive prices.

The success of the H21 programme will depend on multiple drivers, including in particular the long-term costs to consumers, the effective communication and management of a transition to hydrogen-compatible equipment in buildings, and the sustainable production of hydrogen. If successful, the Leeds project will help to demonstrate the potential to enable a hydrogen-based energy transition in the United Kingdom.

* Further information can be found at www.northerngasnetworks.co.uk/archives/document/h21-leeds-city-gate.

Note: James Brass, Stephen Hall and Alice Owen (all from the Sustainability Research Institute at the University of Leeds) provided substantive input into Box 3.7.

Building energy communities and low-carbon synergies

The avoid, shift and improve approach identified in the B2DS underscores the need for integrated energy planning to identify strategies and opportunities to achieve very low-carbon buildings by 2060. A strategic shift away from fossil fuels would require an in-depth look at potential synergies across energy supply and demand to achieve affordable, low-carbon heating and cooling solutions for buildings. Such synergies could include the capture of peak renewable power using heat pump technologies, thermal energy storage and district energy networks to supply efficient, low-carbon heat to buildings. This process includes considering buildings within the broader context of local and regional energy communities, where cost-effective, low-carbon synergies often depend on attaining a scale and density of supply and demand.

Multiple opportunities exist to meet heating and cooling demand in buildings, including advanced district energy systems that can take advantage of multiple energy opportunities

across an integrated energy network, notably by providing enhanced flexibility to the energy system as a whole (see Box 3.8 on advanced and integrated district energy solutions). Modern, efficient building energy communities can be intelligently framed to accommodate integration of various renewable energy sources, excess heat and dynamic demand in buildings, which may not be possible or can be cost-prohibitive in singular building applications. Advanced energy networks can even pair heating and cooling services to increase the net efficiency and flexibility of the entire energy system, for example by augmenting district heat for water heating by capturing heat in district cooling return lines.

Box

3.8. Advanced district energy solutions for energy-efficient, low-carbon communities

Future energy systems will require increased integration of infrastructure to accommodate a changing energy network that includes more dynamic interactions between supply and demand, including greater levels of renewable energy sources and variable heating and electricity demands. Market economics and the need for operational efficiency have already led energy companies to focus on novel and improved approaches to meeting demand reliably and affordably in modern energy networks that are exposed to limitations (or even excesses) in energy supply (e.g. intermittent renewables).

Modern district energy networks can play an important role in achieving energy-efficient and low-carbon energy communities, serving as a flexible and efficient medium in a changing energy landscape. This includes the ability to accept heat from a wide range of sources, including excess heat from industry and variable renewables, using both short- and long-term storage and advanced district energy solutions (e.g. low-temperature heat). Advanced district energy systems can also take advantage of multiple synergies in energy networks, such as heat exchanges between cooling services and hot water supply across multiple buildings, to improve the net efficiency and reliability of the energy system.

The IEA TCP for District Heating and Cooling (DHC) including Combined Heat and Power is a co-operative platform across ten countries in Europe, North America and Asia, with two further countries in the process of becoming members. The DHC TCP aims to advance innovation in, and improve the economics for, district energy solutions and technologies, including multiple programmes of research, development and demonstration (called annexes) addressing the role of DHC and co-generation in achieving sustainable energy communities.

Much of the DHC TCP's work has focused on achieving an optimal match between energy supply and demand. For instance, Annex X looked at economic and design optimisation to integrate renewable energy and excess heat into district energy systems. Annex TS1 on Low Temperature District Heating for Future Energy Systems continued this work. It identified comprehensive, innovative approaches to energy-efficient buildings and their related supply streams as one integrated system that maximises synergies at the community scale. Annex XI (due to conclude in mid-2017) also has an initiative for a transformation roadmap to similarly improve existing district energy systems through evolutions towards lower-temperature operation.

The DHC TCP is preparing its next programme of work for 2017 to 2020, with a call for proposals for research areas addressing a broad range of topics for advanced district energy solutions, including work on system operation and asset management, as well as on cooling technologies. Further information on the TCP can be found at www.iea-dhc.org.

Building energy efficiency measures, including building envelope improvements, across local energy communities will have an important role in achieving cost-effectiveness in energy supply choices. For instance, deep energy renovations allow for lower-temperature heat distribution to maintain the same (or improved) thermal comfort. Pursued across multiple buildings in an energy network, those improvements would allow for lower-

temperature distribution (and production) of heat, which can also allow for integration of low-grade heat sources such as industrial excess heat and renewable energy. Yet such improvements would need to be undertaken at the right scale (e.g. an entire neighbourhood) to ensure the investment is cost-effective for the energy network.

Action at the buildings community level (e.g. deep energy renovations across entire building blocks) can also help to lower the cost of both energy efficiency measures and sustainable energy supply, by creating sufficient economies of scale to attract participation of key stakeholders (e.g. builders and product manufacturers). Without such market scale, buildings-related stakeholders may not be sufficiently interested in developing improvement packages and energy solutions for only a small number of buildings (IEA, 2016b).

Economies of scale can also be applied across building energy communities to take advantage of changing energy flows through better management and optimisation of energy loads in buildings. For example, a pilot project in Gothenburg, Sweden, has applied short-term thermal energy storage (using simple thermal inertia in buildings) across several multifamily residential buildings to manage heat demand more effectively. By periodically slightly overheating or underheating (i.e. less than $\pm 0.5^{\circ}\text{C}$) the buildings relative to energy demand and supply within the district heat network, buildings heat loads can be shifted relative to peak periods of demand (e.g. in the morning when customers take showers). Those slight shifts could decrease heat load variation by as much as 50%, thereby reducing the need for peak (often fossil fuel-based) heat generation in the network (Kensby, 2015).

Under a B2DS pathway, energy-efficient buildings will play an important role in meeting energy sustainability objectives. Energy demand response and management (e.g. connected heat pumps and smart appliances) can be used with various market tools (e.g. peak pricing) to better manage buildings loads and energy demand (see Chapter 6 on smart grids and demand-side management). Energy storage technologies, from hot water storage tanks to battery storage and advanced technologies such as thermochemical storage, can also play a strong role in achieving more effective management of energy demand across the broader energy economy (see Box 3.9 on flexible energy storage solutions to better manage energy supply and demand loads).

Continued support for R&D can help to bring about advanced technology solutions for integrated building energy communities, including advanced and high-efficiency district energy networks, as well as intelligent buildings that are more capable of responding to buildings energy needs with respect to variations in local energy supply. Additional work is needed to address policy and market barriers that typically treat buildings, district energy and power generation separately (IEA, 2014b). This includes valuing energy efficiency and flexibility across supply, distribution and end-use demand through energy policy frameworks that encourage advanced technology solutions and innovative business models (e.g. energy service companies that offer and manage building energy efficiency solutions alongside low-carbon and renewable heat supply).

Efforts to integrate building energy standards and energy supply models under a community energy plan can supplement and support long-term sustainable energy strategies. Achieving energy-efficient, low-carbon building energy communities will require proper planning and co-ordination over periods that are long enough to engage stakeholders and allow for economically viable capital investment. Energy policies and programmes can support this process through multiple measures, including:

- Rewarding flexibility, energy efficiency and low-carbon technology solutions within energy policy frameworks
- Supporting the development of smart business models that increase opportunities for high energy performance and low-carbon footprints across energy communities (e.g. open DHC models that encourage synergies across local energy networks)
- Bringing forward cost-effective, integrated and smart DHC solutions through continued R&D and demonstration projects
- Co-ordinating development of local, regional and national energy infrastructure plans that consider buildings within the framework of energy network strategies

- Sharing experience and best practices that enable sustainable solutions and business mechanisms to meet the needs of an increasingly complex and highly interconnected energy system.

The challenge of transforming buildings networks and achieving high-efficiency, low-carbon energy communities over the next 40 years is not insurmountable. It will require engagement of diverse stakeholders and deployment of multiple technology solutions that are capable of managing and accommodating a modern, flexible energy system. Given the right incentives and favourable market conditions – through planning and policies that push markets away from inefficient, carbon-intensive assets and pull them towards high-performance, carbon-neutral investments – smart, sustainable building energy communities can play a key role in meeting B2DS ambitions.

Box

3.9. Energy storage solutions to manage peak loads and improve system efficiencies

The coming decades will see a rapid increase in production of variable and renewable energy in and around buildings. Matching weather-, season- and climate-dependent sources of energy with the variable demand profiles of the built environment will require new approaches and better management of energy resources to ensure system reliability and efficiency.

Energy storage and flexibility capacity will play an increasingly important role in balancing energy supply and demand. This can be through large, central energy storage technologies, such as pumped hydropower and conversion of surplus electricity into thermal energy storage or hydrogen by electrolysis. Distributed energy storage, such as battery and local thermal energy storage, can also support a growing need for decentralised energy solutions.

The IEA TCP on Energy Conservation through Energy Storage (ECES) includes multiple research and co-ordination activities that consider the development, implementation and integration of energy storage technologies in a changing, more dynamic energy system. Annex 28, for example, is looking at the potential of small to medium-sized distributed energy storage technologies that can balance fluctuation caused by renewable energy. Annex 29 is considering innovative thermal energy technologies (e.g. phase-change materials or thermochemical storage) for compact thermal storage applications to balance on-site renewable energy production with domestic demand (e.g. for water heating).

Additional ECES research addresses energy storage at the district level and the potential for passive thermal energy storage in buildings materials and components (Annex 31). Phase-change materials used in passive systems could increase the energy efficiency of heating and cooling in buildings by controlling indoor temperature and benefiting from solar radiation.

New insights into distributed energy and energy storage will require better input into design and evaluation models. A new ECES annex will address how to incorporate storage aspects in current energy models and optimise operating modes from a more integral assessment of energy systems. Further information on the ECES can be found at <https://iea-ec.es.org/>.

Buildings sector investment needs

Global buildings investment, including buildings construction and envelope measures,⁴² was estimated at nearly USD 6 trillion in 2014, or roughly 5% of global gross domestic product (GDP). Investment in buildings construction (including new buildings and energy renovation

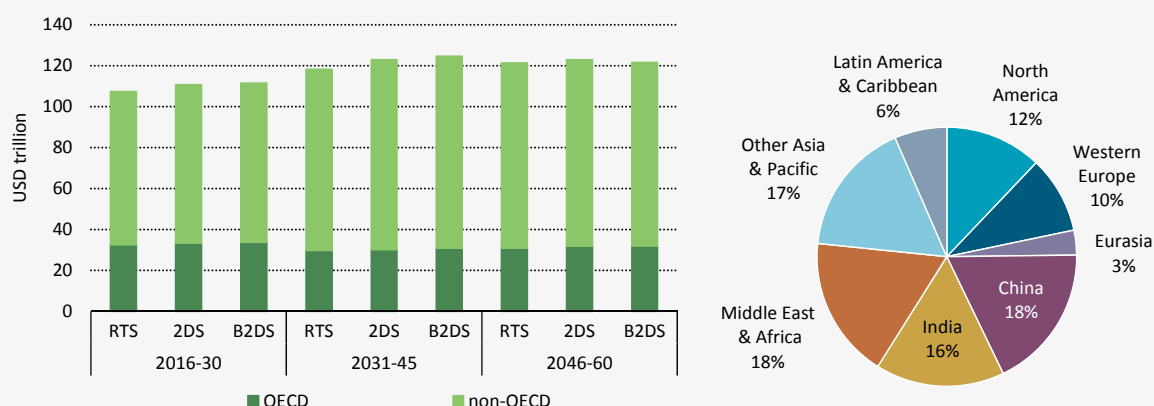
42. Building infrastructure investment estimates (e.g. construction of buildings and energy-related renovation measures for existing building envelopes, such as window replacement and improved insulation) have been included in this *ETP 2017* assessment, whereas in previous editions they were not included.

measures for existing building envelopes, excluding heating, cooling and ventilation equipment) represented two-thirds of that estimated investment, or around USD 4 trillion. The remainder comprised investment in buildings equipment and appliances, including lighting, appliances, and heating and cooling equipment.

Under the RTS, buildings sector investment continues to represent around 5% of global GDP to 2060, where continued rapid growth in emerging economies over the next two decades drives investment to a higher average share of GDP in non-OECD countries relative to more consistent growth in OECD countries (Figure 3.13). Overall, annual average investment in buildings under the RTS grows to nearly USD 8 trillion in 2060, or around USD 340 trillion in cumulative investment to 2060. Buildings construction and envelope measures continue to account for two-thirds of the total, where the largest share (nearly 70%) is driven by growth in non-OECD countries.

Figure

3.13. Buildings investment to 2060 and share of total B2DS investment by key region



Key point

Buildings investment in the B2DS represents nearly USD 11 trillion in cumulative investment beyond the RTS, but continued R&D and larger economies of scale help to drive down the costs for high-performance, energy-efficient and renewable technologies to 2060.

Investment under the B2DS similarly reaches nearly USD 8 trillion in 2060. The difference lies in short- and medium-term expenses (e.g. rapid upfront energy efficiency investments), which could exceed RTS levels by 7% and lead to nearly USD 11 trillion more in cumulative investment to 2060 (or nearly USD 1.5 trillion more than under the 2DS). Investment related to envelope performance improvements, driven by the sharp uptake of nZEBs, high-performance buildings construction and deep energy renovations of existing buildings, also increases considerably and peaks at around USD 5.5 trillion in 2030. By 2030, however, the incremental cost for those high-performance construction and deep energy renovation measures starts to decrease, due to greater economies of scale and continued R&D driving more affordable, high-efficiency building envelope technologies and solutions. As a result, annual investment in building envelope measures is nearly the same as it is in the RTS by 2050, when nZEBs and deep energy renovations are common and standard practice across all countries.

Investment in energy-efficient, renewable and integrated buildings technology solutions, including high-performance lighting, appliances, and heating and cooling equipment in buildings, is on average 90% higher in the B2DS compared with 2014 investment levels, reaching around USD 3 trillion in 2060, or USD 100 trillion in cumulative investments to 2060 (13% higher than the RTS and 3.5% more than the 2DS). Short- to medium-term costs are much higher than in the RTS, but large economies of scale in the B2DS, paired with continued incentives for R&D to bring to market high-efficiency and low-carbon buildings

equipment and energy-consuming products, help to reduce those incremental costs over time. For example, upfront costs for energy-efficient lighting technologies over the next decade would cost as much as USD 110 billion more than anticipated under the RTS. However, the rapid growth in market scale, paired with much longer lifetimes of energy-efficient SSL technologies, would not only help to bring down the upfront costs of LEDs, but also reduce B2DS lighting investment costs by as much as USD 7 billion a year post-2025 compared with the expected RTS investment.

Nearly three-quarters of total investment under the B2DS would occur in non-OECD countries, notably China (18%), India (16%), other developing Asia (13%), and the Middle East and Africa (18%), due to the strong growth in new buildings additions and expected purchases of energy-consuming equipment over the next 40 years. Driving markets to high-performance buildings construction and energy-efficient equipment and appliance investments would require strong policy signals and incentives in the coming decade, including possible subsidies and other financing mechanisms to deliver those investments at an affordable cost to consumers. However, the return on investment, especially for long-lived buildings assets, would have multiple benefits for developing countries. These include improved buildings quality and comfort (e.g. in hot climates), reductions in local air pollution (e.g. from lesser need for peak power generation using coal), and greater capacity to provide affordable and improved energy services with less burden on, and possibly lower investment needs for, power generation.

In OECD countries, upfront investment over the next decade will require strong incentives and possibly financial support to drive market scale, particularly to propel high-performance equipment purchases (e.g. LED lighting and high-efficiency appliances) and a major scaling up of deep building energy renovation. However, those energy-efficiency improvements will play a major role in supporting long-term market transformation to deliver lower upfront and life-cycle costs for high-performance buildings technologies and solutions (a major barrier to energy efficiency deployment in markets today), while also supporting the broader transition to a low-carbon, flexible and more efficient energy system.

Policy actions to support buildings sector decarbonisation

Capturing the enormous energy savings potential in the buildings sector will require immediate action to put the global buildings market on a sustainable pathway towards an energy-efficient, low-carbon future. This is especially true in emerging economies, where a critical window of opportunity exists to address rapid growth in buildings construction over the next 20 years.

Moving towards a B2DS would require swift and assertive policy action, starting first with improving adoption and enforcement of mandatory policies for low-energy buildings construction across all countries. Setting clear and consistent signals (including appropriate price signals and the phase-out of fossil fuel subsidies) to consumers, manufacturers and the buildings construction industry would be necessary to maximise investment in energy efficiency over the next 40 years and limit the need for costly changes in the future, especially given the long life of most buildings sector assets. Capacity building (including appropriate training for skilled labour in the buildings sector) and knowledge sharing across countries can help to speed this process up by ensuring that best buildings practices – including effective energy policy – are achieved as quickly as possible. This is particularly relevant for regions where building energy codes do not currently exist.

Deep energy renovation measures across the world's existing buildings stock would also be a critical item in the B2DS action agenda. A combination of regulatory measures (e.g. mandatory energy performance certificates), financing tools, market incentives, and training and capacity building can be applied in years to come to move the buildings and construction supply chains toward low-carbon, high-efficiency technologies and buildings solutions. These measures would need to be supported by long-term energy strategies for building energy performance and carbon intensity to avoid lock-in of new buildings assets

over the coming decades. Long-term energy strategies should also ensure that buildings are included in the context of the broader energy community.

Significant action is needed to expand existing policies and regulations for energy-consuming equipment in buildings. Labelling programmes and MEPS for major buildings equipment in particular (e.g. boilers, refrigerators, air conditioners and other major household appliances) should be expanded and strengthened as quickly as possible across all countries, pulling from extensive international experience and knowledge. MEPS and policy programmes should also aim to optimise the overall performance of heating, cooling and ventilation systems in buildings, moving beyond traditional regulation of equipment performance to address their overall operation and control (Box 3.2). Programme development, training and capacity building, and upfront financing are also needed to support the implementation and enforcement of best practices for those policies and programmes in developing countries, where the return on investment (from an energy savings perspective) is clearly justified by historical energy efficiency gains in the global buildings sector.

Global effort is also needed in the coming years to expand and strengthen energy performance policies across the vast majority of end-use equipment in buildings. International collaboration and co-operation on setting effective energy policy for small plug loads and networked devices in buildings should be pursued rigorously, as such equipment represents an increasingly important and rapidly growing share of electricity demand in the global buildings sector.

Over the coming decade, governments can also advance the adoption of energy-efficient and low-carbon buildings technologies through appropriate pilot programmes and market incentives. Policy packages include research, development and deployment strategies to bring to market high-performance buildings products at affordable prices, including the many R&D areas highlighted in this chapter. At the same time, lessons should be taken from previous experience in this field, for example with the effective but rather slow global effort to phase out incandescent lighting over the last ten years. Governments should work with manufacturers and buildings supply chains to encourage much faster widespread adoption of BATs and buildings energy services in coming years.

Additional effort will be needed to set forth a clear and consistent expectation on fossil fuel consumption in the buildings sector. A long-term vision and complementary energy strategy are needed to avoid new investment in fossil fuel equipment and infrastructure, while progressively shifting current fossil fuel assets in buildings to low-carbon, high-performance products over the coming decades. Effort is also needed to identify clear strategies for the most appropriate applications of existing fossil fuel networks in the future, including energy mapping and R&D for high-performance gas equipment and alternative supply delivery (e.g. hydrogen infrastructure). These should be considered within the broader energy context and ambitions to achieve a low-carbon, sustainable energy economy.

Future R&D strategies

The B2DS hinges on the rapid deployment of energy-efficient and low-carbon technologies in the global buildings sector. This includes energy policy measures and strategies to move markets quickly to the most efficient energy technologies on the market today (e.g. SSL, heat pumps and solar thermal technology). It also requires technology leapfrogging to bring high-performance products and best buildings practices to emerging markets where energy demand is expected to increase rapidly in the coming decades. The B2DS also considers the integration of energy solutions, including pairing of technologies (e.g. solar thermal, heat pumps and renewable heat with high-efficiency district energy networks) to leapfrog existing net efficiencies for buildings energy services and local energy communities.

The B2DS relies on strong energy performance and cost improvements in critical buildings technologies over the next 40 years, including a near doubling (or more) in average heat pump COPs and LED efficacy. It also requires much greater affordability in technology solutions for high-performance building envelopes, such as those outlined in the IEA *Technology Roadmap: Energy Efficient Building Envelopes* (IEA, 2013a). Market scale will help to drive this process by providing a greater incentive to manufacturers and industry to develop energy-efficient, low-carbon products and services in the global buildings sector. However, this will require complementarity in energy policy and market incentives to ensure

that market scale is achieved quickly. Governments will also need to support continued R&D to pull the market beyond today's BATs and bring about more efficient, innovative, and most importantly, affordable solutions to market in the future.

Innovations highlighted in the B2DS strategy as critical technology needs and opportunities include:

- Lower-cost high-performance building envelope components (e.g. advanced insulation, dynamic shading and highly insulated windows), and whole-building energy renovation measures that have negative life-cycle costs (i.e. positive economic returns relative to investment when energy savings are considered).
- High-performance heat pump solutions, including better responsiveness to heat demand (e.g. response time for temperature change) and better control of latent heat, for heating (e.g. COPs of at least 3.5 or more) and cooling (COPs of at least 4 or more) in buildings, including improved heat pump performance in harsh climates.
- Cost reductions of 40% or more in solar thermal technology for buildings, including in particular significant reductions in installation and maintenance costs.
- Advances beyond expected SSL efficacy (i.e. greater than 150 lm/W) at lower life-cycle costs, with advances in lighting service technologies (e.g. smart and connected lighting).
- Technology leaps in product performance of major household appliances (e.g. heat pump technology solutions for refrigerators, clothes washers and dryers).
- R&D to bring forward affordable energy storage solutions in buildings and across integrated energy communities.
- Advances in low-temperature distribution for district energy networks and improved business frameworks and costs for integrated building energy community solutions (e.g. building envelope measures paired with high-performance district energy networks).
- Development of advanced and clean energy technologies to improve heat demand in buildings, including high-performance gas heat pumps, hybrid heat pumps, fuel cells and hydrogen-ready equipment.
- Rapid progress on affordable clean energy technologies, including solar heating and cooling and low-carbon or low-energy cooking solutions, to improve energy access in developing countries and avoid shifts from traditional use of solid biomass to fossil fuels.

Policy implications for a B2DS buildings sector

High-performance buildings investment under the B2DS, while requiring highly ambitious and possibly unprecedented policy actions, would deliver a broad range of benefits. These include lower electricity and fuel expenses for businesses and households, greater reliability in meeting energy demand without costly infrastructure and vulnerability to grid disruption, and reductions in CO₂ emissions and other pollutants that pose a threat to human health.

To achieve the B2DS, long-term, strategic and aggressive policy action would be needed to promote building energy efficiency measures as a critical element to achieving a sustainable energy economy. This will require a broad range of energy policy and technology measures to ensure that energy efficiency is at the heart of buildings practices and investment globally (Table 3.1). Some of those measures, including the B2DS strategy to shift away from fossil fuel use in buildings, will require going above and beyond priorities already communicated in the 2DS. However, the energy savings and global emissions reduction potential relative to the net investment costs (marginally beyond the 2DS) suggest that pursuing a B2DS strategy in the buildings sector would have multiple benefits, while at the same time ensuring a much higher probability of achieving 2DS ambitions.

Table 3.1. Buildings technology and policy ambitions in the B2DS

Action area	Near-term action to 2025	Long-term ambitions to 2060
Whole buildings	Enforce building energy codes in all regions and strive for nZEBs in new construction. Work with rapidly emerging economies to share best practices and implement efficiency energy policy. Establish policies and market incentives to drive deployment and adoption of deep energy renovation in existing buildings.	Develop advanced building energy codes across all countries with high energy performance standards (e.g. nZEBs or better) for all new construction. Establish clear energy performance targets for existing buildings and work with manufacturers to increase availability of efficiency measures at affordable prices.
Building envelopes	Promote very high-performance envelopes and envelope components, including air sealing, insulation, highly insulating windows and cool roofs. Include requirements for building envelopes in mandatory building energy codes.	Achieve highly insulated, integrated building envelopes (e.g. nZEBs or better) at negative life-cycle cost. Mandate minimum energy performance for building envelope components through enforceable building energy codes.
Space heating	Increase promotion of solar thermal and heat pump technologies. Improve thermal distribution and control systems. Mandate condensing boiler technology for fossil fuel equipment and set clear vision to move to MEPS above 120% efficiency for heating equipment by 2025. Support development of integrated and high-efficiency district energy solutions, including more responsive thermal energy storage in buildings.	Mandate MEPS above 150% for stand-alone heating equipment. Prohibit the use of electric resistance heaters as main heating source in buildings. Prevent expansion of fossil fuel heating and pursue strategic vision to shift demand to high-efficiency and integrated energy solutions with net-zero emissions through energy planning and heat mapping.
Space cooling	Mandate MEPS of 350% efficiency or higher for cooling equipment. Improve thermal distribution and control systems. Pursue high-efficiency district energy solutions where appropriate.	Pursue low-cost solar cooling technologies and require minimum performance above 400% efficiency for cooling equipment.
Water heating	Encourage uptake of heat pump and solar thermal water heaters. Continue R&D on low-cost solar thermal systems. Support development of integrated and high-efficiency district energy solutions with thermal energy storage to improve demand-side response and reduce peak energy loads.	Mandate MEPS greater than 150% efficiency for electric equipment. Achieve affordable thermal storage and increasingly cost-effective solar thermal systems suitable for different climates and regions.
Lighting	Ban all traditional incandescent and halogen light bulbs. Continue R&D and promotion of SSL and support other innovative designs for high-efficiency lighting services in buildings.	Implement minimum lighting energy performance criteria above 120 lm/W. Work with manufacturers to ensure product reliability and to improve SSL efficiencies.
Appliances	Mandate MEPS for major household appliances across all countries. Work on setting forth standards for plug loads in buildings.	Bring to market high-efficiency appliance technologies and mandate MEPS for electric plug loads. Set energy performance standards for networked energy consumption.
Cooking	Work across countries to achieve clean, affordable and energy-efficient cooking solutions.	Support R&D to bring to market high-efficiency cooking technologies at affordable prices.

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Chapter 4



Advancing the low-carbon transition in industry

Industry plays a critical role in the energy system. In 2014, it accounted for more than a third of final energy consumption and about a quarter of energy-related carbon dioxide (CO₂) emissions worldwide. The challenges of decoupling expanding industrial production from CO₂ emissions require significant improvements in material and energy efficiency, deployment of best available technologies (BATs), shifts to lower-carbon fuels and feedstocks, and rapid deployment of innovative technologies, including carbon capture and storage (CCS). Reaching the 2°C Scenario (2DS) pathway, and going beyond, would require collaborative efforts across industrial sectors and regions to decrease energy and CO₂ emissions impacts.

Key findings

- **Energy-intensive industries represent a significant portion of global energy use and CO₂ emissions.** Final energy use in the industry sector represented 38% of global total energy consumption and 24% of CO₂ emissions in 2014, reaching 154 exajoules (EJ) and 8.3 gigatonnes (Gt) of direct CO₂ emissions. Among the energy end-use sectors, industry is the largest consumer of coal (60% of world final coal consumption) and the second-largest consumer of oil products (28%).
- **Countries' deep decarbonisation targets underscore the importance of reducing CO₂ emissions from industry.** Annual direct CO₂ emissions from the industry sector are halved by 2060 in the 2DS compared with the Reference Technology Scenario (RTS). In the Beyond 2°C Scenario (B2DS), industry needs to further reduce its carbon emissions to 80% below RTS by 2060 to contribute to system-level carbon neutrality. Similarly, energy consumption growth must be limited to 0.3% annually in the 2DS and 0.2% per year in the B2DS, compared with the 2.9% annual increase in the 2000-14 period. These energy and CO₂ reductions are based on shifts to BAT, energy and material efficiency improvements, switching to lower-carbon fuels and feedstocks, and widespread deployment of CCS and innovative process technologies.
- **In the 2DS, 55% of cumulative direct CO₂ emissions reductions in the industry sector compared with the RTS hinge on deployment of BAT and energy efficiency.** About 19% of the cumulative emissions reductions depend on processes that are not yet commercially available and that require additional research, development and demonstration investment. Progress in both, energy efficiency and BAT deployment, as well as innovation in low-carbon options over the next decade, is crucial to enable commercial availability and their widespread deployment.

- **The tremendously challenging B2DS would rely even more heavily on innovative technologies, including CCS, which account for 42% of cumulative emissions reductions.** Energy efficiency and BAT deployment remain critical, however, with 37% of CO₂ emissions reductions.
- **Reaching a significant cut in direct CO₂ emissions from industry would require global effort.** While Organisation for Economic Co-operation and Development (OECD) countries have a relevant role in deploying and transferring innovative technologies for industry, 86% of the global cumulative direct CO₂ emissions reductions by 2060 in the B2DS are from non-OECD countries where faster-growing material demand prospects, new capacity installations and growing importance in world markets increase the potential to widely deploy innovative industrial process technologies.
- **Of the total investment required for energy-intensive industry in the 2017–60 period in the B2DS, 34% needs to be made before 2030.** Early action prevents the lock-in of inefficient technologies in industrial capacity additions and avoids additional investments in low-carbon process technologies in the long term. The B2DS investment costs are 11% higher than in the 2DS.

Opportunities for policy action

- Performance standards and fiscal incentives for **energy-efficient equipment and process integration measures** should be put in place regardless of the scale of decarbonisation required.
- Regulatory measures, such as the **removal of fossil fuel subsidies and effective internationally co-ordinated carbon pricing schemes**, should be implemented in order to encourage action in the industry sector.
- **Research, development, demonstration and deployment (RDD&D) is needed** in a variety of areas to provide options to ensure that a viable portfolio of low-carbon industrial process technologies will be ready in the post-2030 time frame, as it is unlikely that all innovative routes being researched today will be commercially deployed.
- **Material efficiency strategies offer an important opportunity for emissions reduction.** Policy actions such as price signals, raising awareness, encouraging shared responsibility among consumers and producers for collection, separation and processing of waste materials, and providing fiscal incentives favouring the valorisation of recycled materials can be effective to remove barriers for material efficiency.
- **Integrated assessments that map local energy resources and demand patterns** are needed to identify cost-effective energy supply strategies that suit local, national and regional needs. Strategic planning for heating and cooling can help to identify cost-effective opportunities for the recovery of industrial excess heat and its productive use.
- Programmes that collect **technology-specific energy performance statistics** should be encouraged to enable more detailed evaluation of industrial energy and CO₂ profiles.
- **Co-operative frameworks** such as public-private or cross-sectoral partnerships with robust intellectual property agreements can balance competitiveness with energy and climate goals to effectively foster low-carbon innovation in industrial processes.
- **Going beyond the 2DS** towards more ambitious climate scenarios would require a much more aggressive deployment of similar policy levers. Additionally, in a B2DS, policy action to support the low-carbon transition would need to occur earlier and support a more rapid scale-up and deployment of innovative low-carbon technologies.

Overview

This chapter outlines opportunities for CO₂ emissions reduction in the industry sector. It examines technology trends and the CO₂ emissions implications with a focus on five energy-intensive industrial subsectors and recommends policy actions that could support the achievement of global climate ambitions. It does this in the context of three scenarios that look to 2060 with varying levels of ambition to achieve climate change goals.¹

- RTS, in which industry sector improvements in energy consumption and CO₂ emissions are incremental, in line with currently implemented and announced policies and targets.
- 2DS assumes the decoupling of production in industry from CO₂ emissions growth across the sector that would be compatible with limiting the rise in global mean temperature to 2°C by 2100.
- B2DS pushes the available CO₂ abatement options in industry to their feasible limits in order to aim for the “well below 2°C” target of the Paris Agreement. This scenario represents a dramatic shift in the industry sector, including a large role for innovative low-carbon process routes and a steep decline in direct CO₂ emissions.

Energy demand in industry is higher than in the buildings or transport sectors. It represents 38% of the world’s total final energy consumption (TFEC) and 24% of energy-related CO₂ emissions, reaching 154 EJ and 8.3 Gt of direct CO₂ emissions in 2014.² Among the end-use sectors, industry is the largest consumer of coal (60% of global final consumption) and the second-largest consumer of oil products (28%). Energy-intensive industries (including iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium) account for more than two-thirds (69%) of total industry energy demand, an increase from 66% in 2000. These five industrial subsectors are the primary focus in this chapter, though the scenarios include the entire industry sector.

Over the decades since 1980, the use of fossil fuels in industry has decreased from 79% to 72% of final energy consumption in industry, with oil losing prominence. The aggregated industrial energy intensity has decreased by 11% since 2000 globally, driven by structural changes, efficiency improvements and the optimisation of locally available energy resources to minimise production costs and reduce exposure to volatile energy price environments. Nonetheless, challenges remain to continue reducing energy consumption and CO₂ emissions in the industry sector. Total energy demand in industry has increased by 2.9% per year since 2000. This would moderate to 1.1% per year in the period to 2060 in the RTS.

The decarbonisation challenge in industry

In the coming decades, population growth and rising income levels will require more industrial production, particularly in non-OECD countries. This amplifies the challenge of reducing the sector’s energy demand and CO₂ emissions impact without compromising social and economic development goals.

Industries will need to increase their activity levels while moderating energy consumption and carbon emissions. This will require effective implementation of energy efficiency strategies, implementation of BAT, material efficiency strategies, switching to lower-carbon fuels and feedstocks, and adopting innovative low-carbon processes and technologies such as CCS.

Emerging economies have particular opportunities to leverage growth in indigenous industrial production by deploying BAT; integrating energy use in industry with the energy supply sector, e.g. putting industrial waste heat to productive use; adding value through efficient resource use; and enabling synergies with other sectors. The availability of

1. For additional information on the three scenarios, see Chapter 1, “Global outlook.”

2. Industry as discussed in this report includes International Standard Industrial Classification (ISIC) divisions 7, 8, 10–18, 20–32, and 41–43 and Group 099, covering mining and quarrying (excluding fuel mining and extraction), construction and manufacturing. Petrochemical feedstock energy use and blast furnace and coke oven energy use are also included.

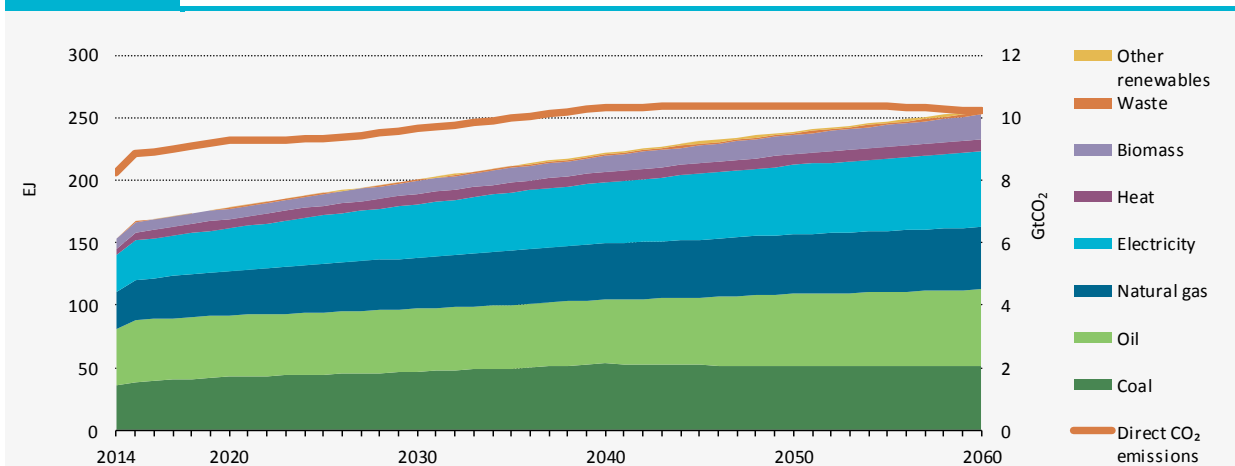
technical expertise and the ability of energy policy makers to effectively engage with industry stakeholders are also critical to transition the industry sector to a low-carbon path.

Future impact of current ambitions: industry sector in the RTS

The RTS represents the level of effort that is in line with existing and announced policies and targets that do not encompass strong price signals or incentives for reducing carbon emissions. While there are some improvements driven by economic incentives and existing policy commitments, the high-level picture of energy demand and CO₂ emissions in the industry sector in 2060 does not differ dramatically from 2014. Current policies and announced targets do not go far enough to promote the needed CO₂ emissions reductions for a low-carbon transition in the industry sector.

On a regional basis, India, Africa and the Middle East see some of the strongest energy consumption growth in industry of 2.7%. In other Asian countries, excluding the People's Republic of China (hereafter, "China"), energy demand in industry increases by more than 2% per year. Energy consumption in industry slows in China to 0.7% per year and in OECD countries declines by 0.1% per year. CO₂ emissions increase in most regions but decline by about 1% per year in China and OECD countries.

Figure 4.1. Final energy use and CO₂ emissions in industry in the RTS



Note: GtCO₂ = gigatonnes of carbon dioxide.

Source: IEA (2016), *World Energy Balances 2016*.

Key point *Industrial direct CO₂ emissions in the RTS peak by 2055 while energy use continues to grow.*

In the RTS, energy consumption in industry grows moderately at 1.1% per year through 2060 – the end of the modelling time horizon.³ The shift from fossil fuels to lower-carbon fuels is rather limited, with fossil fuels accounting for 64% of energy demand in industry in 2060 compared with 72% in 2014. Electricity's share rises from 20% to 23% in the same period. CO₂ emissions from industry rise 0.6% per year through 2055, when they peak at 10.4 Gt CO₂ and then slightly decline through to 2060 (Figure 4.1).

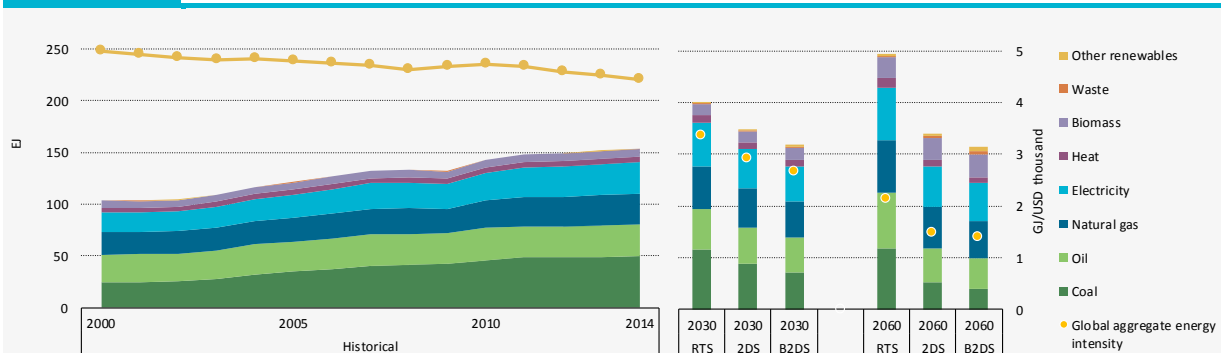
3. *Energy Technology Perspectives (ETP)* modelling is for the period 2014 through 2060. All growth rates are calculated on a compound average annual growth rate basis.

Decarbonisation pathways

The levels of climate change ambition expressed in the Paris Agreement require a much more ambitious pathway for the energy system than the current and announced policies and targets in the RTS imply. The energy demand and CO₂ emissions reduction needed to reach the 2DS pathway or a more ambitious climate target are significantly deeper. The annual improvements in aggregated energy intensity in the industry sector since 2000 would need to triple to meet a 2DS trajectory and almost quadruple to meet the more ambitious B2DS pathway through 2030 (Figure 4.2). The contribution of fossil fuels to the overall energy mix in industry, which has remained nearly flat since 2000, would need to fall by 4–7% over the next 15 years to avoid the more costly 2DS or B2DS trajectories in the long term, which would require much more drastic technological and structural changes to reduce CO₂ emissions in the post-2030 period. Without early action, as more carbon-intensive capacity in industry is installed, stranded assets or costly retrofits are likely in order to shift to a less carbon-intensive industry sector and compensate for early CO₂ emissions by reducing more dramatically in later time periods.

Figure

4.2. Energy use and aggregated energy intensity in industry per value added by scenario



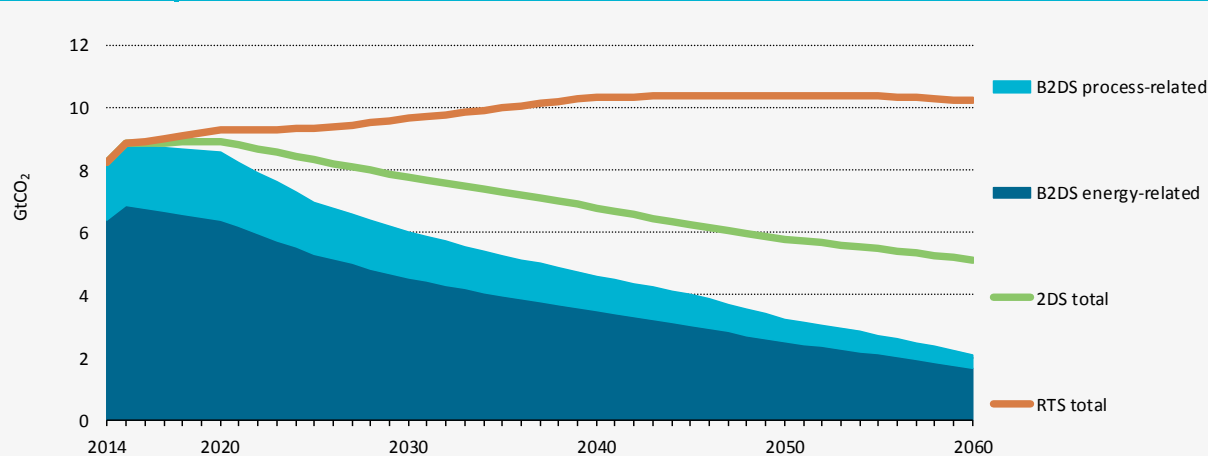
Notes: Final industrial energy use includes blast furnaces (BFs), coke ovens (COs) and petrochemical feedstocks. Energy intensity is given in gigajoules (GJ) per thousand United States dollars (USD) of aggregated industrial value added.

Source: IEA (2016), *World Energy Balances 2016*.

Key point

Final industry energy intensity decreases dramatically by 2060 in the low-carbon scenarios.

In the 2DS, global direct CO₂ emissions from industry are reduced by 44% by 2050 and halved by 2060 compared with the RTS. However, to reach net-zero CO₂ emissions at the system level, by 2060, which is required for the B2DS, industry would need to further reduce its carbon emissions by 69% by 2050 and 80% by 2060 compared with the RTS (Figure 4.3). These reductions would have to include efforts to address process CO₂ emissions, generated in industrial processes from the use of carbon-based raw materials, which accounted for 23% of total CO₂ emissions in industry in 2014, in addition to emissions from fuel combustion. Such an ambitious change in the direct CO₂ intensity of industrial activity will need to occur along with development of new infrastructure and sustainable consumer products, which will require considerable amounts of material commodities to be produced and adapted to new applications.

Figure 4.3. Global direct CO₂ emissions from industry by scenario

Note: Process CO₂ emissions refer to those generated in industrial processes from the use of carbon-based raw materials.

Key point *Direct CO₂ emissions from industry in the B2DS are cumulatively 47% below RTS levels.*

Energy-intensive industries account for the largest part (82%) of the sector's cumulative direct CO₂ emissions reductions in the B2DS in the period 2014-60 (compared with 77% in the 2DS) and still account for 1.2 gigatonnes per year (Gt/yr) of direct CO₂ emissions, or 55% of the total, by 2060 (4.0 Gt/yr or 79% in the 2DS). The other industrial subsectors also contribute to the reductions in energy use and CO₂ emissions. Energy consumption in the non-energy-intensive subsectors falls to 64 EJ in 2060 in the B2DS, compared with 94 EJ in RTS, and CO₂ emissions decrease to 930 million tonnes of CO₂ (MtCO₂) in the B2DS in 2060 from 2.5 GtCO₂ in the RTS.

Early carbon mitigation action before 2030 in the industry sector enables 15% of the total 2014-60 direct CO₂ emissions reductions in the B2DS, thus preventing lock-in of inefficient technologies in new capacity additions and avoiding additional investments in low-carbon innovative process technologies in the long term. Early actions include improvements in recycling, energy efficiency investments and shifts to lower-carbon fuels. In both the 2DS and B2DS, some capacity must be retired or retrofitted before the end of its technical lifetime in order to meet emissions reduction targets. Additionally, in B2DS, more aggressive CO₂ abatement options are chosen despite higher investment cost.

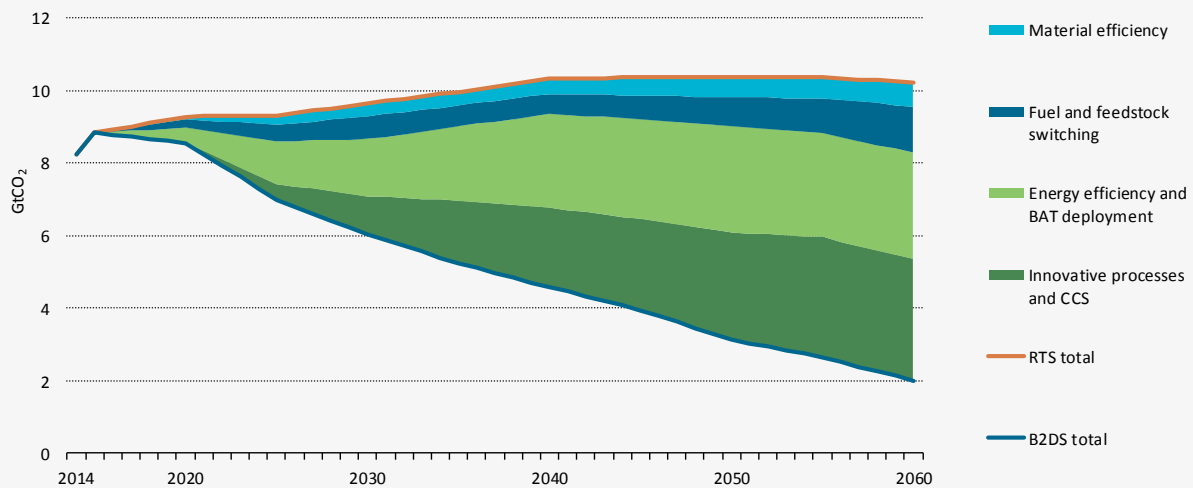
Strategies to support climate ambition

Several key strategies enable CO₂ emissions reduction in the industry sector: material efficiency, energy efficiency and BAT deployment, fuel and feedstock switching, and innovative processes including CCS (Figure 4.4). Of the 217 Gt cumulative direct CO₂ emissions reductions in the B2DS, energy efficiency and BAT deployment contribute the largest share (42%), followed by innovative processes and CCS (37%). Switching to lower-carbon fuels and feedstocks accounts for 13% of the reductions, with the remaining 8% from material efficiency strategies in manufacturing processes.⁴

4. Percentages may not sum to 100% due to rounding.

Figure

4.4. Direct CO₂ emissions in industry by mitigation strategy in the B2DS compared with the RTS



Key point

While energy efficiency and fuel switching dominate carbon mitigation impact in the near term, low-carbon innovative processes become crucial in the long term to meet the B2DS.

Energy savings and reduced direct CO₂ emissions from efficiency gains and low-carbon fuel switching play the most important role in the period before 2030, whereas low-carbon innovative processes are crucial in the long term. Material efficiency strategies have an impact on carbon emissions reduction in the near term, which increases slightly over time as recycling rates and manufacturing yields improve, and their effect in reducing materials production is scaled up by the increasing material demand levels.

Material efficiency

Industrial materials are critical for economic and social development and the transition to a low-carbon system. Production of a number of major materials continues to expand in all of the scenarios. The B2DS would require significant levels of key materials to be produced and used in the most efficient way possible to minimise their impact on energy demand and the carbon footprint (Figure 4.5). Material efficiency refers to strategies to deliver the same material service with less overall production of materials. Those services can be provided using fewer or different materials in order to reduce energy demand, or for other motivations; material efficiency can also reduce other environmental impacts of material production or meet other policy objectives such as resource security (Allwood et al., 2013). In a low-carbon transition, industry should maximise the use of locally available energy resources and optimise material use to deliver the desired service, while minimising the energy and CO₂ footprints of the manufacturing processes. Material efficiency is relevant to all industry subsectors throughout the value chain of production, e.g. yields can be improved when producing materials, and post-consumer scrap can be put to productive reuse. This analysis focuses on impacts of several material efficiency strategies related to energy use and CO₂ emissions at the manufacturing stage, whose implementation delivers 144 EJ of cumulative savings through 2060 in the B2DS compared with the RTS (Table 4.1).

End-use material intensity: At the aggregate level, reduction in the use of industrial materials, while delivering similar services, could help to reduce energy demand and overall system-level CO₂ emissions. Reducing material intensity can include reducing overall material consumption or using materials more intensively or at higher capacity. For example, extension of product lifetimes and material substitution in final products could

each contribute to material intensity improvements. As discussed in the International Energy Agency (IEA) *World Energy Outlook 2015*, material efficiency and energy efficiency are often complementary; for example, light-weighting of automobiles not only provides benefits associated with reduced material intensity but also boosts fuel efficiency (IEA, 2015a). Accounting for the energy and emissions benefits of reduced material intensity in end uses of industrial materials requires detailed life-cycle analysis, co-operation and collaboration along supply chains, and detailed data.

Manufacturing process material efficiency: The B2DS also explores the energy and CO₂ emissions benefits of improving yields in metals manufacturing and semi-manufacturing, such as crude steel and aluminium, by cutting material losses and thus reducing the overall demand for the materials. Manufacturing yields increase by 8% on average in crude steel and 16% in aluminium production by 2060 in the B2DS. The combined effect of manufacturing yield improvements and the increased recycling and reuse rates result in a cumulative decrease of crude steel of 10.8 Gt and aluminium demand of 1.3 Gt by 2060 compared with the RTS (Figure 4.5). Overall, increased manufacturing yields decrease the total amount of available metal scrap, though this is offset by the increase in post-consumer scrap from recycling and reuse strategies. The total scrap available has an impact on the carbon mitigation technology strategies implemented by the metal sectors in the B2DS compared with the 2DS.

Inter-industry material synergies: Material efficiency strategies include opportunities across various industrial subsectors. For instance, clinker substitution in cement manufacturing directly reduces the thermal energy and process carbon emissions associated with the production of this precursor of cement for the same amount and quality (within applicable cement standards) of final cement produced. Approximately 3.7 GJ and 0.83 tonnes of CO₂ (tCO₂) can be saved per tonne of clinker displaced.⁵ In the B2DS, the clinker ratio decreases by almost 10% by 2060 (0.59 t clinker/t cement) compared with current levels (0.65 t clinker/t cement) on a worldwide basis, thanks to the introduction of substitution materials.⁶ For example, slag generated as a byproduct in blast furnaces for pig iron production (estimated at 324 million tonnes [Mt] in 2014), due to its chemical composition, can be used as a clinker substitute in cement manufacturing.⁷ However, system interactions become important to evaluate the potential of these strategies, as in the B2DS the availability of blast furnace slag is reduced in the long term due to technology shifts in the iron and steel subsector.

Post-consumer recycling: The collection and recycling of post-consumer scrap of different materials (plastic, metals and paper) reduces the need for primary material production with the consequent reduction in energy consumption not only at the manufacturing stage but also related to the extraction, treatment and provision of raw materials in the primary routes. Global collection of waste plastics for recycling improves from 10% in 2014 to 41% by 2060 in the B2DS (as in the 2DS) compared with a continuation of current trends in the RTS.⁸ This results in a cumulative reduction in the demand for primary chemicals for plastics production of 1 292 Mt of HVC,⁹ 68 Mt of methanol and 70 Mt of ammonia with associated cumulative energy savings of 17.8 EJ¹⁰ by 2060. The recycling of various consumer paper products globally reaches 65% by 2060 to provide 0.5 EJ in savings in the B2DS by increasing the availability of recovered pulp for paper production. Recycling of post-consumer aluminium scrap is 22% higher in the B2DS by 2060 than in the RTS and 14% higher for steel. Reuse of post-consumer scrap increases by 20% in aluminium and 32% in steel during the same period. Barriers to further increasing collection and recycling

5. Savings based on global average clinker production. CO₂ intensity from IEA estimates.

6. Current global average clinker ratio is an IEA estimate based on CSI, 2017, and communications from national industry associations.

7. The blast furnace slag captures all ash residues from the coal, coke and ore. As the iron and steel sector shifts mainly towards the smelting reduction process route in the B2DS, the slag produced has different chemical properties and is no longer suitable for use as a clinker substitute.

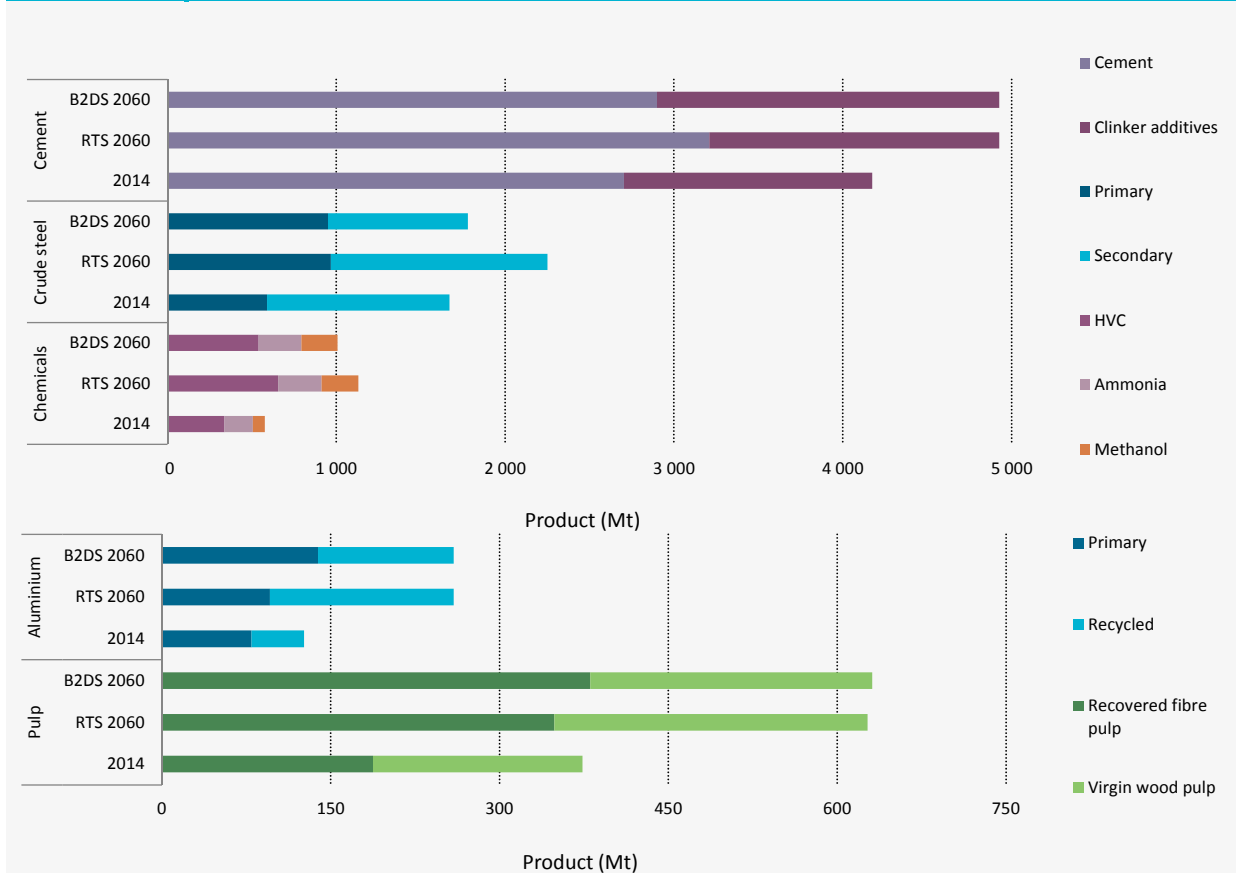
8. This rate refers to post-consumer waste plastic collection; it does not include processing yields. Recycling rate refers to plastic consumption levels and is based on different resin categories: PET (polyethylene terephthalate), HDPE (high-density polyethylene), PVC (polyvinyl chloride), LDPE (low-density polyethylene), PP (polypropylene), PS (polystyrene) and other (including PC [polycarbonate], ABS [acrylonitrile butadiene styrene], SAN [styrene acrylonitrile], PMMA [polymethyl methacrylate], PAN [polyacrylonitrile] and PVA [polyvinyl acetate]).

9. HVC refer to ethylene, propylene and BTX (benzene, toluene and xylene).

10. Energy savings exclude feedstock energy use.

rates include the cost and time to develop infrastructure, stimulating behavioural change and technical issues related to the quality of scrap.

Figure 4.5. Global material production projections in the RTS and B2DS



Notes: HVC = high-value chemicals. HVC refer to ethylene, propylene and BTX (benzene, toluene and xylene). Crude steel and aluminium production levels are expressed in liquid metal terms.

Key point *Production levels are decreased for crude steel, aluminium and primary chemicals in the B2DS due to material efficiency strategies.*

Table 4.1 Material efficiency strategies by subsector and scenario

	RTS	2DS	B2DS
Iron and steel	<ul style="list-style-type: none"> Post-consumer scrap recycling – continue current trends. 	<ul style="list-style-type: none"> Post-consumer scrap recycling – improved collection rates. 	<ul style="list-style-type: none"> Same strategy as 2DS. Improved manufacturing and semi-manufacturing yields. Post-consumer scrap reuse.
Cement	<ul style="list-style-type: none"> Clinker substitution – continue current trends. 	<ul style="list-style-type: none"> Maximised clinker substitution ratios. 	<ul style="list-style-type: none"> Same strategy as 2DS.

Chemicals and petrochemicals	<ul style="list-style-type: none"> Plastics recycling – continue current trends. 	<ul style="list-style-type: none"> Plastics recycling – improved collection rates. 	<ul style="list-style-type: none"> Same strategy as 2DS.
Aluminium	<ul style="list-style-type: none"> Post-consumer scrap recycling – continue current trends. 	<ul style="list-style-type: none"> Post-consumer scrap recycling – improved collection rates. 	<ul style="list-style-type: none"> Same strategy as 2DS. Improved manufacturing and semi-manufacturing yields. Post-consumer scrap reuse.
Pulp and paper	<ul style="list-style-type: none"> Paper products recycling – continue current trends. 	<ul style="list-style-type: none"> Paper products recycling – improved collection rates. 	<ul style="list-style-type: none"> Same strategy as 2DS.

Energy efficiency and BAT deployment

Improving energy efficiency and deploying the BATs in industry is an important strategy for reducing energy demand and related CO₂ emissions in a world of increasing material demands. Although the reduction potentials are site- and process-specific, global energy efficiency and BAT deployment would improve aggregate energy intensity in industry by 30% by 2060 in the B2DS and save 90 GtCO₂ cumulatively compared with the RTS.

These strategies are especially important in the early years; they account for 47% of cumulative emissions reductions before 2030 in the B2DS. While industrial processes are often already well optimised, cost-effective energy efficiency opportunities remain, and additional energy savings from energy efficiency could be realised given additional economic incentives. Because of their importance in the near term, it is imperative to make an economic case for further efficiency gains to stimulate the needed investment.

Energy efficiency in the industry sector takes many forms; one of the most prominent is energy management systems (EMS). EMS, including those certified under ISO standard 50001, facilitate the optimisation and monitoring of energy consumption in industrial facilities to improve energy efficiency without compromising product quality or process reliability. EMS have increasingly been adopted and by 2015 there were more than 12 000 ISO 50001 certified facilities.

Moving towards BAT is also a critical driver of energy demand and CO₂ emissions reductions in the *ETP 2017* scenarios. BAT refers to the current state-of-the-art practices, techniques, equipment and processes. Without further technology breakthroughs or improvements, deploying high-performance equipment and practices in new installations and retrofits can bring the sector closer to today's BAT level. There are limitations to fully achieving BAT-level performance, which are often region- or site-specific, such as raw material quality, product standards, and plant design and layout, among others. Initiatives to benchmark against BAT performance must consider the specific circumstances. In the low-carbon scenarios, major industrial process routes in the five energy-intensive subsectors improve significantly towards BAT levels as equipment is retrofitted and replaced at the end of its lifetime and integrated energy management systems are put in place.

Shifting to low-carbon fuels and feedstocks

As illustrated, resource efficiency strategies to reduce the material and energy intensity of industrial processes reduce energy intensity and energy-related CO₂ emissions. To further progress on the decarbonisation pathway, energy demand should be met using the least carbon-intensive energy sources available. Although there are process limitations in specific industries, many industrial processes can be fuelled by biomass, electricity, wastes and renewables rather than by fossil fuels.

Shifting energy consumption away from energy sources with higher carbon content is critical for industry to reach lower overall carbon emissions intensity levels. Switching between combustible fuels is limited, however, based on the calorific content and characteristics of

the fuels, which must be compatible with the equipment design and process needs. It may require retrofitting of equipment and can be hindered by relative fuel prices in a given market area.

Industrial processes that use fossil fuel feedstocks could shift to lower-carbon feedstocks at the design stage or through equipment upgrades. For example, natural gas can replace oil or coal in the production of some chemicals, which reduces, though does not eliminate feedstock-related CO₂ emissions per tonne of product.¹¹ Biomass, which is considered carbon neutral in the *ETP* scenarios, can also replace fossil fuels in some industrial applications as either a solid or liquid fuel or a feedstock, though fuel characteristics and specific process needs must be taken into account.¹² Waste can also be a low-carbon fuel source, though as with other energy sources, specific characteristics of the waste fuel must be taken into account to understand both the applications where it can be used and the life-cycle emissions reduction. For biomass and waste, their availability, logistics and storage must be taken into account in determining appropriate roles in a low-carbon energy system. For biomass in particular, resource sustainability is an important consideration.

The non-energy-intensive industry subsectors, which have a higher share of low- and medium-temperature heat demand, shift significantly towards lower-carbon fuels, particularly electricity and renewables. In 2014, fossil fuels had a 56% share of TFEC in these subsectors, which decreases to one-quarter by 2060 in 2DS and 22% in B2DS. Biomass use increases from 14% in 2014 to 23% of the total in 2DS by 2060 and 24% in B2DS. Other renewables increase to 4% in 2DS and 7% in B2DS, compared with less than 1% in 2014.

Another option for fuel switching is electrification. In a low-carbon world, where power supply is increasingly decarbonised, using electricity for a greater proportion of total energy demand in industry can lower overall CO₂ emissions and add an element of flexibility to operation of the power grid via load management. Electrification of heat demand, such as with the use of heat pumps, can require significant equipment retrofits, and is most economical and technically feasible in low- to medium-temperature heat applications. Similarly, other renewables such as solar thermal and direct-use geothermal can also be used to meet low- and medium-temperature heat demand in suitable industry subsectors such as food and beverage.

Innovative processes and CCS

Most of the innovative low-carbon processes needed to achieve the B2DS pathway have not yet been fully commercialised. These processes account for 38% of cumulative CO₂ emissions reductions in the B2DS. Without major deployment of new low-carbon processes, the 2DS and B2DS will not be achievable. Bringing these technologies and processes to commercial deployment will require significant investment in research and development (R&D) as well as a major effort to deploy innovative processes across the industry sector.

In the 2DS and the B2DS, some examples of innovative low-carbon process routes include:¹³

- New steelmaking processes such as upgraded smelt reduction and upgraded direct reduced iron (DRI)¹⁴
- Inert anodes for aluminium smelting¹⁵
- Full oxy-fuelling kilns for clinker production in cement manufacturing.

11. Feedstock-related emissions are based on stoichiometric calculations comparing carbon content of feedstocks and final products, excluding the part of fuel that is combusted. It should be noted that changes in feedstocks also impact process yields and product mix structure in the case of multi-product processes, so there are other implications apart from the feedstock-related CO₂ emissions.

12. Biomass is considered carbon neutral in the *ETP* scenarios, as CO₂ emitted during combustion is absorbed during growth. (See Chapter 7 for further discussion.)

13. This list is not exhaustive. For additional examples, refer to subsector discussions in this chapter. Technologies at the R&D phase have not been included in the *ETP* scenarios, nor have those at later technology development phases for which sufficient robust techno-economic data are not available.

14. Upgraded smelt reduction includes HIsarna and upgraded DRI includes Ulcored.

15. Inert anodes made from alternative, non-carbon-based materials could eliminate process CO₂ emissions from primary aluminium smelting.

- Enhanced catalytic and biomass-based processes for chemical production.
- Integration of CCS in energy-intensive industrial processes.

The RDD&D portfolio in the industry sector should include a wide range of innovative technologies and process routes, as many options that are not yet commercial could play a role in the low-carbon transition. Future technology development and cost will determine which will be commercialised, and RDD&D investments should include a wide range of options with the potential to achieve positive results. Technology development is uncertain, and other currently unknown technology options could also transform industrial production processes.

CCS also plays a major role in decarbonising the industry sector to meet a 2°C or below-2°C target. In the 2DS, cumulatively 37 GtCO₂ emissions are captured and stored, and the number is even higher in the B2DS at 90 GtCO₂. In 2060, this makes up 38% of total emissions reductions in industry between RTS and B2DS, or more than double the 2DS share. Innovative process routes are often complementary to CCS, facilitating capture by creating concentrated streams of CO₂. For example, many new steelmaking process routes have more concentrated CO₂ streams, which are more economical to capture than diluted sources. Capturing CO₂ from industrial processes sometimes has an associated energy penalty and sometimes requires additional capital investment for retrofits to the process equipment to allow for capture.

Capturing and storing CO₂ generated from bioenergy sources (bioenergy CCS [BECCS]) results in net negative CO₂ emissions or removes CO₂ from the atmosphere.¹⁶ The implementation of BECCS technologies, within the limits of sustainable biomass availability, thus compensates for carbon emissions generated in other areas of the economy where it is costlier to reduce them. BECCS can be implemented in several areas in the industry sector, such as integrating CCS in clinker kilns with biomass co-firing, in flue gases generated in biomass-intensive pulp-making processes and in biomass-based captive utilities.¹⁷ In the B2DS, BECCS in industry represents 4.5 GtCO₂ captured cumulatively in the period to 2060.

Carbon capture and utilisation (CCU) is also an area of interest for the industry sector. It is already commercial in some applications. For example, 92 MtCO₂ emissions were captured from the ammonia production process in 2014 and used to produce urea. Such processes are often located near each other, and it is typically economical to use the CO₂ stream from ammonia production to meet the nearby demand. In this application, greenhouse gases are ultimately still emitted, typically in the agriculture sector as the urea is used to create fertilisers, thus it is not considered a carbon abatement option. However, increased deployment of CCU in industry could help to develop the transport infrastructure that will ultimately be needed for CCS and could bring down the cost of initial CCS projects through technology learning with regard to capture and transport technologies. (See Chapter 8 for more details on CCS and CCU technologies.)

Optimising industry for system-level efficiency

Industrial energy resources

Industrial plants should minimise their energy consumption and emissions footprint to the fullest cost-effective level. Nonetheless, in practice, excess energy, usually as waste heat, may be inevitable. Recovering and reusing this waste heat to economic levels benefits the overall energy system by displacing fuel consumption at industrial sites or in other applications.

Heat from flue and exhaust gases, solid and liquid industrial streams, and dissipated from hot equipment surfaces can be partially recovered depending on the characteristics of the industrial excess heat (IEH) source (such as cleanliness, temperature level and intermittency of supply) as well as the availability of a compatible end-use application. Energy efficiency

16. Because biomass is considered carbon neutral, biogenic emissions captured and permanently stored result in net removal of CO₂ from the atmosphere. (See Chapters 7 and 8 for additional discussion of bioenergy and CCS.)

17. Captive utilities refer to heat and power production located at industrial sites.

and process integration strategies should focus on minimising the production of excess energy. The recovery and use of unavoidable excess energy within the industrial site should be prioritised. If a compatible on-site use is not available, then off-site applications may be well suited, e.g. in district heating networks or in nearby industrial facilities.

A portfolio of IEH recovery technologies available today could technically recover an estimated 2.1 EJ in the iron and steel subsector and 0.7 EJ in the cement subsector.^{18,19} However, the availability of IEH becomes more limited in the long term, especially in the low-carbon scenarios, as levels of process integration at industrial facilities increases and industrial process routes become less carbon-intensive. Thus, optimising the use of recovered IEH plays a transitional role in supporting the decarbonisation of the industry sector. The transitory nature of this opportunity could be a disincentive for investment in IEH recovery equipment in the absence of supporting financial incentives and as industry is more likely to take up the applications with short payback periods. Additionally, carbon mitigation technologies with considerable deployment in the long term, such as CCS, incur additional thermal energy needs that can be satisfied using IEH sources, thus reducing the potential for recovered IEH in applications outside the industrial facility.

Industrial processes also produce off-gases or byproducts with calorific content such as blast furnace gas (BFG) and coke oven gas (COG) among other off-gases, which can be used as fuel in on-site utilities for heat and electricity generation. In 2014, 8.2 EJ of BFG, COG and other coal-based gases were produced. In the B2DS, 3.5 EJ is available from the iron and steel sector by 2030, and 0.7 EJ by 2060, as the process route of coke oven-blast furnace drops its share of total crude steel production in the long term. Some of these industrial off-gases can also be used as feedstock for the production of chemicals thanks to their chemical composition. For instance, in 2014 in China, 5.7 Mt of methanol was produced from COG (typically containing 55-60% hydrogen, 23-27% methane and 5-8% carbon monoxide [Razzaq, Chunshan and Soujiang, 2013]). The production of chemical wood pulp for papermaking produces a biomass byproduct called black liquor that can be used as a chemical feedstock to produce liquid fuels or can be combusted to produce heat and electricity; 2.7 EJ was estimated to be produced in 2014.

Captive utilities for heat and electricity generation within industrial sites enable additional flexibility to reduce exposure to price volatility in local energy distribution grids, while becoming an additional source of revenue by exploiting surplus energy sources. Electricity generation in on-site utilities (electricity-only and co-generation²⁰ plants) reached 1 719 terawatt hours in 2014, and this increases by 68% by 2060 in the B2DS.

Industry sector energy demand and flexibility

While some systems integration opportunities may be reduced as novel process routes or low-carbon feedstocks are adopted, other areas may emerge to offer new opportunities for systemic benefits. For example, greater penetration of electricity in the energy mix could reduce the overall CO₂ footprint of industrial activities as power supply is decarbonised (electricity CO₂ intensity drops from 599 grammes of CO₂ per kilowatt hour [gCO₂/kWh] in 2014 to -13gCO₂/kWh²¹ in 2060 in the B2DS). Globally, the share of electricity in the final industrial energy mix increases by 27% (16 EJ) by 2060 in the B2DS compared with current levels. Additional electrification of heat demand in industry could contribute to overall system sustainability by unlocking substantial opportunities for shifting power demand away from system peak demand. Equipment and processes with higher thermal inertia would provide more substantial demand-shaping potential, as the ability to arbitrage between different energy values is extended over a longer time period. This would be especially relevant for continuous processes with significant low-temperature thermal demand levels (Figure 4.6). Not all industrial fuel use can be replaced with electricity, and electrification

18. Technical potential for IEH recovery based on the industrial stock in 2014.

19. IEH recovery technologies considered in the technical potential analysis include: sensible heat recovery through coke dry-queenching, sensible and chemical heat recovery from basic oxygen furnace (BOF) off-gas, sensible heat recovery from electric arc furnace exhaust gas and from sinter cooler exhaust in the iron and steel sector; and sensible heat recovery from clinker kiln exhaust gas and from clinker cooler exhaust air in the cement sector.

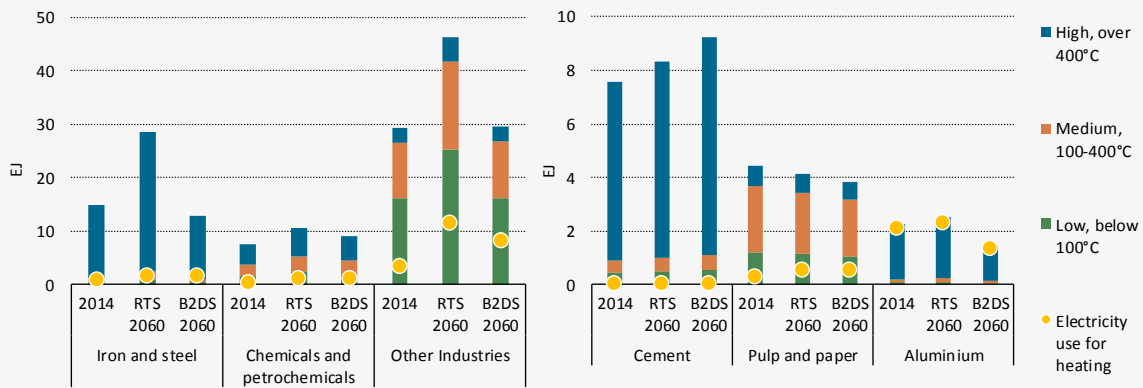
20. *Co-generation* refers to the combined production of heat and power.

21. Negative average CO₂ intensity of electricity stems from negative emissions from biomass-based generation with CCS (BECCS). (See Chapter 6 for discussion of power sector scenarios.)

would have other effects on the process, including impacts on plant design, cost and available process integration options.

Figure

4.6. Electricity consumption for heat generation and heat demand in industry by temperature level and scenario



Notes: Electricity used in alumina electrolysis for primary aluminium production is allocated to electricity-based heating, as is electricity used for electric arc furnaces (EAF) in the steel sector. Energy use as petrochemical feedstock is excluded.

Source: Ecoheatcool and Euroheat & Power (2006), *Ecoheatcool Work Package 1: The European Heat Market Final Report*.

Key point

Electricity use for industrial heating increases 46% by 2060 from 2014 in the B2DS, with the most notable increases in pulp and paper and non-energy-intensive industry.

Demand-side management strategies could modulate the level of industrial activity in line with the needs of the power system (Box 4.1). This could imply a shift away from peak demand and as power supply decarbonises, this demand-shaping potential could shift some load to times with high portions of low-carbon electricity generation. Industrial processes designed to operate in batches rather than in continuous mode, such as some food processing activities, are better suited to implement such strategies. However, even for industrial processes that rely on continuous operation, in some applications it is possible to modulate electricity consumption without affecting output. This would require storage capacity of intermediate products and an oversizing of some components of the value chain. Seasonal processes such as sugar making can also adapt the nature of their operations over the year, using plant capacity during low-production periods for heat and/or electricity generation, making use of accumulated agriculture wastes. In addition, developing thermal storage capacity would increase the flexibility to adapt to grid fluctuations and maximise plant revenues by exporting/importing from the grid when it is more cost-effective to do so. Demand-side management is already being implemented in the industry sector where it is economical, but this strategy could have additional potential given appropriate incentives, regulatory frameworks and infrastructure availability. The trade-off between flexibility and efficiency should be considered and system-level benefits weighed against sector- and site-level efficiency.

Box

4.1. Providing flexibility to the electricity grid through demand response

Electricity load management in aluminium production

Aluminium electrolysis is an electricity-intensive industrial process, averaging 14.2 megawatt hours (MWh) per tonne of aluminium produced globally in 2015 (IAI, 2017). TRIMET's facility in Essen, Germany, produces approximately 250 kilotonnes (kt) of aluminium annually, of which 165 kt is primary aluminium. TRIMET's pilot demand-response programme has indicated that the supply of power to an electrolysis system can be decreased or increased by up to 25% for hours at a time without adverse effects on the smelting process or the quality of the finished product. This flexibility allows TRIMET to modulate the amount of power that the facility draws from the grid – maximising production when power is cheap and abundant, effectively “storing” surplus electricity in molten aluminium, enabling the facility to reduce its power consumption during times of peak demand, without shutting production. In addition to reducing operational costs and enabling more efficient grid management, demand-side management in the aluminium sector can help to facilitate the grid integration of large shares of variable renewable generation. After completion of the pilot test phase, TRIMET will retrofit its smelter at Essen by the end of 2017 to conduct a full-scale industrial test of its “virtual battery” concept. If the virtual battery system were applied to all of TRIMET's capacity in Germany, it would be equivalent to adding 7 700 MWh of storage capacity to the grid.

Sources: TRIMET (2015), “TRIMET Aluminium SE press release”; Depree et al. (2016), “The ‘virtual battery’ – operating an aluminium smelter with flexible energy input”.

Decoupling production and CO₂ emissions in energy-intensive industry

Energy-intensive industries, including iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium, represent a significant portion of the overall final industrial energy use (69%) and CO₂ emissions²² (74%) (Figure 4.7). Each of these subsectors has specific characteristics and so their opportunities for decarbonisation vary significantly.

- The **chemicals and petrochemicals** subsector is the largest industry energy consumer, with 28% (42.5 EJ)²³ of the total global industry final energy demand (of which 25 EJ is related to feedstocks), and the third-largest CO₂ emitter in the industry sector, with 13% (1 061 MtCO₂/year)²⁴ of the total industry direct CO₂ emissions in 2014.
- The **iron and steel** subsector is the second-largest industry energy consumer, with 23% (35.6 EJ)²⁵ of the total global industry final energy demand, and the largest CO₂ emitter in industry, with 28% (2 338 MtCO₂/year)²⁶ of the sector's total direct CO₂ emissions in 2014.

22. Including CO₂ emissions from fuel combustion and industrial processes.

23. Including energy use as petrochemical feedstock.

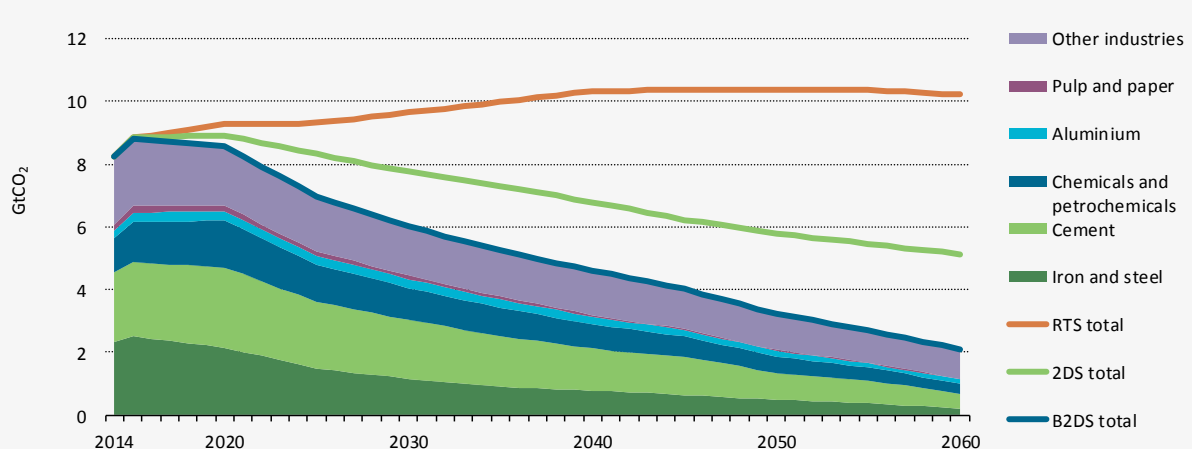
24. Direct CO₂ emissions in the chemicals and petrochemicals sector include energy-related (e.g. CO₂ emissions generated in the combustion of energy commodities) and process CO₂ emissions generated from the carbon contained in feedstocks.

25. Including energy use in blast furnaces and coke ovens, as well as energy use in captive utilities for the generation of steam used on-site.

26. Direct CO₂ emissions in iron and steel include energy-related (e.g. CO₂ emissions generated in the combustion of energy commodities) and process CO₂ emissions generated from the use of lime as a fluxing agent in blast furnaces and basic oxygen furnaces.

- The **cement** subsector is the third-largest industry energy consumer, with 7% of total final energy use in industry, at 10.6 EJ. However, due to the high level of process-related emissions, the cement sector has the second-largest share of CO₂ emissions from industry, at 27% (2 230 MtCO₂/year) in 2014.
- The **aluminium** subsector is the fourth-largest industrial energy consumer, with 4% (6.2 EJ) of the global industry final energy demand, and the fourth-largest CO₂ emitter from industry, with 3% (261 MtCO₂/year) of the sector's total direct CO₂ emissions in 2014.²⁷
- The **pulp and paper** subsector, the fifth-largest energy consumer, accounts for 4% of total industry energy consumption (5.9 EJ) and 2% of industry CO₂ emissions (195 MtCO₂/year).

Figure

4.7. Direct CO₂ emissions by industry subsector

Key point

Energy-intensive industrial subsectors account for 82% of the cumulative direct CO₂ emissions reductions in the B2DS compared with the RTS.

Chemicals and petrochemicals

The chemicals and petrochemicals subsector accounts for 16% of industry's cumulative direct CO₂ emissions²⁸ reductions by 2060 in the B2DS. Direct CO₂ emissions²⁹ reach 321 MtCO₂/year in 2060 in the B2DS globally (30% of current levels). A cumulative reduction from RTS of 19 GtCO₂ is needed in the subsector in the 2DS, with annual emissions falling to 975 MtCO₂ in 2060.

HVC, ammonia and methanol account for almost three-quarters of the total final energy use, including feedstock, in the chemicals and petrochemicals subsector in 2014.³⁰

Currently the chemicals and petrochemicals subsector is heavily dependent on oil and natural gas, together accounting for three-quarters of its global total final energy mix. Coal has a more modest share of 10% worldwide but a higher share in some countries, e.g. 32% in China, especially for ammonia and methanol production.

27. Aluminium sector CO₂ emissions include process emissions from the use of anodes in smelting processes.

28. Including energy-related and feedstock-related CO₂ emissions.

29. Net CO₂ emissions, after CCS.

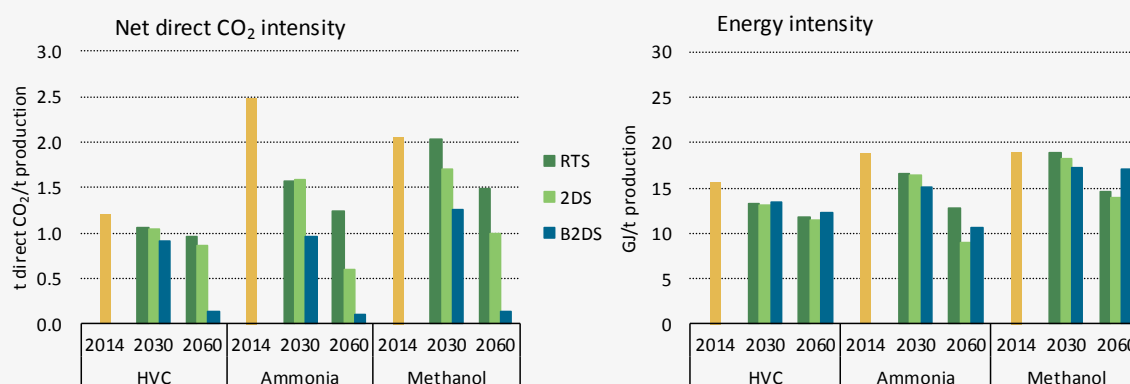
30. The chemicals and petrochemicals subsector includes ISIC Divisions 20 and 21, including petrochemical feedstock (part of ISIC Group 201).

The B2DS level of cumulative direct CO₂ emission reductions implies reducing the specific final energy consumption (SEC) per tonne of product to produce ammonia to 10.7GJ/t ammonia³¹ globally by 2060, and drastically reducing the direct CO₂ footprint of ammonia production, by 96% to 0.1 t direct CO₂ per tonne of ammonia.³² Methanol production experiences similar changes by 2060 in the B2DS with a 10% decrease in process energy intensity and a 94% decrease in direct CO₂ emissions from current levels. HVC improve their process energy intensity by 21% and their direct CO₂ intensity more sharply by 89% by 2060 as global energy performance levels are closer to best practice. These are driven by a number of changes: energy efficiency improvements, advances towards BAT-level processes, shifts to lower-carbon fuels and feedstocks, and deployment of CCS.

However, reaching deep carbon emissions reduction in the chemicals subsector requires early action to avoid locking in effects of inefficient capacity or a delayed uptake of low-carbon innovative process technologies, which could drastically increase costs of the overall transition of the subsector. As emissions reduction is delayed and the cumulative remaining carbon budget for the subsector diminishes, more drastic actions would be needed for deeper cuts in later years. To minimise these costs, the direct CO₂ intensities of primary chemicals production in the B2DS are already reduced by between 24% and 62% by 2030 compared with current levels (Figure 4.8).

Figure

4.8. Global direct CO₂ emissions and process energy intensities of primary chemicals by scenario



Notes: Energy intensity of methanol production increases in 2030, primarily due to coal-based production in China. Direct CO₂ intensity includes process CO₂ emissions related to the difference in the carbon content between feedstocks and chemical products, and is calculated based on net CO₂ emissions after CCS. Process energy intensity excludes energy related to feedstocks.

Key point

Ammonia and methanol lead the decrease in process energy and direct CO₂ intensities in the B2DS by 2060 compared with 2014 among the primary chemicals.

Material efficiency can play an important role in improving environmental sustainability of product manufacturing. Improving collection and processing rates of plastic-based consumer products in the B2DS and 2DS results in a cumulative 362% increase in collection of post-consumer waste plastic globally, compared with the RTS. This translates to a decrease in the global production of primary chemicals of 4% in the period 2014-60 or about 1 292 Mt less HVC, 70 Mt less ammonia and 68 Mt less methanol demanded

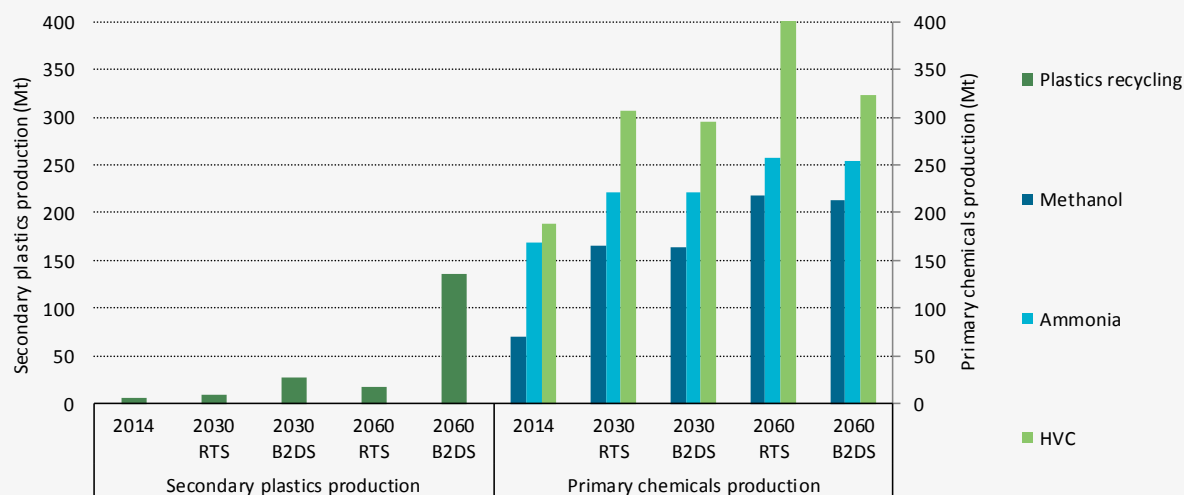
31. Excluding energy use in feedstocks.

32. Net CO₂ emissions, after CCS.

cumulatively (Figure 4.9). The effect of decreased primary chemicals demand translates to 17.8 EJ or 1.3 GtCO₂ cumulative savings in the same period compared with the RTS.³³

Figure

4.9. Secondary plastics and primary chemicals production by scenario



Notes: Secondary plastics refer to plastics production from recycled resins. Recycled plastics production estimates are based on the following specific resins: PET, HDPE, PVC, LDPE, PP, PS and other (including PC, ABS, SAN, PMMA, PAN and PVA).

Key point

Recycled plastics production more than triples in the B2DS compared with the RTS and accounts for a decrease of 4% in primary chemicals production.

The deep decoupling of primary chemicals production from carbon emissions required to meet the B2DS would imply a significant change in the production routes compared with today's technologies, as well as finding alternative production methods with significantly lower carbon footprints. Exploiting the energy efficiency potentials by widely reaching BAT performance levels in commercial technologies would not suffice even if material efficiency strategies were prioritised to minimise the demand of primary chemicals while maintaining the same final service of consumer products. The specific process routes chosen are sensitive to today's techno-economic information on process equipment for the chemicals sector, and the cost-optimal pathway will depend on technology development. However, the need for deep cuts to CO₂ emissions would require dramatic changes to the subsector's technology mix.

The global average process SEC for primary chemicals is estimated at 15.6 GJ/t HVC for steam cracking (today's most widely used process technology), 18.7 GJ/t ammonia and 19.0 GJ/t methanol.³⁴ If the production levels in 2014 had been met with BAT energy performance, then on a global basis 2.2 EJ of energy consumption and 401 Mt of direct CO₂ emissions would have been saved in the chemicals and petrochemicals subsector.

The introduction of carbon capture for permanent storage becomes an important strategy in the chemicals and petrochemicals subsector to meet the B2DS direct CO₂ emissions reduction objectives. On a cumulative basis, 21 GtCO₂ are captured and permanently stored from 2014 to 2060 globally (one-third of the total cumulative carbon emissions reductions in the subsector compared with the RTS) (Figure 4.10). CCS is most widely implemented in ammonia and methanol production as the core process technologies inherently include

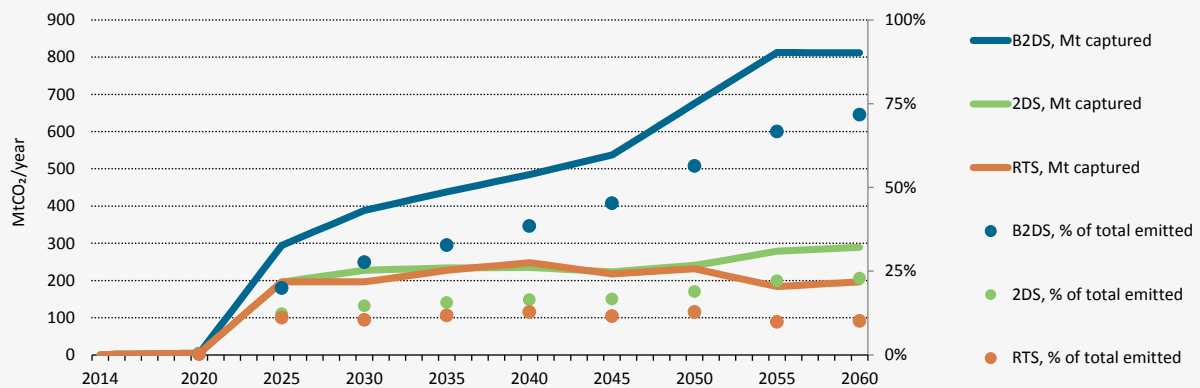
33. Energy and CO₂ emissions savings are calculated based on the avoided production using B2DS energy and direct CO₂ intensity of production of each primary chemical at each time step through the modelling horizon.

34. SEC includes only energy use as fuel; feedstock use is excluded.

carbon separation processes, which make capture more cost-competitive than other processes. Ammonia production accounts for almost half and methanol production for 29% of CO₂ emissions captured in the chemicals subsector in the B2DS.

Figure

4.10. Global CO₂ captured and stored in the chemicals and petrochemicals subsector



Note: CO₂ capture technologies cannot be deployed in the chemicals sector before 2025 in the *ETP* scenarios, except for specific projects already in the pipeline.

Key point

Nearly 75% of CO₂ emitted must be captured by 2060 in the B2DS.

Utilisation of captured CO₂ for industrial processes is already economical in some applications and could have co-benefits in terms of accelerated development of capture technologies and CO₂ transport infrastructure. Commercial CCU connections between carbon sources and applications could develop infrastructure and capture technology that could then be used in the longer term in combination with permanent storage. In primary chemicals production, CCU accounts for almost 6 GtCO₂ by 2060 in the B2DS, of which 97% is carbon capture from CO₂ emissions from ammonia production for making urea.³⁵

Of the global cumulative CO₂ captured and stored in the B2DS, 39% is in China and 13% is in the Middle East. Primary chemicals production is expected to double in China and more than double in the Middle East by 2060 from current levels.

High-value chemicals

To reduce CO₂ emissions from chemicals production beyond the recycling and energy efficiency improvement potentials, switching to lower-carbon feedstocks and process routes is an option. For HVC, steam cracking is the most widely established process, mainly using naphtha and ethane as feedstocks (81% of global HVC capacity excluding production in refineries). Several shifts in process routes and feedstocks for HVC production would be driven by CO₂ emissions reductions in the B2DS (Figure 4.11):

- Steam cracking shifts slightly from naphtha-based (32% reduced global HVC production share in the period 2014-60) to ethane-based steam cracking (increased by 82% in the same period) with a lower direct CO₂ footprint. This structural change impacts the resulting

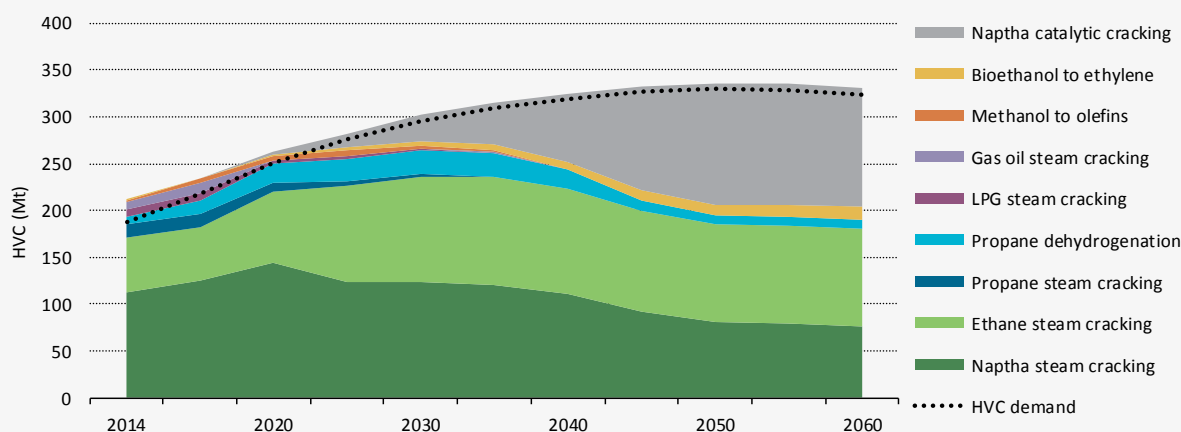
35. The *ETP* industry model includes two CCU options in the chemicals and petrochemicals sector: urea and electrolysis-based methanol production. These are driven by established product value chains to mitigate the limitation of lack of geospatial information and as a consequence of the product scope of the model. Other avenues may arise for the commercial use of CO₂, though these are highly dependent on local synergies.

steam cracking ethylene-to-propylene ratio, as ethane-based steam cracking produces almost three times more ethylene per unit of total HVC than naphtha-based steam cracking.

- Propane dehydrogenation (PDH), a process technology producing only propylene (and no ethylene or BTX) as HVC within its product mix, is further deployed to cover the deficit of propylene demand in the system (10 Mt HVC per year in 2060).
- Naphtha catalytic cracking gains an important share of the HVC production stock globally (reaching production of 126 Mt HVC per year in 2060 from negligible current levels). Naphtha catalytic cracking is a recently demonstrated catalyst-based process technology that enables HVC production with an SEC almost 20% lower than global average naphtha-based steam cracking.
- Biomass-based routes for the production of HVC, such as ethylene from the dehydration of bioethanol, play a marginal role in the B2DS, reaching 7% of global HVC production by 2060, as they are not identified as a cost-competitive carbon abatement opportunity in the ETP 2017 low-carbon scenarios, mainly due to high SEC compared with other available process routes, high capital expenditure needed for biomass-based routes, and the relatively high cost of biomass feedstocks compared with fossil-based options, especially in the B2DS context where biomass demand is high due to its potential negative emissions when coupled with CCS and for use in other applications, such as transport fuels.

Within the B2DS pathway, there are regional differences resulting from existing diverse contexts related to energy and feedstock prices and HVC production capacity structures. For instance, naphtha steam cracking is currently the main HVC production route in regions with relatively high natural gas prices (such as Japan and Europe), whereas ethane-based steam cracking is the preferred route where cheap natural gas is available (such as North America and the Middle East). For this reason, while naphtha-based steam cracking is mainly replaced by naphtha catalytic cracking in China in the B2DS by 2060, ethane-based steam cracking sees an increase in HVC production stock in the Middle East, though overall, ethane loses market share to naphtha (Figure 4.12). Coal can also become a HVC feedstock through the methanol-to-olefins (MTO) process route, which today is mainly deployed in China due to wide availability of coal at very competitive prices. As 2.1 Mt ethylene per year of MTO capacity is expected to come on line in China by 2020, this process will continue to play a large role in HVC production, energy consumption and CO₂ emissions through 2045 in the RTS; in the B2DS it would be phased out by 2040 due to its high CO₂ emissions intensity.

Figure 4.11. Global HVC production by process technology in the B2DS

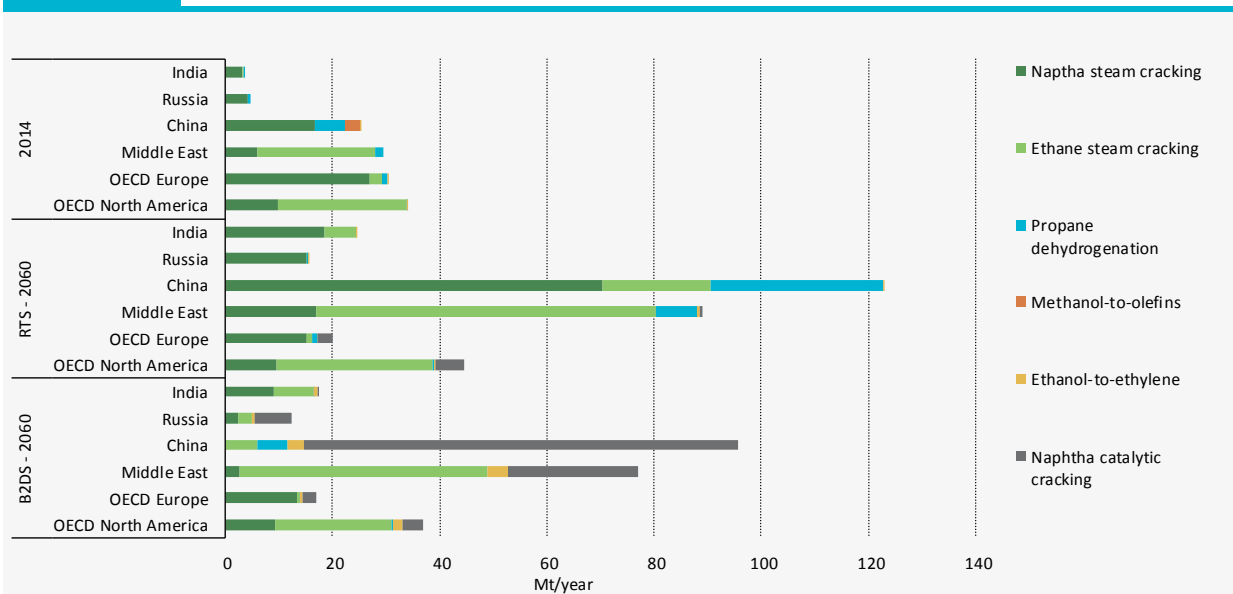


Note: LPG = liquified petroleum gas.

Key point

HVC production remains dependent on oil-based feedstock even in the B2DS.

Figure 4.12. HVC production by process route, scenario and region



Notes: Not all regions are shown. HVC production shown does not sum to global production.

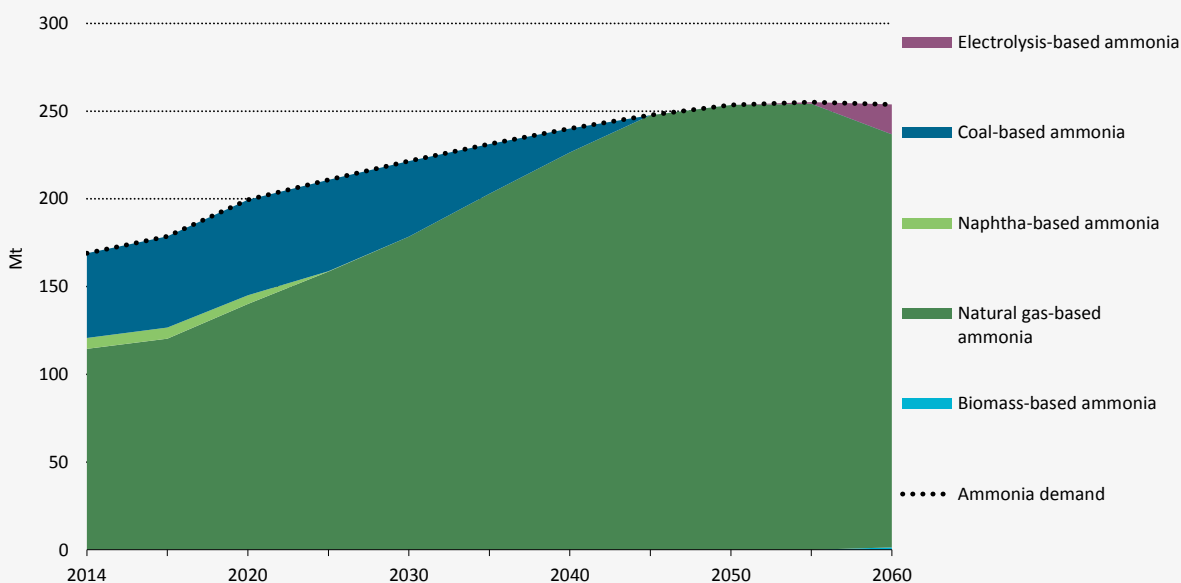
Key point *Naptha catalytic cracking takes on a much larger role in the B2DS, especially in China.*

Ammonia

Ammonia is mainly produced from natural gas feedstock (about 68% of current installed global capacity), with the exception of China where coal is the main feedstock. Coal-based ammonia accounts for 29% of global production. The required direct CO₂ emissions reduction in the B2DS drives several shifts in ammonia production (Figure 4.13):

- Coal-based ammonia production is almost entirely replaced by natural gas-based production by 2060.
- As with HVC, biomass gasification-based routes for the production of ammonia are not identified as cost-competitive options for carbon mitigation in the low-carbon scenarios. In the B2DS, the high SEC of biomass gasification for ammonia production, the high capital expenditure needed for process equipment and the high cost of biomass feedstocks in the B2DS context limit the economic potential of this process route. By 2055 electrolysis-based ammonia starts to gain marginal shares of production and rises to 7% by 2060. Ammonia from electricity-based hydrogen plays a limited role due primarily to high electrolyser capital expenditure and high electricity prices in the low-carbon scenarios (Box 4.2).

Figure 4.13. Global ammonia production by process technology in the B2DS



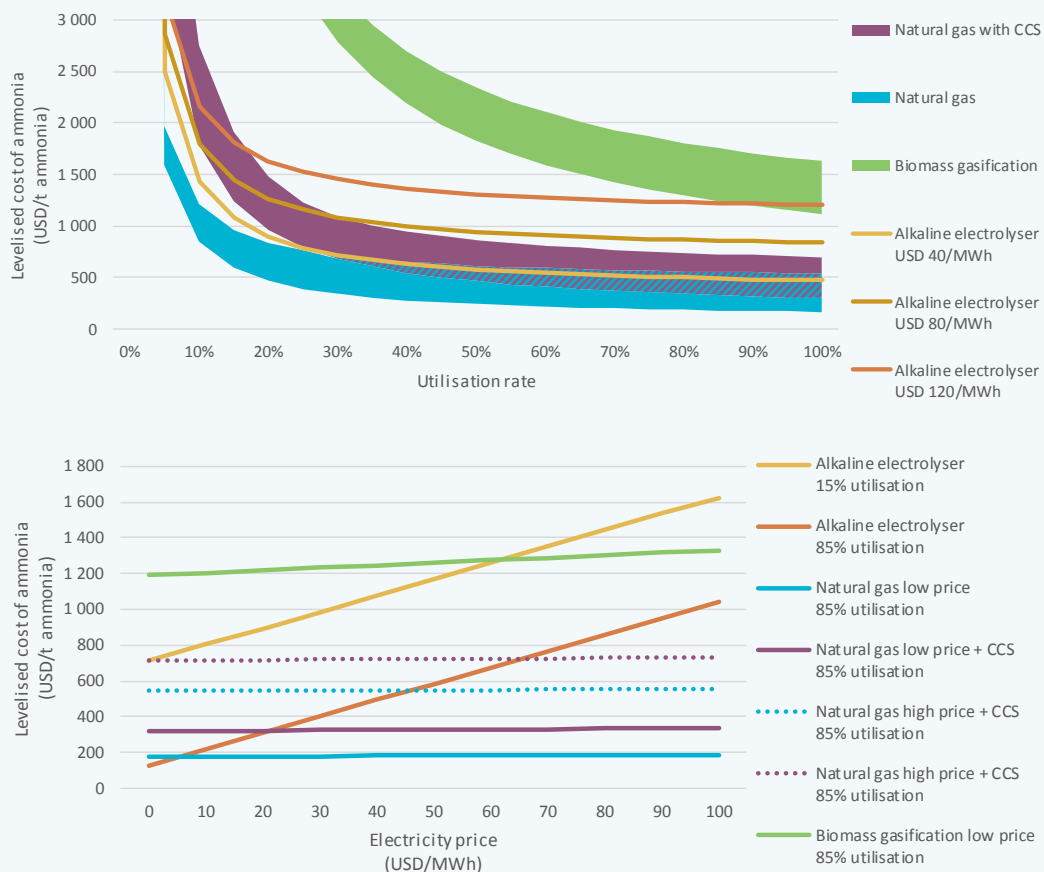
Key point *Natural gas-based ammonia is the primary process route in the B2DS.*

Box 4.2. Competitiveness of low-carbon ammonia production routes

In 2014, global production of ammonia, a primary chemical that is an essential precursor of fertilisers among other uses, was 169 Mt and is expected to increase by around 53% by 2060 in the 2DS. Ammonia (chemical formula NH_3) is synthesised from hydrogen and nitrogen. The production of hydrogen is the most energy- and carbon-intensive step in the ammonia production, as the CO_2 generated in the process must be separated before the synthesis step so that it does not adversely affect the synthesis reaction catalyst. Traditionally, fossil fuels have been the feedstock used to produce hydrogen (either through steam reforming of natural gas or partial oxidation/gasification of naphtha and coal). Currently over 95% of hydrogen is produced from steam reforming, primarily based on natural gas, though other fossil fuels are predominant in certain regions (e.g. coal-based ammonia production in China). Globally, ammonia production is responsible for about 420 Mt of net direct CO_2 emissions annually, 1.2% of the world's total. There are several options to drastically reduce the carbon footprint of ammonia production, including hydrogen generation through gasification of biomass or renewable electricity-based water electrolysis, and capturing and permanently storing the process CO_2 from fossil fuel-based hydrogen production. The limited availability of sustainable biomass, along with high demand levels, leads to relatively high biomass prices in the low-carbon scenarios, which together with high capital investment needs, makes the biomass gasification route for ammonia production less cost-competitive in most modelled regions, compared with permanently storing CO_2 generated from fossil fuel-based hydrogen or using hydrogen produced from renewable electricity. Generally, hydrogen produced through electrolysis combined with ammonia synthesis, in combination with renewables-based electricity, could provide CO_2 emissions reduction compared with fossil fuel-based process routes, at a more competitive cost than with biomass gasification.

For electrolysis routes for ammonia production to be competitive with steam methane reforming with CCS, either natural gas prices would need to be consistently high, or there would need to be a reliable supply of very low cost renewables-based electricity (Figure 4.14). Within a low-carbon scenario context, it is unlikely these conditions would be widespread enough to make this process route competitive at a large scale (see Chapter 6); the exception could be investment in dedicated renewables capacity with power purchase agreements.

4.14. Figure : Levelised cost of ammonia by process route



Notes: Alkaline electrolyzers are assumed to have capital expenditure (CAPEX) of USD 1 175 per megawatt (MW) for a unit with capacity of 150 kilowatts (kW) and a 71.5% efficiency rate. Natural gas-based ammonia production has assumed CAPEX of USD 635/t ammonia, for 1.15 Mt/year capacity. Biomass gasification has CAPEX of USD 6 000/t ammonia. Air separation units CAPEX = USD 9/t nitrogen; ammonia synthesis CAPEX = USD 95/t ammonia; and CO₂ capture, transport and storage costs of USD 9/tCO₂ captured (process emissions are inherently separated). A discount rate of 8% and a 25-year technical lifetime are applied to all technologies. Natural gas prices considered are USD 2.5/GJ to USD 15.4/GJ and biomass prices range from USD 8.2/GJ to USD 18.7/GJ. High to low cost ranges refer to the range of fuel prices and electricity prices. Costs are current assumptions based on 2015 USD. Energy prices and utilisation rates are hypothetical ranges.

Sources: IEA (2015b), *Technology Roadmap: Hydrogen and Fuel Cells*; Morgan (2013), "Techno-economic feasibility study of ammonia plants powered by offshore wind".

Key point Competitiveness of alternative routes for ammonia production is dependent on energy price, CAPEX, and utilisation rate.

Furthermore, capital expenditure for electrolyzers remains high compared with that of steam reforming equipment. Additional technology development and equipment scale-up could bring the costs of this process route down in the future. If these conditions are met, in some regions, future ammonia production capacity could be sited near renewable electricity capacity, as the ammonia can be stored and transported more easily than hydrogen.

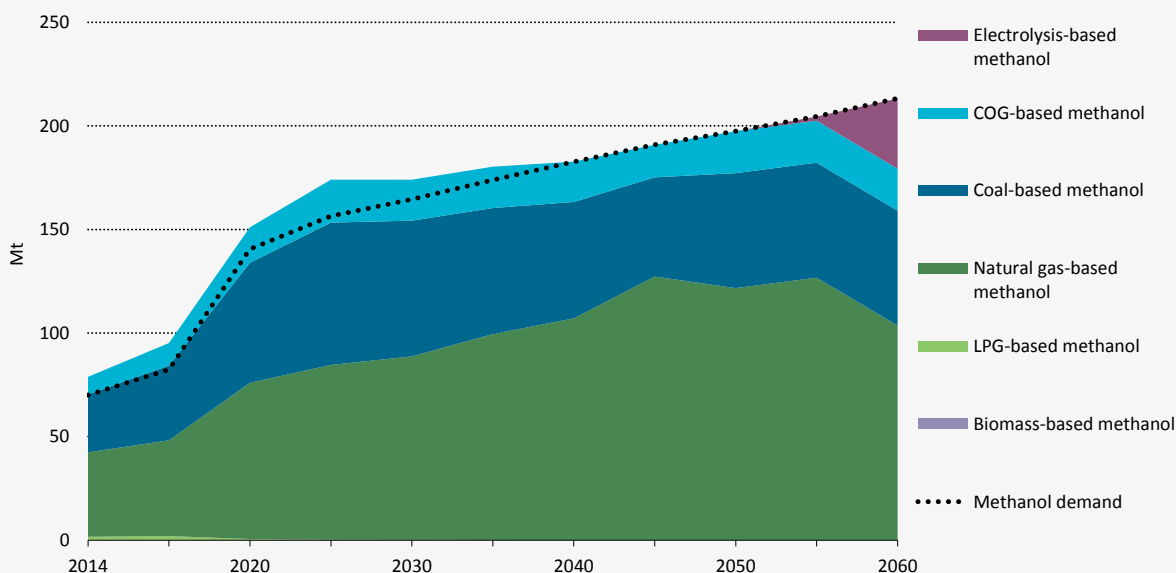
Methanol

Methanol is commonly produced from natural gas feedstock (representing 52% of installed global capacity in 2014). Coal and coke oven gas-based methanol also play important roles, especially in China. These account for 46% of global production (Figure 4.15). In the B2DS:

- As the industry sector becomes increasingly carbon-constrained, methanol production shifts slightly away from coal-based production, which accounts for 26% of global methanol production in 2060. Coke oven gas also loses share slightly, at 9% in 2060.
- Natural gas-based methanol production does not completely dominate the global methanol market as is observed in ammonia production, as its share of global methanol production remains at similar levels in 2060.
- The electricity-based hydrogen and captured CO₂ route for the production of methanol makes inroads only by about 2055 due to greater relative production costs than other process routes. As with HVC and ammonia, biomass gasification for methanol production is not identified as cost-competitive among other options for carbon mitigation in the extreme low-carbon scenario, thus playing a marginal role in the B2DS.

Figure

4.15. Global methanol production by process technology in the B2DS



Key point

About half of global methanol production by 2060 in the B2DS comes from natural gas. Surplus production is due to methanol used as feedstock in the methanol-to-olefins process.

Box

4.3. Current status of low-carbon processes in the chemicals and petrochemicals subsector

Commercial low-carbon process technologies:

- **Naphtha-based catalytic cracking for the production of olefins**³⁶ shows an improvement in energy intensity compared with the widely used steam cracking process (Ren, Patel and Blok, 2006). After successful pilot testing, the first commercial catalytic cracking plant was constructed in Korea in 2010 based on technology developed by the Korea Research Institute of Chemical Technology, with a capacity of 40 kt per year of light olefins (Tallan et al., 2011).
- While the **MTO** route is more energy-intensive than steam cracking when including the methanol production stage, it enables the production of light olefins from gas and coal, as well as from biomass in the longer term.

Innovative low-carbon process technologies at the demonstration phase:

- While **carbon capture applications** are mature in ammonia and methanol production processes that generate high-purity CO₂ gas streams, carbon capture techniques in steam cracking, as well as from diluted CO₂ flue gas streams generated in chemical production sites, have yet to be scaled up (IEA, 2011, 2013).
- The use of **biomass as feedstock for chemicals production** is being explored by many research projects, pilot plants and semi-commercial plants. Biomass can be used to produce light olefins and subsequent products in several ways, including biomass gasification with subsequent MTO, or biomass fermentation to ethanol followed by dehydration into ethylene. The energy consumption of these biomass-based routes is 3.5 to 5 times greater than fossil fuel-based routes overall, so emissions reduction benefits should be weighed against energy requirements (IEA, ICCA and Dechema, 2013). Reducing energy consumption and costs in current biomass-based chemical production routes are areas for further research.

Low-carbon innovative process technologies at the R&D phase:

- **Low-carbon hydrogen generation could reduce energy requirements for producing ammonia and methanol**,³⁷ as hydrogen generation is one of the most energy-intensive stages within these processes. Catalysts could enable photo-catalysis or photovoltaic-assisted water electrolysis, which are at the fundamental research phase, to open new research avenues for less CO₂-intensive ammonia and methanol production processes. A number of research projects looking at electrochemical ammonia production are ongoing.
- **Enhanced membrane separation techniques** involve a wide range of research activities.³⁸ Innovative nature-inspired mechanisms for membrane synthesis, including nanoscale surface patterning and self-organisation, are aimed at improving the sustainability of separation processes (Jullok, 2014).

36. The most important olefins are ethylene and propylene. These are major feedstocks for a variety of chemical products.

37. Water electrolysis with alkaline and PEM (proton exchange membrane) electrolyzers combined with ammonia synthesis have been included in the *ETP* scenarios, but other electrochemical ammonia production routes are not included.

38. Enhanced membrane separation techniques have not been included in *ETP* scenarios.

Iron and steel

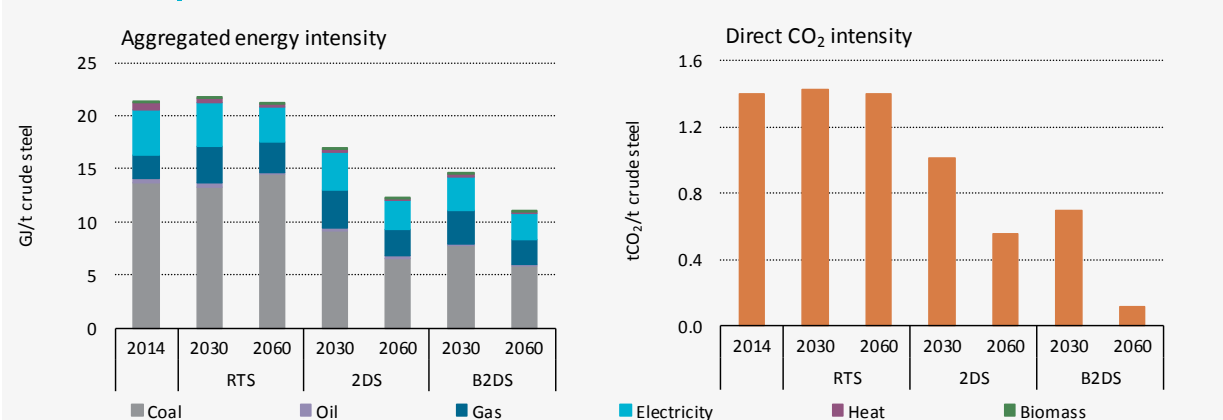
The iron and steel subsector accounts for 40% of the cumulative direct CO₂ global industry emissions reductions by 2060 in the B2DS compared with 44% in the 2DS.³⁹ Direct CO₂ global emissions must be dramatically reduced to 208 MtCO₂/year in 2060 in the B2DS (9% of current levels and about one-fifth of emission levels in the 2DS).

Currently, crude steel is primarily produced through the coke oven–blast furnace–basic oxygen furnace (CO-BF-BOF) route (70% of global production), while scrap-based electric arc furnaces (EAF) represent most of the remaining production. Thus the iron and steel sector is heavily dependent on the use of coal for the production of coke, the main reducing agent used to convert iron ore into pig iron (almost half of the total final energy mix of the subsector globally). Even by 2060 in the B2DS, 11 EJ of coal are consumed in the iron and steel sector.

The B2DS level of cumulative direct CO₂ emissions reductions imply a 48% reduction of the specific final energy requirements to produce crude steel by 2060 to 11.0 GJ/t crude steel⁴⁰ compared with the current global energy intensity and a drastic reduction in the direct CO₂ footprint of crude steelmaking to 0.12 t direct CO₂ per tonne of crude steel by 2060, a 92% reduction from current levels. However, reaching these long-term goals requires early action to avoid lock-in effects of inefficient capacity or delayed uptake of low-carbon innovative process technologies that would translate into a cost penalty in subsector's decarbonisation. The direct CO₂ intensity of crude steel production in the B2DS is reduced by 50% by 2030 compared with 2014, and aggregated energy intensity is reduced by 32% by 2030 compared with 2014.

Figure

4.16. Global energy intensity and direct CO₂ emissions of crude steel production by scenario



Notes: Direct CO₂ intensity includes process CO₂ emissions due to the use of lime as a fluxing agent in BFs and BOFs. Aggregated energy intensity includes energy use in process technologies from iron ore agglomeration to finishing of crude steel, as well as energy use in captive utilities for thermal energy generation that is used on-site.

Key point

While the aggregated energy intensity of crude steel decreases by 43% by 2060 compared with 2014 in the B2DS, direct CO₂ emissions intensity drops sharply by 61% in the same period.

The deep decoupling of crude steel production from CO₂ emissions needed in the B2DS requires a drastic change from current methods of producing crude steel to alternatives with

39. Including CO₂ emissions from blast furnaces and coke ovens, as well as from captive utilities for the generation of steam used on-site.

40. Including energy use in blast furnaces and coke ovens, as well as energy use in captive utilities for the generation of steam used on-site.

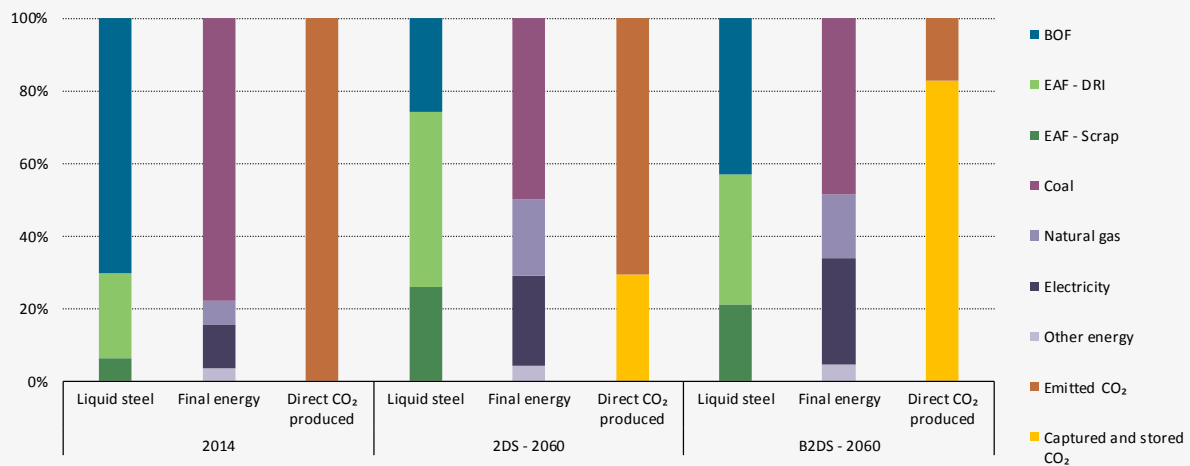
significantly lower carbon footprints. Exploiting the energy efficiency potentials by widely reaching BAT performance levels in commercial technologies and a higher penetration of more energy-efficient commercially available production routes such as scrap-based EAFs would not suffice for the B2DS target even if material efficiency strategies were also prioritised.

The global average energy intensity of the main production routes are: CO-BF-BOF crude steel production at 18.7 GJ/t crude steel; direct reduced iron-electric arc furnace (DRI-EAF) at 22.4 GJ/t crude steel; and smelt reduction-basic oxygen furnace (SR-BOF) at 21.4 GJ/t crude steel. These intensities compare to the lower energy footprint from scrap-based EAFs of 6.7 GJ/t crude steel (World Steel, 2017). Reaching BAT energy performance levels worldwide in all steel production routes would save 9 EJ per year.⁴¹ In the B2DS, while the shift to DRI and SR routes from BOF production increases energy intensity of steelmaking, the boost in the share of EAF-based production, which has a much lower energy intensity, fully offsets this change and decreases the global aggregated energy intensity of the subsector (Figure 4.16).

The further uptake of scrap-based and DRI-based EAFs is limited by the availability of scrap and electricity at competitive cost. In the case of DRI-EAF, availability and cost of either coal or natural gas can also be a limiting factor. Improving collection and processing rates of crude steel products results in a 173% increase in post-consumer scrap availability in 2060 globally in the 2DS compared with the RTS, and as a consequence, 57% higher uptake of EAF routes in global crude steel production in 2060 (Figure 4.17).

Figure

4.17. Global shares of liquid steel by route, final energy and direct CO₂ emissions in crude steelmaking



Notes: BOF = basic oxygen furnace; EAF = electric arc furnace; DRI = direct reduced iron. The BOF route includes BF-BOF and SR-BOF routes. The EAF route includes scrap-based and DRI-based EAF technologies. Final energy use includes BFs and COs, as well as energy use in captive utilities for the generation of steam used on-site. Other energy includes the use of commercial heat. Liquid steel is steel in molten form before casting.

Key point *Reduced electricity use due to lower overall scrap availability in the B2DS is offset by a higher uptake of CO₂ capture technologies.*

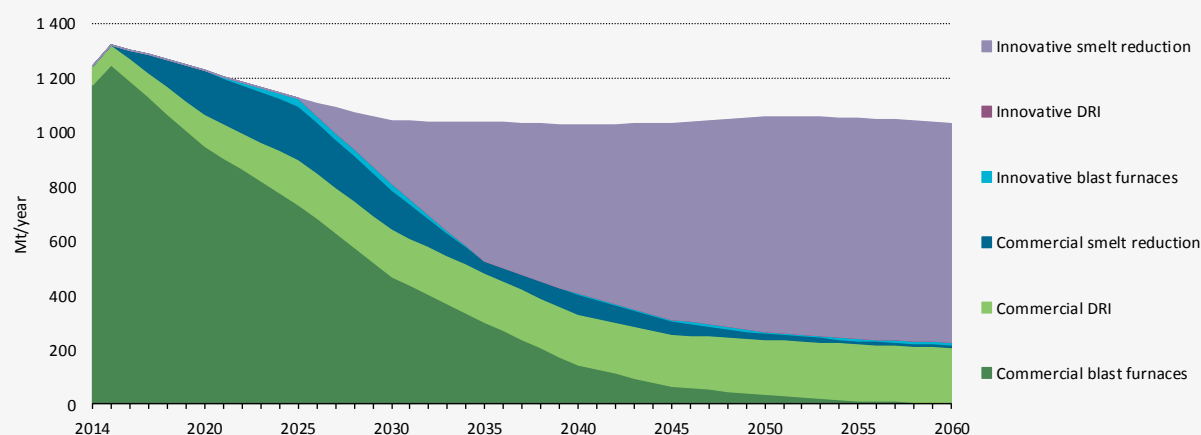
In contrast with the 2DS, in the B2DS the implementation of additional material efficiency strategies, such as improving the manufacturing and semi-manufacturing yields in

41. Based on 2014 shares of different process routes and compared with global average energy intensities in 2014.

steelmaking, enables a significant reduction of internal scrap and pre-consumer scrap production, which results in a cumulative decrease in global crude steel demand.⁴² As products are produced with less material loss, the amount of crude steel needed to meet demand for final steel products decreases by 12% in the period 2014-60, or about 11 Gt less crude steel demand. As a consequence, there is a reduction in the overall amount of scrap available compared with the 2DS (26% less over the period to 2060). The effect of decreased crude steel demand translates to 99 EJ or 7.7 GtCO₂ of cumulative savings compared with the 2DS, which offsets the impact of having more limited potential to increase the share of EAFs in the total production stock, about 25% reduced share in 2060 (23 EJ or 2.0 GtCO₂ cumulative savings).⁴³

Figure

4.18. Global hot metal production in the iron and steel subsector by process technology in the B2DS



Notes: Hot metal is provided in million tonnes of pig iron for BFs and SR technologies, and in million tonnes of DRI for DRI technologies. Innovative BFs include blast furnaces with top gas recovery, where BFG is reinjected into the blast furnace after the removal of the CO₂ contained in the off-gas stream and hydrogen amplification. Innovative DRI includes Ulcored, which is a DRI-based technology using natural gas as the feedstock to generate the synthesis gas for the reduction of iron ore. Innovative SR includes Hlsarna, an advanced smelt reduction process.

Key point

Crude steel production shifts significantly from the blast furnace route to smelt reduction and DRI technologies in the B2DS.

While a shift towards BAT-level commercial DRI (especially natural gas-based) and SR processes for hot metal production play a transitional role globally in the B2DS (from 6% today to 29% in 2030), accelerated demonstration and rapid deployment of innovative low-carbon approaches in steelmaking are crucial to realise the long-term objectives of the B2DS. The hot metal production structure in crude steel manufacturing sees a dramatic shift from the CO-BF route to upgraded SR and DRI processes from 2030 onwards in the B2DS (Figure 4.18). According to the latest techno-economic demonstration results and assuming successful demonstration at commercial scale, upgraded innovative SR processes such as Hlsarna are found to be the most cost-effective strategy to deeply reduce the direct carbon footprint of hot metal production in crude steelmaking (Box 4.4). In the B2DS, they represent 43% of global hot metal production by 2060, compared with 17% in the 2DS and only 1% in the RTS. However, these results are sensitive to the techno-economic characteristics of innovative low-carbon processes, which are likely to change as

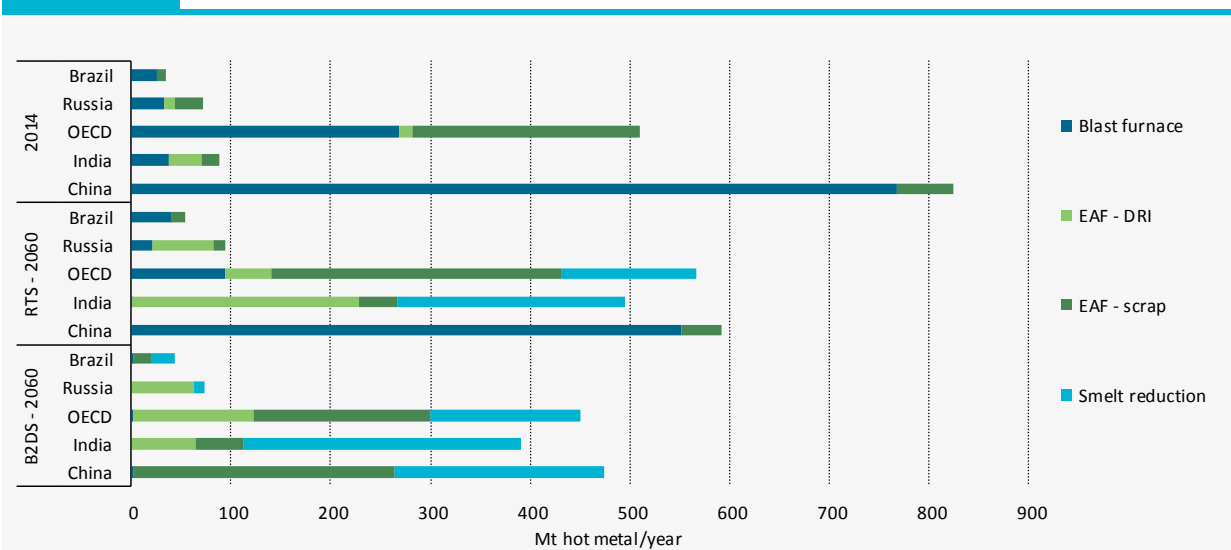
42. Internal scrap and pre-consumer scrap refer to material losses generated within the manufacturing (e.g. continuous casting) and semi-manufacturing processes (e.g. rolling) of crude steel. These material losses are typically reintroduced in the process through after being remelted.

43. Energy and CO₂ emissions savings are calculated based on the B2DS energy and direct CO₂ intensity of crude steelmaking at each time step through the modelling horizon.

commercial-scale demonstration advances. Thus it is important to accelerate demonstration activities in all steel production routes to ensure that there are sufficient alternatives in the long term to fulfil objectives within various regional contexts, while also assuring operation reliability and scalability at competitive cost.

There are considerable differences in the hot metal process routes deployed in various countries/regions (Figure 4.19). In China, which accounts for 26% of global crude steel production in 2060 in the B2DS, SR process shares more than double in that scenario compared with the 2DS. In India, where currently one-third of global DRI production is located, this process route maintains an important role in the B2DS by 2060 (16%), although it is 61% lower than in the 2DS in 2060.

Figure 4.19. Hot metal production in the iron and steel subsector by process route and region



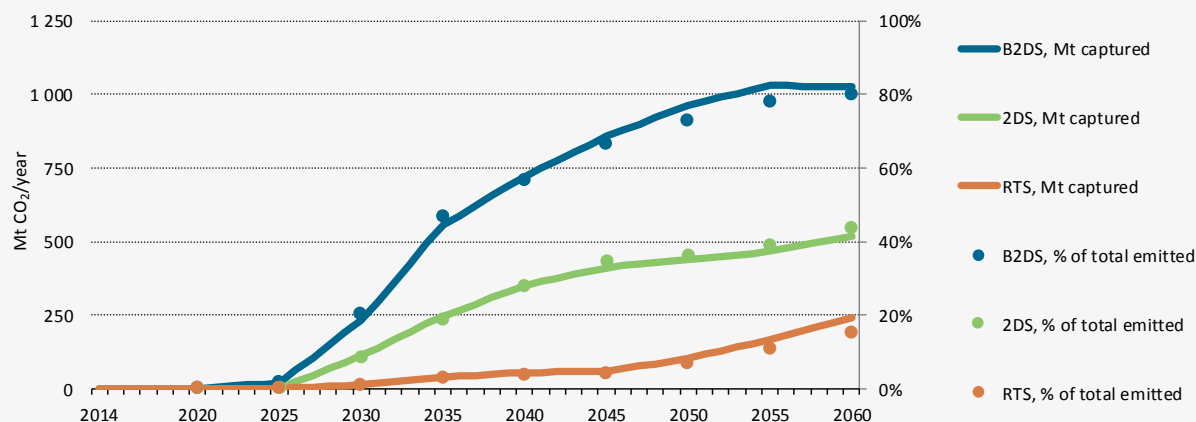
Notes: Hot metal is provided in million tonnes of pig iron for blast furnaces and smelt reduction technologies, and in million tonnes of DRI for DRI technologies. Not all regions are shown. Hot metal production shown does not sum to global production.

Key point *The shift to SR and DRI process routes accelerate in the B2DS.*

The introduction of carbon capture for permanent storage coupled with upgraded process technologies for hot metal production that incorporate oxygen-rich conditions becomes an important strategy in the iron and steel subsector to meet the direct CO₂ emissions reduction needed in the B2DS (Figure 4.20). Cumulatively 26 GtCO₂ are captured and permanently stored from 2014 to 2060 globally (about one-fourth of the total carbon emissions reductions in the subsector compared with the RTS).⁴⁴ Of the global cumulative CO₂ captured and stored, 31% is in India and 25% in China in the B2DS.

44. These operating conditions facilitate the implementation of carbon capture technologies as the generated off-gases have a greater concentration of CO₂.

Figure

4.20. Global CO₂ emissions captured and stored in the iron and steel subsector by scenario

Key point

Cumulatively, about 26 GtCO₂ emissions are captured and stored from crude steel production by 2060 in the B2DS, more than double the level in the 2DS.

Box

4.4. Current status of low-carbon innovative processes in the iron and steel subsector

Innovative low-carbon process technologies at the demonstration phase:

- Promising first steps have been taken in the iron and steel subsector to **integrate carbon capture technologies** in hot metal processes. The first commercial project came on line in 2016 in the United Arab Emirates and is a natural gas-based DRI process, where the 800 kt per tonne of captured CO₂ per year is used for enhanced oil recovery purposes (Global CCS Institute, 2017).
- **Hlsarna** is an upgraded SR-based process developed by Ultra-Low Carbon Dioxide Steelmaking (ULCOS), a research programme of the European Commission. Hlsarna combines a hot cyclone and a bath smelter and does not require the use of coke or sinter. As the process operates with pure oxygen, off-gases have a CO₂ concentration almost high enough to be directly stored (Birat, 2010). Commercial-grade steel was first produced through the Hlsarna process in 2013 and continued in June 2014 supported with private funding. A longer trial of about three to six months to test process stability and continuous operation began in 2016 (Tata Steel, 2017) and additional public funding has been provided by the LoCO₂Fe programme through Horizon 2020 (European Commission, 2017). The outcome of this trial will determine design parameters for a commercial-scale plant (ESEC, 2014).
- **COG reforming** is a process that partially converts carbon compounds of COG into hydrogen and carbon monoxide. The COURSE 50 programme in Japan (CO₂ Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) is developing a process that uses this technique to produce enhanced reducing gas for BF, coupled with CO₂ capture. An experimental BF for testing a hydrogen-enriched reducing agent is planned to be built by the end of 2017 (ESEC, 2014). POSCO, a Korean

steelmaker, and its Research Institute of Industrial Science are also developing a conversion process to produce a hydrogen-rich gas from COG and CO₂ through steam reforming, which could be used for iron ore reduction in a BF or SR process. The design of the COG reforming process was completed in 2012 and a pilot plant was under construction as of 2013 (RIST, 2013).

- **BF top gas recovery (BF-TGR) with carbon capture** is a process technology developed by ULCOS. Top gas, a byproduct of BFs, is collected, treated and reused as a reducing agent to displace coke use. The BF-TGR system also operates with pure oxygen, which enables a higher concentration of CO₂ in the top gas and thus easier carbon capture (Birat, 2010). A commercial-scale plant planned for the ArcelorMittal site in Florange, France, was stopped in 2013 for financial reasons.
- **Ulcored**, a DRI-based process, was also developed by the ULCOS research programme. DRI is produced by reducing iron ore in a shaft furnace with reducing gas from coal gasification or gas reforming. Off-gases from the shaft are reused in the process after CO₂ capture (Birat, 2010). In 2013, there were plans to build a pilot plant to produce 1 t of DRI per hour to demonstrate this process. However, these plans have not materialised as of first quarter 2017 (LKAB and ULCOS, 2013).
- **Use of renewables-based electricity to produce hydrogen** instead of fossil fuel-based synthesis gas, as a reducing agent in natural gas-based DRI processes, would reduce CO₂ emissions (SSAB, 2016).⁴⁵ A commercial-scale facility using fluidised-bed systems with fossil-based hydrogen as a reducing agent operated in Trinidad from 2000 to 2005 (Nuber, Eichberger and Rollinger, 2006). A pre-feasibility study for a project using electricity-based hydrogen is under way in Sweden and is expected to be followed by a pilot operation through 2024 and a large-scale demonstration through 2035 (SSAB, 2017).

Innovative low-carbon process technologies at the R&D phase:

- **Ulcowin and Ulcolysis are electricity-based process concepts that produce iron using electrolysis reduction systems**, developed by ULCOS.⁴⁶ Ulcowin consists of an aqueous electrolysis of iron oxide at 110°C. The principle of Ulcolysis is the decomposition of iron ore into oxygen and liquid metal at 1 550°C in a similar manner to the Hall-Hérout aluminium production process. Both concepts have been proven at experimental scale. Wider sustainability benefits of these processes rely on the use of renewables-based or carbon-free electricity.

Cement

Increasing demand for cement, driven partially by population growth and urbanisation, will fuel more cement production with a consequent rise in energy consumption and CO₂ emissions. However, despite this pressure, to meet the climate objectives of the B2DS, the cement sector requires aggressive carbon emissions reductions to limit residual emissions to 485 MtCO₂ in 2060, equivalent to 32% of the 2DS level.⁴⁷ These emissions reductions must be rapidly achieved, with 2030 emissions levels in the B2DS already 18% below the 2DS. The cement sector has a high share of process CO₂ emissions that cannot be reduced via energy efficiency or fuel switching and cannot be fully captured, which emphasises the scale of the challenge in cement manufacturing.

45. Renewables-based electricity to produce hydrogen for steelmaking has not been included in *ETP* scenarios.

46. Ulcowin and Ulcolysis have not been included in *ETP* scenarios.

47. Residual emissions refer to those that remain in 2060, which will need to be offset by negative emissions elsewhere in order to reach net-zero emissions for the energy system.

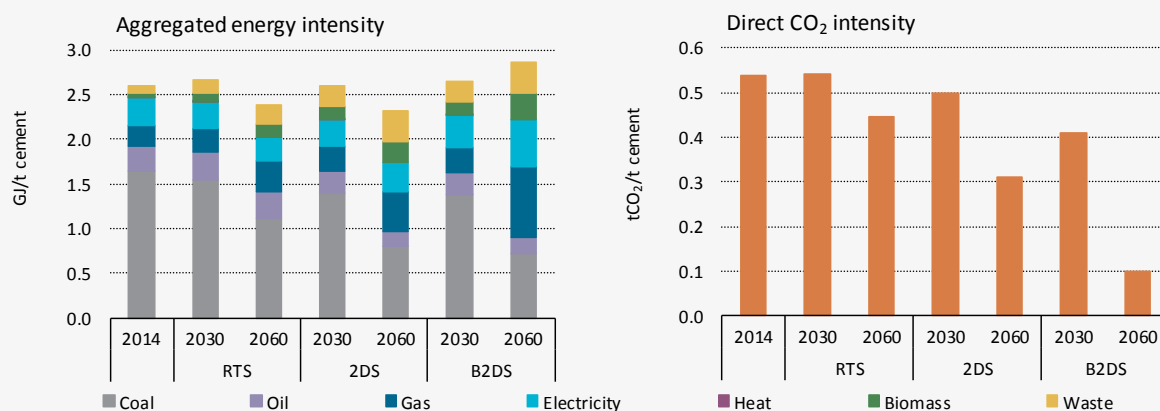
Currently, rotary dry-process kilns are the most widely deployed process technology for cement production. These kilns heat raw materials, including limestone for calcination, to about 1 450°C, calcining the limestone and creating clinker, which is the main ingredient in cement. Dry kilns have better energy intensity compared with wet-process kilns, as they operate with a low level of raw material moisture content thereby reducing the energy intensity.

In many regions, the cement production uses coal and oil for fuel, though the co-firing of alternative fuels, such as biomass and wastes, is becoming more prevalent. However, the most significant share of CO₂ emissions from making cement is process-related. Cement manufacturing requires calcined limestone as its primary raw material, and the calcination of limestone releases carbon dioxide ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$). These emissions, which stem from the chemical reactions inherent in the process, rather than from fuel combustion, accounted for 63% of the cement subsector's total CO₂ footprint in 2014. Process emissions, combined with cement production's reliance on fossil fuels, make deep decarbonisation of cement production difficult. By 2060 in the B2DS, process emissions account for two-thirds of the subsector's total emissions, as lower-carbon fuels gain ground and the energy-related emissions are reduced.

In the B2DS, aggregated sector-level energy intensity increases to 2.9 GJ/t cement in 2060, 11% above 2014 and 24% above the 2DS level, due primarily to the energy penalty associated with CO₂ capture (Figure 4.21). Meanwhile, the overall direct CO₂ intensity of the cement subsector (in tCO₂ per tonne of cement produced) drops dramatically by 2060 in the B2DS, to 73% below the level of the 2DS.

Figure

4.21. Energy intensity and direct CO₂ emissions intensity of global cement production by scenario



Notes: Direct CO₂ intensity includes process-related CO₂ emissions generated in the calcination of limestone for the production of clinker, the main precursor of cement. Petroleum coke is included in oil. Aggregated energy intensity includes energy use in process technologies from raw materials preparation to cement finishing. Energy intensity increases in later years in low-carbon scenarios primarily due to the energy penalty associated with CCS.

Key point

While the aggregated energy intensity of cement increases by 11% in the B2DS by 2060 compared with 2014, direct CO₂ emissions intensity drops sharply by 82%.

Early action is required in the cement sector, in order to avoid more costly investments in the long run. In the B2DS, 83% of cumulative emissions reductions come from implementing CCS, which is still only at demonstration phase for cement production and requires additional investment before 2030 in order to be ready for deployment at commercial scale. Similarly, construction standards and regulatory changes will be needed to allow new and innovative low-carbon cement products to be widely adopted, which may delay the implementation of these options. Energy efficiency improvements and switching to

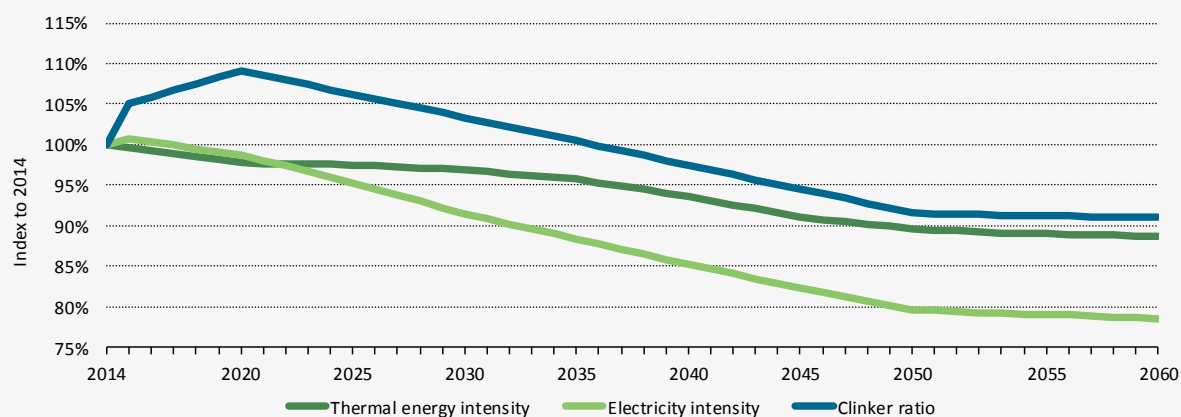
lower-carbon fuels should be deployed as soon as possible to maximise their carbon emissions reduction potential and to bridge the gap in CO₂ emissions reductions until more innovative and early-stage technology options are available. In the B2DS, one-quarter of annual emission reductions in 2030 come from energy efficiency and fuel switching, compared with 9% in the 2DS.

Though aggregated energy intensity increases overall, the cement subsector shifts towards a higher share of low-carbon fuels in the 2DS and B2DS. By 2060, the share of coal decreases to 25% from 63% in 2014, while biomass increases from 2% to 11% and waste fuels from 3% to 12%. Overall, fossil fuels drop from 83% to 59% and natural gas makes up 48% of fossil fuels, compared with 11% in 2014.

A main lever for reduction of energy intensity and CO₂ emissions from cement manufacturing is switching the remaining wet-process and vertical kilns to dry kilns, and adding preheaters and pre-calciners to all existing dry kilns. The BAT, dry kilns with 4-5 stage preheaters and pre-calciners, can achieve a thermal energy consumption of about 2.9 GJ/t clinker. The global average for 2014 was 3.5 GJ/t clinker. Though the potential varies depending on raw materials characteristics and regulatory standards, there is significant room for improvement in many regions (Figure 4.22).

Figure

4.22. Improvements in thermal energy intensity, electricity intensity and clinker ratio in the B2DS



Notes: Global average values are shown. The short-term increase in clinker ratio is primarily due to limited availability of clinker substitutes in China.

Key point

Each of the three drivers improves significantly by 2060 relative to 2014.

Grinding technologies also present opportunities for energy efficiency in cement manufacturing. Efficient grinding technologies – such as roller presses and vertical mills – offer electricity savings over traditional ball mills. Electricity savings in grinding cement would benefit the overall energy efficiency of the manufacturing process. CO₂ emissions savings associated with this reduced electricity demand are accounted for in the power sector.

Reducing the clinker ratio is one of the simplest and most effective ways of reducing energy and CO₂ intensity of cement manufacturing. Clinker is the main ingredient in cement; its production is the most energy- and CO₂-intensive part of cement production. Clinker is then blended with other minerals, which influence the hardening properties of the cement, such as setting time. National average clinker ratio can be reduced to 50-60% for some regions, depending on availability of alternative materials and clinker substitutes. The exact specifications for different cement types vary according to regulatory requirements and the

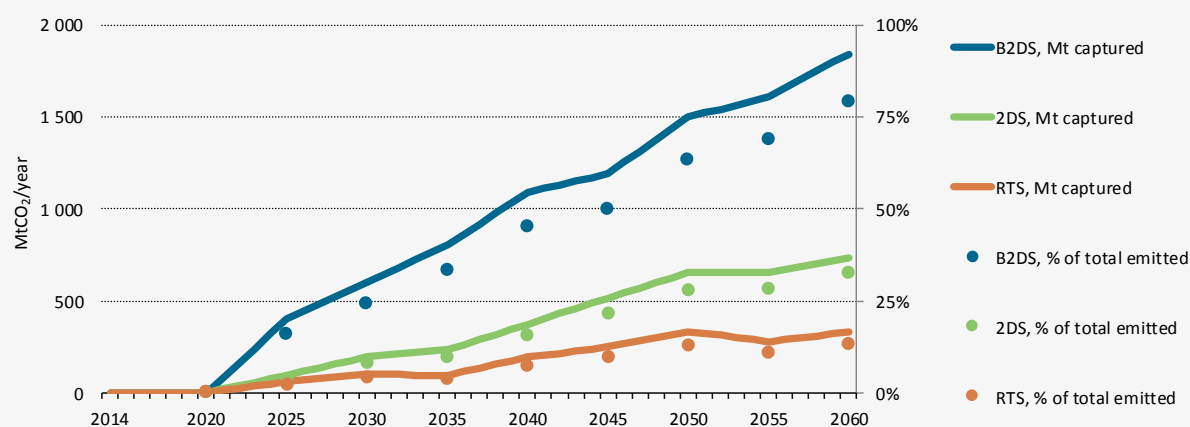
properties needed according to the application where the cement will be used. Traditional clinker substitutes (such as BF slag and coal fly-ash) will be less available in a B2DS context due to decreased conventional BF steelmaking and fossil fuel-based power generation, so alternative sources need to be explored. For example, calcined clay, which is widely available across regions, could be used as a clinker substitute. However, calcined clay has an associated energy penalty, in that it must also be calcined, though calcination occurs at around 800°C and uses about 55% of the energy needed for clinkerisation (LC3, 2017).

In the B2DS, global average clinker ratio reaches 0.59 by 2060, but the potential for substitution is not uniform. India, which is the world's second-largest producer of cement (275 Mt in 2014), has the highest reduction in clinker ratio in the B2DS, reaching 0.50 by 2060 from 0.70 in 2014. China, the world's largest cement producer, also reduces its clinker ratio, reaching 0.55 by 2060 from 0.57 in 2014, though in the short term China faces constraints on traditional clinker substitutes that will delay the realisation of these reductions. Even a small reduction in clinker content per tonne of cement can have a large impact for a producer like China, which produced nearly 2.5 Gt of cement in 2014, about 60% of global production. Though China's production is expected to peak before 2020, it will remain the world's largest cement producer and in the *ETP* scenarios produces about 1.7 Gt of cement in 2060.

The B2DS requires drastic reductions in energy demand and CO₂ emissions from cement production, most of which will have to come from alternative low-carbon process technologies. Oxy-fuelling kilns, which have synergies that facilitate integrated carbon capture, are a key technology option for the long term. Though this technology is proven, it is not currently commercially deployed; this would need to be scaled up so that 7% of clinker production will come from kilns with full oxy-combustion conditions by 2060 in the B2DS, compared with just 0.2% in the 2DS. Partial oxy-combustion with enriched oxygen conditions in the preheater only, which also facilitates CCS integration, is an option though a smaller share of the overall CO₂ emissions are captured compared with full oxy-fuelling. Partial oxy-combustion accounts for 30% of clinker production in the B2DS in 2060, compared with 12% in the RTS and 28% in the 2DS.⁴⁸

Figure

4.23. Global CO₂ emissions captured and stored in the cement subsector by scenario



Key point

By 2060, nearly 80% of emitted CO₂ is captured and stored in the B2DS.

48. Both full and partial oxy-combustion with carbon capture are more economical options for the cement subsector than post-combustion CO₂ capture with chemical absorption according to available techno-economic data. These considerations could change based on technology learning rates and cost reductions that come as additional demonstration projects become operational and as deployment accelerates.

In the B2DS, CCS is deployed extensively in cement production by 2060, reaching a total of 1.8 Gt CO₂ captured annually by 2060 (Figure 4.23). CCS is deployed at an aggressive rate in China and India, as the two main producers, and in developing Asia in general (1.1 GtCO₂ captured in 2060). OECD countries also see significant CCS deployment in 2060 in the B2DS (228 MtCO₂). In 2060 in the 2DS, the global level of CCS deployment is about 40% of B2DS levels (737 MtCO₂ annually by 2060). This reliance on CCS to offset process emissions demonstrates the need for early development of CCS transport and storage infrastructure in all sectors (see Chapter 7).

In addition to capturing fossil fuel-based emissions from cement kilns, CCS in cement manufacturing could also capture some emissions associated with biomass combustion. As biomass is considered to be carbon neutral in the *ETP* scenarios, any biomass-based emissions captured are counted as negative emissions. As biomass co-firing becomes more common in kilns in the cement industry, and as carbon budgets become more restrictive in a 2DS or B2DS context, this could offer significant added value at the system level. The amount of sustainable biomass available, as well as its cost and its value for CO₂ reductions in other sectors, will dictate how much of the potential can be used (see Chapter 8). In the B2DS, negative emissions from the capture of CO₂ from biogenic sources in the cement subsector account for 146 MtCO₂ annually by 2060, compared with 48 MtCO₂ in the 2DS.

Despite the significant role that carbon capture needs to play in the cement sector, and the necessity of rapidly scaling up its deployment in order to meet a 2DS or B2DS target, progress has been limited to date. Early-stage research is ongoing and several technologies are being tested at pilot scale. In the B2DS, almost 400 MtCO₂ must be captured in 2025; however, there are currently no large-scale demonstration projects in operation.

Additional long-term opportunities could arise from development and implementation of low-carbon cement processes based primarily on carbon-free raw materials, which could avoid the problem of process emissions and exploit synergies with CCS. Accelerated laboratory endurance tests to validate new materials are needed to bring these options to commercial scale. Early deployment is expected to begin in niche applications, as a starting point to build market confidence, before expanding the portfolio of applications where they can be used and revising construction and infrastructure codes to allow further penetration of these materials in the market (Box 4.5).

Box

4.5. Current status of low-carbon innovative processes in the cement subsector

*Commercial low-carbon process technologies.*⁴⁹

- **Cement with reduced clinker content** is present in the market. These cements use clinker substitutes such as BF slag, fly ash, natural pozzolanas, calcined clays, additional limestone, or other materials such as industrial byproducts and residues with pozzolanically reacting properties. The extent of their deployment and future potential depends on market acceptance, standards and regulations, and price and availability of raw materials. Each has slightly different characteristics and suitable applications (ECRA, forthcoming; Scrivener et al., 2016).
- **Alkali-activated binders** (sometimes called geopolymers) are an alternative to traditional cement products, which can reduce CO₂ emissions depending on the emissions associated with production of alkaline activators. One commercial plant producing these binders has been built, but to date they have been primarily used in non-structural applications. Availability of slag, the primary clinker substitute in alkali-activated materials, is a major limitation to deployment and system-level CO₂ reductions (ECRA, forthcoming; Scrivener et al., 2016).
- **Belite cements**, suitable for large concrete structures and commercially available, have a lower limestone content and reduced burning temperature (1 350 °C), thereby reducing the fuel needed for calcination and consequent CO₂ emissions, though energy use for grinding is increased. Belite cements produced at even lower temperatures (600°C to 900°C) have been produced at lab scale (ECRA, forthcoming; Scrivener et al., 2016).
- **Calcium sulphoaluminate clinker** with lower sintering temperatures and energy requirements for grinding have been produced commercially for decades, primarily in China. Their use for emissions reduction is limited primarily by market acceptance in a broad range of applications, and the cost of alumina and sulphates (ECRA forthcoming; Scrivener et al., 2016).

Innovative low-carbon innovative process technologies at the demonstration phase:

- **Post-combustion carbon capture in cement kilns** can be implemented in existing facilities where there is enough space for the additional equipment (IEA and WBCSD, 2013). Several separation technologies (amine scrubbing, dry adsorption, membranes and carbon looping) were studied through small-scale trials at the test facility in Brevik, Norway, in 2013–16. A pilot plant using calcium looping to capture 1 tCO₂ per hour was commissioned in 2013 in Chinese Taipei. A plant has been constructed in Texas, United States (US), to capture and transform 75 kt of CO₂ per year from a cement plant into sodium bicarbonate, bleach and hydrochloric acid, which can be sold on the market (ECRA, forthcoming).
- **Oxy-fuel combustion for carbon capture** in cement kilns uses oxygen-enriched gas in the combustion process, which increases the concentration of CO₂ in the flue gases. Implementation requires re-engineering the plant to accommodate the needed equipment. It also incurs additional operating costs for the provision of oxygen and could lead to a net increase in energy consumption depending on operating conditions (ECRA, forthcoming). The implementation of oxy-fuelling in the kiln pre-calciner was tested in a pilot plant capturing 1 tCO₂ per hour in Dania, Denmark, with positive results that led to a feasibility and cost study of retrofitting this technology to an existing commercial-scale facility in Le

49. Types of cement with reduced clinker content are included in the *ETP* scenarios, but alternative materials and products are not included.

Havre, France (IEAGHG, 2014). A first large-scale demonstration of this concept is not expected before 2020 (ECRA, forthcoming).

- **Low carbonate clinkers with pre-hydrated calcium silicates** could emit about 40% less CO₂ than standard Portland cement with low consumption of limestone and gypsum, although the manufacturing process is complex. The first industrial-scale demonstration is planned for 2017-18 (ECRA, forthcoming; Scrivener et al., 2016).

*Innovative low-carbon process technologies at the pilot phase.*⁵⁰

- **Direct separation of CO₂ from pre-calciner** will be piloted at a cement plant in Belgium, which will aim to separate and capture 95% of process CO₂ emissions from the cement plant. The project will operate from 2017-20 (LEILAC, 2017).
- **Cement based on carbonation of calcium silicates** can sequester CO₂ as they are cured. It has been tested at pilot scale. These types of cement are primarily suited to precast applications, but some existing manufacturing equipment could be maintained (ECRA, forthcoming; Scrivener et al., 2016).

Innovative low-carbon innovative process technologies at the R&D phase:

- **Post-combustion capture using solid sorbents** involves carbonation of minerals to form stable carbonates that can be used as construction materials or safely stored. Energy requirements are estimated at 3 GJ per tCO₂ captured and mineral mass requirements at about 1.8 t to 3 t per tCO₂ (ECRA, forthcoming).

Aluminium

The aluminium subsector accounts for 3% of the cumulative reduction of global direct CO₂ emissions from the industry sector by 2060 in both the B2DS and the 2DS. Annual global direct CO₂ emissions from aluminium production fall to 124 MtCO₂/year by 2060 (equivalent to 54% of current emission levels).⁵¹ This is about half of the 2060 levels in the 2DS, which stand at around 244 MtCO₂/year by 2060. The subsector also plays a significant role to curb process-related CO₂ emissions. In the B2DS, it accounts for 12% of total cumulative process-related CO₂ emissions reductions.

Global production of primary aluminium in 2014 was 55 Mt, of which about 28 Mt was in China, 3.5 Mt in the Russian Federation (hereafter, "Russia") and 2.9 Mt in Canada. Smelting is an electrolytic process, which means that electricity plays a significant role with 62% of total energy demand in this subsector. Coal and gas are used primarily for anode production and refining of bauxite. Production of recycled aluminium involves refining and remelting scrap. The primary production route is significantly more energy-intensive than recycled production, which uses 93% less energy per produced tonne of aluminium.⁵²

In addition to its higher energy intensity, primary aluminium production also implies more CO₂ emissions per tonne of aluminium than recycled production. Apart from additional fuel combustion, process-related CO₂ emissions released from the reaction in the smelter of alumina (aluminium oxide) with the carbon-based anodes make up 1.53 tCO₂/t primary aluminium. In 2014, 37% of direct CO₂ emissions in the aluminium subsector were process-related emissions.

The carbon emission reductions needed in B2DS demands that total energy intensity of primary aluminium production decrease by 18% to around 84 GJ/t by 2060 compared with current levels. Further it requires that CO₂ emissions intensity decrease to 1.7 tCO₂/t

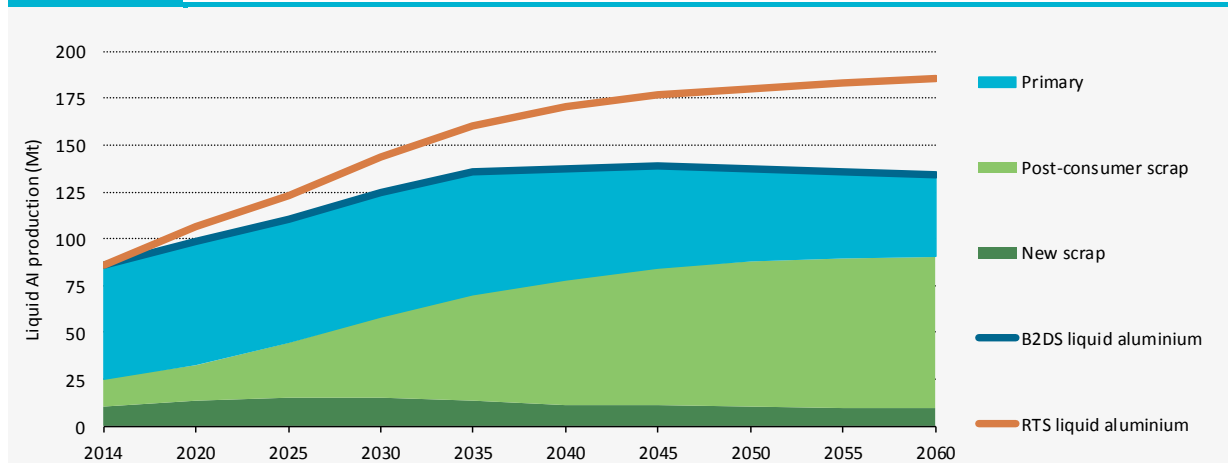
50. Cement sector process routes and products at the R&D phase have not been included in the *ETP* scenarios.

51. Including process CO₂ emissions from anodes.

52. The energy intensity for the primary production route includes energy use for refining of bauxite, the production of anodes and the smelting process. The calculation of energy intensity for secondary aluminium production does not include the energy for scrap cleaning and alloy dilution.

aluminium, a 59% reduction. In addition, the energy and emissions intensity levels of recycled production would both need to be cut in half to reach current BAT levels by 2060. Early investment is needed to avoid a more costly transition, as most energy intensity reductions are needed by 2030 to meet the B2DS.

Figure 4.24. Liquid aluminium production in the B2DS



Notes: Al = aluminium. Internal scrap is excluded.

Key point *Material efficiency strategies significantly reduce overall demand in the B2DS.*

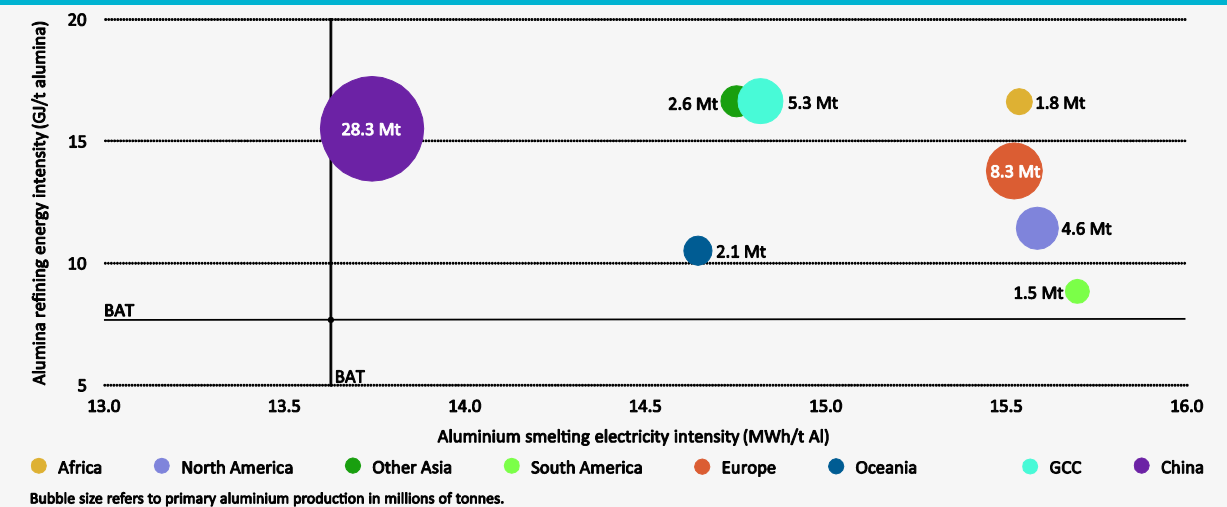
Material efficiency can play an important role in reducing the CO₂ impact of aluminium production. In the RTS, aluminium production levels are expected to more than double by 2060, while in the B2DS, production of aluminium increases by only 59% by 2060 due to material efficiency strategies, including improved manufacturing and semi-manufacturing yield rates and post-consumer scrap reuse.

Increases in scrap-based production of aluminium are limited by the availability of scrap. Improving recycling rates across all types of product categories increase the total cumulative availability of scrap by 16% through 2060 in the 2DS compared with the RTS. Cumulative recycled production of aluminium makes up 61% of total production of aluminium in 2DS, compared with 57% in the RTS. In the B2DS further material efficiency, specifically improving semi-manufacturing and manufacturing yields, reduces the availability of internal and new scrap by 24% compared with 2DS, shifting the composition of scrap toward post-consumer scrap.⁵³ As a result, cumulative production of aluminium from recycled production as a share of total production decreases by 9% relative to the 2DS. The improved yields result in a 16% reduction of total cumulative aluminium production needed over the period 2014-60, compared with 2DS and RTS (Figure 4.24). This reduction in production corresponds to a 62 EJ decrease in cumulative energy consumption and a 2.4 Gt decrease in cumulative CO₂ emissions compared with 2DS.⁵⁴ The reduction in demand more than offsets the increase in primary production, providing cumulative net energy savings of 43 GJ and emissions savings of 1.9 GtCO₂ over the 2014-60 period.

53. *Internal and new scrap* refer to material losses generated within the manufacturing and semi-manufacturing processes.

54. Energy and CO₂ emissions savings are calculated based on 2DS energy and direct CO₂ intensity of aluminium production at each time step throughout the modelling horizon.

Figure 4.25. Alumina refining and aluminium smelting energy intensity, 2014



Notes: GCC = Gulf Cooperation Council. Alumina production and aluminium production do not always occur in the same region, as both products can be shipped and traded. Sizes of circles and labelled values refer to primary aluminium production levels.

Sources: IAI (2017), *World Aluminium Statistics* (database); USGS (2017), *Commodity Statistics and Information*.

Key point *Opportunities to move towards BAT differ by region, with some already approaching BAT levels in either primary aluminium smelting or alumina refining.*

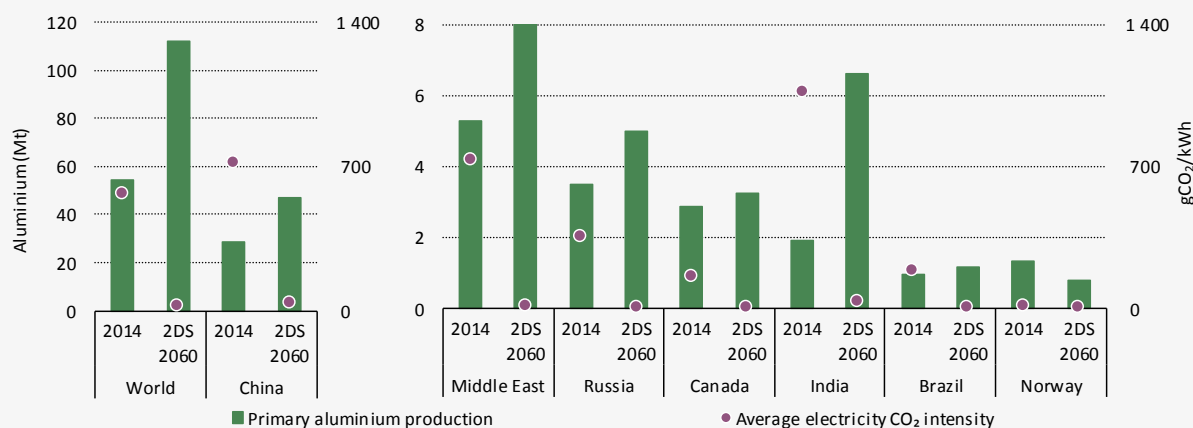
The global average energy intensity of refining bauxite into alumina in 2014 was around 14.7 GJ/t alumina, with 90% of total alumina refining using the standard Bayer process. In China and Russia, some alumina is produced via more energy-intensive processes for refining lower quality ores. For the Bayer process, the BAT-level energy intensity is estimated to be 10.4 GJ/t, which, if implemented in all production globally, would decrease energy consumption for alumina refining by 21%.⁵⁵ Global average primary smelting energy intensity in 2014 was 14.3 MWh per tonne of liquid aluminium, with 95% of total production using the standard Hall-Héroult smelting process. BAT-level for the Hall-Héroult process is estimated to be 13.6 MWh/t aluminium (Figure 4.25). Since the global average energy intensity is approaching BAT, implementing BAT-level capacity in total primary aluminium production would decrease final energy consumption by only 4%. The production of aluminium through the secondary route has an estimated global average energy intensity of around 4.6 GJ per tonne of liquid aluminium. Final energy consumption for recycled aluminium production would be reduced by as much as 28% if BAT were implemented globally.⁵⁶

The aluminium smelting process, which is very electricity-intensive, raises the question of indirect emissions. As the aluminium sector cannot directly reduce emissions from electricity generation, it becomes increasingly important to be able to rely on decarbonised power supply. Siting additions in smelting capacity should be part of an integrated energy planning process, taking into account the emissions intensity of electricity production in the local grid and possible flexibility and stability benefits to the grid from aluminium manufacturing's opportunities to contribute to load management (Figure 4.26).

55. This estimate varies by region given differences in scale and maturity (LBNL, 2008).

56. The BAT level for different furnaces varies by source, so this estimate is uncertain.

Figure

4.26. Average CO₂ intensity of electricity production and primary aluminium production

Notes: National or regional average grid CO₂ intensity of electricity production is shown. As aluminium producers can purchase electricity from specific sources via power purchase agreements, this may not be representative of their specific CO₂ intensity of electricity production. Not all regions are shown. Primary aluminium production shown does not sum to global production.

Sources: IAI (2017), *World Aluminium Statistics* (database); USGS (2017), *Commodity Statistics and Information*.

Key point

Indirect CO₂ emissions from electricity generation are an important component of the aluminium subsector's impact.

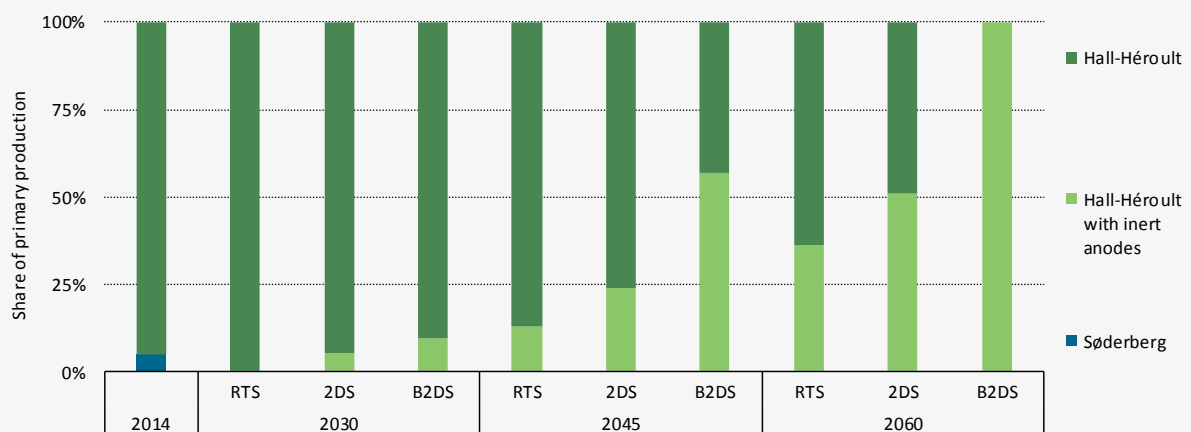
Decarbonising aluminium production is challenging, because very few alternative technological options are available and since it already has made strong progress in energy efficiency, as the current processes are very mature. Less efficient Söderberg smelters have already been phased out in most regions. Progress has been slow in developing alternative processes. In 2013, the global average energy intensity of alumina refining decreased significantly, by 1.9%, as did primary aluminium smelting, by 5.3% (IAI, 2017). Even reaching BAT performance levels in the entire aluminium sector and maximising the production of aluminium from the recycled route would not be enough to entirely decouple aluminium production and CO₂ emissions within the scenario horizon.

Rapid demonstration and deployment of low-carbon innovative technologies are needed for the emissions reduction required in the B2DS. A low-carbon technology alternative to the traditional carbon anode smelter is to introduce the use of inert anodes, which are potentially carbon-free, thus eliminating process-related CO₂ emissions as well those of other greenhouse gases such as perfluorocarbons (Moya et al., 2015). In the B2DS, the Hall-Héroult smelting process with inert anodes expands to account for a 34% share of global cumulative primary aluminium production in the period to 2060, compared with 16% in 2DS and 9% in RTS, mitigating 2.6 GtCO₂ emissions that would have been released if using carbon-anodes (Figure 4.27).⁵⁷ Deployment of Hall-Héroult with inert anodes varies by region, with high deployment in North America (56%) and the Middle East (52%) of the regional total primary production by 2040. Deployment of inert anodes for Hall-Héroult smelting in China accounts for 14% and in India for 33% of their total primary production. In order for this technology to fulfil this role in a low-carbon pathway, it is critical that progress is made in R&D and that demonstration projects are realised (Box 4.6). CCS is currently not economically feasible in the type of processes used in bauxite refining, in smelters or for furnaces, because streams of emissions are diluted and widespread within industrial sites.

57. Comparing BAT Hall-Héroult with carbon anodes to BAT Hall-Héroult with inert anodes.

Figure

4.27. Share of primary aluminium production, traditional and inert anodes by scenario



Key point

Inert anodes are critical to reducing process CO₂ emissions from aluminium production in the B2DS.

Box

4.6. Current status of low-carbon innovative processes in the aluminium subsector

Innovative low-carbon process technologies at the demonstration phase:

- **Inert anodes for primary aluminium production** could reduce process emissions from the primary aluminium smelting process by replacing carbon-based anodes with anodes made from alternative materials. Carbon anodes produce CO₂ as they degrade; inert anodes produce pure oxygen. This technology is being tested by RUSAL, but it has not been commercially deployed or demonstrated at large scale (RUSAL, 2017). The use of inert anodes could curb CO₂ emissions by as much as 1.65 tCO₂ per tonne of aluminium compared to a typical Hall-Héroult smelter (Moya et al., 2015).

Innovative low-carbon process technologies at the R&D phase.⁵⁸

- **Solar thermal for alumina refining** would integrate renewable heat into the alumina production process, reducing the need for fossil fuels and lowering CO₂ emissions. The Australian government provided funding for R&D of this technology, beginning in April 2016 (ARENA, 2017).
- **Direct carbothermic reduction of alumina** could reduce energy consumption by 20%, though it has substantially lower aluminium conversion yields than standard processes. Researchers are looking at ways of resolving this issue, such as vacuum carbothermic reduction (Balomenos et al., 2011). If improved, then this technology may offer the option of reducing capital investment costs by up to 50% (Sayad-Yaghoubi and Smith, 2013).
- **Kaolinite reduction** could reduce on-site energy requirements by 15% and use domestically available ore though it would increase the amount of materials required by the process (Green, 2007).

58. Aluminium sector process routes at the R&D phase have not been included in ETP scenarios.

Pulp and paper

In 2014, 400 Mt of paper and paperboard were produced. Growth in production is slow, as opposing trends offset each other. Product mixes in pulp and in paper are projected to shift as digital technology replaces some paper products, as demand increases for household and sanitary products as incomes rise in emerging economies, and as increased shipping of consumer goods requires more packaging materials.

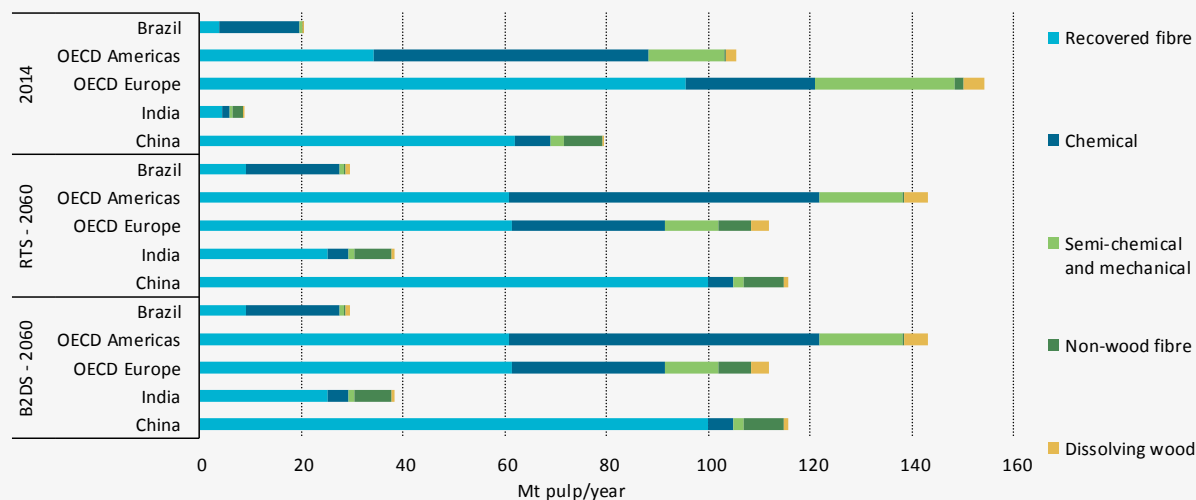
In order to meet the B2DS pathway, the pulp and paper subsector would need to reduce its aggregated energy intensity by 4.5 GJ/t paper and paperboard (30% below 2014 levels) by 2060, compared with a 28% reduction in the 2DS.

Aggregate direct CO₂ intensity per tonne of paper and paperboard must also decrease significantly in the B2DS, by 93% in 2060 compared with RTS levels, or by 78% to meet the 2DS. Cumulative direct CO₂ emissions are reduced by 62% in the B2DS compared with RTS, or 52% in the 2DS. By 2060, 21 MtCO₂ emissions remain unabated in pulp and paper.

Material efficiency can play a role in reducing emissions in the pulp and paper subsector, where paper can be recycled in order to recover fibre, which provides significant energy and CO₂ benefits compared with virgin wood pulps. Producing 1 t of recovered fibre pulp from recycled paper typically requires about 2 GJ/t pulp, compared with about 5 GJ/t for unbleached kraft pulp.⁵⁹ Recycling, which stood at 55% in 2014, increases to 66% by 2060 in the 2DS and B2DS, compared with 61% in the RTS. Increased recycling decreases emissions by 136 MtCO₂ over the 2017-60 period, or 2.3% of total emissions reductions in the B2DS.

OECD Europe and OECD Americas remain important pulp-producing regions in each of the scenarios, particularly for virgin wood pulp. China is the world's largest producer of recovered fibre pulp, which becomes more important in the 2DS and B2DS (Figure 4.28).

Figure 4.28. Product mix of pulp production by region and scenario



Notes: Not all regions are shown. Pulp production does not sum to global production.

Source: UN FAO (2017), *Forestry Production and Trade* (database).

Key point

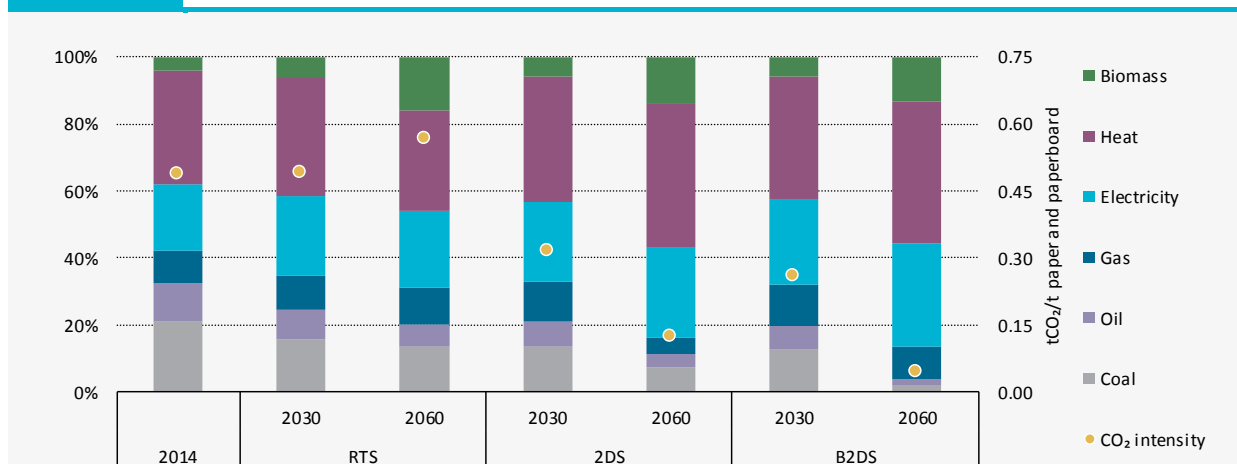
Recovered fibre pulp plays an important role in all scenarios.

59. Pulp and paper amounts are referred to in air-dried tonnes with 10% moisture content. Kraft pulping (or sulfate pulping) is the conversion of wood into pulp, breaking the bonds between lignin, hemicellulose and cellulose with a solution of sodium hydroxide and sodium sulphide. Kraft pulping is the most commonly used pulping process worldwide.

Drying of paper products and market pulp is a major energy-consuming process step in pulp and paper mills. Through lowering water content and improving heat integration through process optimisation and integration, the pulp and paper subsector could reduce its energy intensity. Integrated mills, which produce both pulp and paper, also reduce energy consumption by avoiding the energy associated with pulp drying, shipping and reconstitution. However, the choice to build an integrated pulp and paper mill is site-specific and dependent on local resources and markets.

Another major lever for reducing carbon emissions in pulp and paper manufacturing is by improving efficiency and carbon intensity of captive utilities through fuel switching (Figure 4.29). On-site heat and combined heat and power utilities provide a major part of the energy needs in pulp and paper industries, as most of the energy consumption the production processes is in the form of electricity or steam, rather than direct fuel use. Switching to low-carbon fuels for electricity and heat generation is an important strategy for decarbonising pulp and paper production. As wood is the main material input, a significant amount of solid biomass byproducts (an estimated 0.6 EJ in 2014), such as wood shavings and bark, are available for use in captive utilities. In the B2DS, 76% of on-site heat production in pulp and paper manufacturing in 2060 is provided by electric or biomass boilers, compared with 40% in 2014, which contributes 13 MtCO₂ of emissions reductions.

Figure 4.29. Energy mix of pulp and paper production and CO₂ intensity



Note: Energy derived from black liquor combustion is included as heat and electricity use.

Key point CO₂ intensity is reduced by more than 90% by 2060 compared with 2014 in the B2DS.

Black liquor, a biomass-based byproduct from chemical pulping, can also be used as a fuel in on-site utilities.⁶⁰ It is most often combusted in recovery boilers, through which pulping chemicals are recovered for reuse in the process, while the remaining residues of lignin and hemicellulose are combusted to generate steam and electricity. This is an important source of carbon-neutral fuel for the pulp and paper industry; in 2014 an estimated 2.7 EJ of black liquor was generated globally. The availability of black liquor depends on chemical pulp production levels, which are expected to remain high throughout the projection period. Despite increased recycling rates and the higher share of recovered fibre pulp, 3.5 EJ of black liquor is generated in 2060 in the 2DS and B2DS. Black liquor can also be upgraded via gasification in order to create syngas for power and heat generation, for use as feedstock in the chemical production, or for production of synthetic liquid fuels for

60. Black liquor is a byproduct from kraft pulping. It is an aqueous solution of sulphate chemicals used in the pulping process and lignin and hemicellulose residues extracted from wood.

transport. Black liquor gasification can also facilitate integrated CO₂ capture, which would contribute to negative emissions as the CO₂ captured is primarily biogenic.

Pulp mills often generate enough power and heat to be self-sufficient and to export surplus power to the grid or steam to district heating networks. Integrated pulp and paper mills can use surplus energy from pulping processes for papermaking to minimise the need for purchased energy. The opportunities for black liquor gasification – the concept of turning pulp mills into biorefineries – could transform the subsector. It could allow it to provide biomass-based fuels and products to other parts of the energy system to replace fossil fuel-based products and to add value to waste streams for system-level decarbonisation. The feasibility of widespread deployment of these concepts will depend on economic considerations such as electricity and fuel prices and chemical pulp demand. Plus further RDD&D is needed to bring black liquor gasification technologies to technological maturity (Box 4.7).

There are several possible applications of CCS in the pulp and paper industry under investigation. The most economical, based on per tonne of CO₂ captured, is in chemical recovery. CCS can also be applied to boilers or to lime kilns. In the B2DS, by 2060 37 MtCO₂ per year are captured from recovery boilers and other on-site heat utilities and 1.5 MtCO₂ from lime kilns. Captured emissions from recovery boilers, biomass-based utilities and most of the captured CO₂ from lime kilns are considered to be mainly BECCS, with negative emissions, as the CO₂ is biogenic, primarily derived from raw materials. CCS accounts for 15% of the cumulative emissions reductions in the B2DS, of which 221 MtCO₂ is from BECCS.

Box

4.7. Current status of low-carbon innovative processes in the pulp and paper subsector

Commercial low-carbon process technologies:

- **Biomass gasification and black liquor gasification** have been research areas in the pulp and paper subsector since the 1960s. More than 20 different technologies have been tested. Currently two designs are under investigation: a low-temperature steam reforming process (developed by Thermochem Recovery International [TRI]) and a high-temperature entrained flow reactor (developed by Chemrec). There are currently two commercial facilities operating with TRI's steam reforming technology: a Norampac containerboard mill in Ontario, Canada, and a Georgia-Pacific mill in Virginia, United States. The Chemrec entrained flow reactor technology was demonstrated in a plant in Piteå, Sweden, before being transferred to Luleå University in 2013 and subsequently shut down for lack of funding. Another demonstration plant operated in the US state of North Carolina (Berntsson, 2008; Naqvi, Yan and Dahlquist, 2010; IEA Bioenergy, 2013; Abrahamson, 2016).

Innovative low-carbon process technologies at the demonstration phase.⁶¹

- **Lignin extraction** is used to isolate lignin as a potential feedstock for new industrial products, such as new chemicals and plastics. Several methods, including hydrolysis and solvent-based pulping, have been tested to extract lignin from wood pulp. Though estimates of the potential have been high, no process for extraction has reached technical and economic maturity.

61. Lignin extraction has not been included in ETP scenarios as a carbon abatement option.

*Innovative low-carbon process technologies at the R&D phase.*⁶²

- **Steam forming** involves condensing dry fibres into paper and paperboard, minimising energy use for drying as the water content after forming would be below 30%. It is expected to need an additional ten years of research to understand the fluid dynamics of fibres and the additional cleaning steps needed (CEPI, 2013).
- **Extraction drying with supercritical CO₂** could be used to minimise water use and energy use for paper drying, while also removing contaminants. More research is needed, and major retrofits would be required to bring this technology to commercial scale, which is not expected within at least 15 years (CEPI, 2013).
- **Deep eutectic solvents** were the most promising concept developed through the Confederation of European Paper Industries (CEPI) Two Team Project and with funding from Horizon 2020. These solvents would dissolve wood and separate lignin, hemicellulose and cellulose, allowing them to replace traditional chemical pulping processes. The new process could have significantly lower energy needs for pulping and could produce additional added value for pulp producers through the sale of pure lignin for use as a material. This technology is expected to need 15 years of additional research (CEPI, 2013).
- **Superheated steam drying** involves replacing air and water with superheated steam in the papermaking process. Initial estimates indicate a potential for 25% energy savings and early deployment by 2030, with an additional 20 years needed for large-scale deployment (CEPI, 2013).

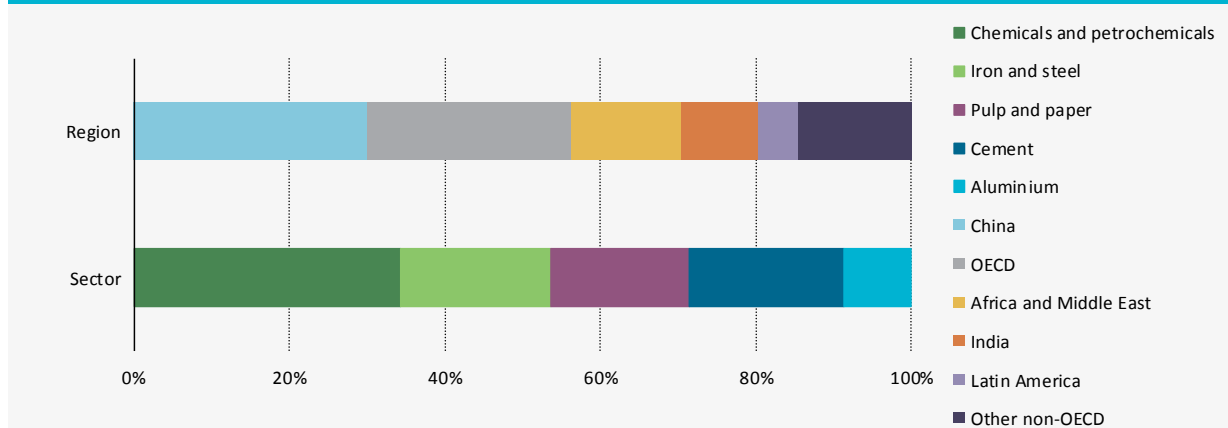
Investment needs for deep CO₂ emissions reductions in energy-intensive industry

Globally, estimated cumulative investment needs for energy-intensive industry in the RTS between 2017 and 2060 are USD 6.8 trillion to USD 8.0 trillion. Required cumulative investment in the B2DS is estimated to be USD 7.0 trillion to USD 8.7 trillion, while the 2DS would require USD 6.3 trillion to USD 7.3 trillion (Figure 4.30). These estimates are based on bottom-up technology modelling of five energy-intensive industry subsectors (cement, iron and steel, chemicals and petrochemicals, aluminium and pulp and paper), including full plant capital costs for industrial process equipment installed during the time horizon of the scenarios (to 2060). Thus no additional costs are allocated to energy savings from improved operation and maintenance practices. Also, site-specific potentials to reduce energy consumption or CO₂ emissions without a process change or major integration revamp are not captured in the discussed investment costs due to their dependency on local conditions. The 2DS is the least costly scenario; this stems from how some levers that play an important role in low-carbon scenarios are considered in the ETP investment assessment. The investment estimation methodology considers a boundary specific to industry plants, so that cost impacts of activity outside the plant fence are not included. Thus, costs associated increased need for scrap collection and handling as a consequence of increased recycling in low-carbon scenarios, or costs related to CO₂ transport and storage, are not included in the discussed investments. On the other hand, the implementation of certain material efficiency strategies (such as improving production yields) in low-carbon scenarios result in lower demand levels for primary materials, which lowers the overall investment needs as primary process routes are typically more capital-intensive, and overall activity levels are reduced. These options

62. Pulp and paper subsector process routes at the R&D phase have not been included in ETP scenarios.

play a more significant role in the 2DS, offsetting the investments related to deployment of more costly innovative process for CO₂ abatement, and making the scenario is less costly than the RTS. In the B2DS, because of early replacement of capacity, deployment of more costly carbon abatement options and the rapid deployment of CCS, equipment costs offset these effects so that the B2DS becomes the most costly scenario. Nonetheless, the level of effort required in the 2DS in terms of structural shifts in industry and redefining product value chains is significantly more ambitious than in the RTS, and even more ambitious in the B2DS.⁶³

Figure 4.30. Cumulative investment needs in B2DS by region and sector



Notes: Costs shown are associated with low-range industrial production estimates. Investment costs are cumulative to 2030 and to 2060.

Key point *China would contribute the most investment in energy-intensive industry in the B2DS, and chemicals and petrochemicals would be the most important subsector.*

The chemicals and petrochemicals subsector makes up the largest share of investment in the 2DS with nearly 30%, followed by iron and steel (24%), pulp and paper (20%), cement (15%) and aluminium (12%). Regionally, a large part of the investment in 2DS occurs in China (29%), though 25% of cumulative investment would occur in OECD countries. India, with 12% of cumulative investment needs in 2DS, is also important, as is Africa and the Middle East (14%). Broadly speaking, major investments are needed where high levels of industrial production occur.

A large part of the cumulative investment associated with the 2DS occurs in the early years; USD 2.0 trillion of investment (33% of cumulative investment in 2DS) occurs before 2030. In the B2DS this share is slightly higher, with USD 2.4 trillion (34%) occurring before B2DS. These shares show the importance of early action; failing to make these investments in the years before 2030 would force a faster and more expensive technology transition to occur in the later years of the scenarios.

Policy actions to support industry sector decarbonisation

Realising substantial CO₂ emissions reductions in the industry sector requires a strong set of policy priorities and aggressive implementation based on a systemic approach to

63. Variable costs, including fuel costs, and fixed operating and maintenance costs are excluded from the investment estimates, as are costs associated with on-site electricity generation from purchased fuels. Financial costs are excluded from the analysis, and cost estimates are undiscounted. High-range costs are associated with higher demand variants of the ETP scenarios, a sensitivity range to capture the uncertainty of production levels for industrial materials in the future. Costs of scenarios could vary significantly depending on the future evolution of production in the industry sector.

decarbonisation, as well as full understanding of sustainability impacts of materials and products throughout evolving value chains. There is a strong need to design and implement more targeted and effective policy strategies for governments that encourage effective public-private collaboration and significant investment in BAT and low-carbon innovative process technologies. Policies to support industry sector decarbonisation should also include measures to improve publicly available statistics to enable technology-level industrial energy performance monitoring to support the validation of results-oriented policy mechanisms.

As energy efficiency and BAT deployment play a critical role in the low-carbon scenarios, the full utilisation of these levers should be encouraged and incentivised. Implementation of energy management systems (such as ISO 50001) can deliver significant energy savings and can be more broadly deployed across industry subsectors and regions. Experience and knowledge sharing across subsectors and regions should also be encouraged, for example by the implementation of energy efficiency networks. Process integration, aimed at minimising energy consumption and CO₂ emissions without compromising production processes, should also be a key priority. In some cases these options can already be implemented quickly and cost-effectively; additional barriers to their deployment should be removed.

Advancing on low-carbon industrial innovation will require substantial investment in demonstration projects and RDD&D activities. Investment de-risking mechanisms should be linked to long-term low-carbon strategies to effectively foster development of innovative technologies and processes, an activity that has inherently high risk and a long investment cycle. Governments can play an active role in guiding industrial innovation activities towards a sustainable path by indirectly reducing investment risks, such as by implementing strategies to improve long-term energy market stability and by providing direct support measures such as grants and low-interest loans, while stimulating private financial participation in RDD&D projects.

Public-private and cross-sectoral partnerships can be used effectively to design and deploy integrated solutions that minimise carbon emissions along the overall product value chains while maintaining competitive advantages. Traditional measures to overcome some of the associated challenges to low-carbon industrial innovation include strengthening intellectual property rights, subsidising RDD&D activities, incorporating environmental externalities in material costs and encouraging RDD&D collaboration. However, radical breakthroughs will require more targeted mechanisms that prioritise areas with the greatest potential for carbon mitigation benefits and where there is a low likelihood of the private sector investing independently.

In the short term, policy makers should focus on fully exploiting cost-effective energy efficiency potentials and widespread deployment of BATs in production capacity additions. Fiscal incentives for proven energy efficiency improvements and process integration measures, equipment performance standards, and regulatory measures such as removal of energy price subsidies should be put in place. These early actions provide important emissions reduction in the pre-2030 time frame before more drastic options become necessary and available, and they reduce pressure on strategies that are less certain to deliver emissions reduction in the longer term (Table 4.2).

Material efficiency strategies also offer cost-effective opportunities, but barriers preventing them from being widely implemented must be tackled. Inefficient use of materials should be discouraged through price signals reflecting the energy and CO₂ footprint of production and by raising consumer awareness of ways to avoid wasting materials. Government purchasing policies could also be used to stimulate markets for material efficiency in industrial production (Allwood et al., 2013). Reuse of post-consumer materials should be a first priority, through measures such as refunding schemes upon product return, followed by improvement of post-consumer scrap collection and recycling rates. Improvement of separation and collection practices among consumers is needed, as well as shared responsibility with industrial producers. Production of materials from recycled raw materials should be incentivised where it is not currently economical. For remaining waste, post-consumer scrap should be valorised for electricity or heat generation instead of landfill disposal. Furthermore, technology developments to improve manufacturing yields should be promoted through facilitating investment and experience sharing.

In the longer term, policy makers should guide industrial innovation towards low-carbon options. The progress of environmentally sustainable industry innovation over the next decade will be crucial to enable low-carbon technologies with the best potential to achieve commercial availability to support industry and other sectors' efforts to reach deep carbon emissions reductions. Developing a broad portfolio of low-CO₂ emissions industrial process technologies and products is critical to ensure that enough viable options will be ready in the post-2030 time frame. The 2DS and B2DS highlight cost-optimal pathways given available data and current technology knowledge, but other technologies, including more radical, early-stage options, could play a role as technology evolves and should not be excluded from investigation.

In parallel with process and technology development, governments and industry should work jointly to widely deploy innovative low-carbon industrial processes by facilitating investment while implementing effective mechanisms for broad international technology transfer and capacity building. International public-private collaboration will also be critical in order to strategically identify, design and roll out cost-optimal CO₂ transport and storage infrastructure for CCS to enable the deep carbon emissions reductions necessary in the long term.

Long-term environmental sustainability at the energy system level should be considered from an industrial perspective as well; incentives for implementation of demand-side management strategies, such as energy price schemes that reward low-carbon electricity/thermal exports and flexible imports from the grid, can have significant benefits for the overall energy system. Similarly, integrated assessments of energy demand and mapping of local energy resources and demands are needed to identify cost-effective energy supply strategies. Strategic heating and cooling planning can help to identify cost-effective opportunities for IEH recovery at the local and national levels.

Table

4.2 Policy recommendations to support the low-carbon transition for industry

Focus	Short term	Long term
Tracking progress	<ul style="list-style-type: none"> ■ Improve publicly available statistics. ■ Encourage benchmarking initiatives at the industry subsector level to overcome confidentiality challenges. 	<ul style="list-style-type: none"> ■ Set stable long-term targets and choose appropriate indicators to track progress towards those goals.
Energy efficiency and BAT	<ul style="list-style-type: none"> ■ Incentivise implementation of BATs for new capacity additions. ■ Implement and progressively strengthen equipment performance standards. ■ Implement internationally co-ordinated carbon pricing mechanisms. ■ Remove fossil fuel subsidies. ■ Support deployment of energy management systems and energy audits. 	<ul style="list-style-type: none"> ■ Continue to incentivise energy efficiency for new processes and technologies. ■ Update benchmarks and targets as BAT improves.
Material efficiency	<ul style="list-style-type: none"> ■ Incorporate price signals into consumer products related to environmental externalities of materials. ■ Encourage reuse prior to recycling. ■ Improve post-consumer scrap collection and recycling. ■ After reuse and recycling, valorise post-consumer waste for energy recovery. 	<ul style="list-style-type: none"> ■ Improve post-consumer scrap collection infrastructure in all countries. ■ Encourage R&D for new processes and products that optimise use of industrial materials.

Fuel and feedstock switching

- Implement internationally co-ordinated carbon pricing mechanisms.
- Remove fossil fuel subsidies.
- Encourage technology development and RD&D (research, development & demonstration) focused on use of low-carbon alternative fuels and feedstocks.
- Develop assessments of long-term availability of alternative fuels and feedstocks to enable effective planning for industrial development that adequately considers sustainability issues of resources and impacts.

Low-carbon innovation

- Ensure that a broad range of technologies are the subject of research in order to ensure viable post-2030 options. Ensure timely demonstration of successful options at scale.
- Strengthen intellectual property rights.
- Encourage public-private partnerships and international collaboration among industry stakeholders.
- Implement internationally co-ordinated carbon pricing mechanisms.
- Explore permanent storage sites for captured CO₂.
- Roll out transport and storage infrastructure to enable CCS deployment.
- Facilitate international technology transfer and capacity building.

Transition to a low-carbon energy system

- Perform integrated geospatial assessments of heat demand and available energy resources to facilitate use of waste heat.
- Streamline regulations to allow for industrial demand response in electricity markets.
- Develop life-cycle assessments for industrial materials and consumer products.
- Increase awareness of a broad range of technology options for low-carbon production in industry.
- Valorise industrial potential to contribute to sustainability of other sectors, through innovative new products, utilisation of industrial byproducts, energy recovery and demand management.

Policy implications of B2DS

Going further than the 2DS towards more ambitious climate objectives – as postulated in the B2DS – would require similar policy levers in the areas described in the previous section, but they would need to be much more aggressively deployed. This could mean unprecedented ambition in climate policy, including higher carbon pricing, stronger incentives, additional support for RDD&D, and strengthened cross-sectoral and cross-regional co-ordination on energy technology and carbon mitigation options in the industry sector, among other policy options. As with the 2DS, long-term stability and visibility of the policy framework is important for investment decision making in the industry sector. Additionally, in the B2DS, policy action to support the low-carbon transition would need to occur earlier and support a more rapid scale-up and deployment of innovative low-carbon technologies. This early action would come with a cost, as the industry sector must transform itself more quickly, and de-risking and incentive mechanisms would need to be implemented to ensure the competitiveness and viability of the industry sector in a B2DS world.

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Chapter 5



Steering transport towards sustainability

The task of decarbonising the transport sector to levels needed to achieve greenhouse gas (GHG) emissions reductions consistent with aggressive climate scenarios is formidable. It requires changing the nature and the structure of transport demand, major improvements in efficiency, and rapid transitions in the energy mix used to move people and goods. Decarbonising long-distance transport modes – in particular aviation, heavy-duty road transport (i.e. trucking and buses) and shipping – is most challenging. This transition cannot be realised without major policy and technology developments. Policies and technologies that increase the share of public transport modes and optimise road freight can significantly reduce the investment required for the decarbonisation of transport by cutting vehicle purchase and related road-building costs.

Key findings

- **Transport accounts for 28% of global final energy demand and 23% of global carbon dioxide (CO₂) emissions from fuel combustion.** In 2014, the transport sector consumed 65% of global oil final energy demand.
- **In the Reference Technology Scenario (RTS), total final energy consumption grows from 113 exajoules (EJ) in 2015 to 165 EJ in 2060. In 2060, most of the demand (36%) comes from road freight vehicles** (light commercial vehicles [LCVs] and trucks), followed by passenger light-duty vehicles (PLDVs) (28%). Energy use increases most in long-distance transport modes (rail, air, shipping and road freight) between 2015 and 2060.
- **Decarbonising transport requires the combination of measures that alter the nature and the structure of transport demand, major improvements in efficiency, and rapid transitions towards low- and zero-carbon fuels.**
- **Measures to shift and to avoid passenger transport result in a 25–27% reduction in passenger activity (passenger kilometres [pkm]) for cars by 2060 in both low-carbon scenarios relative to the RTS.** Systemic improvements in road freight can reduce the vehicle kilometres (vkm) driven by trucks by 16–26% relative to the RTS by 2060.
- **Cities offer specific opportunities that can have a major impact on passenger and freight transport energy demand.** In urban environments, the transition takes the form of shorter trips, increased reliance on collective transportation (ranging from public transport to ride- and goods-transport sharing) and non-motorised transport solutions (e.g. walking and cycling), and ultra-low or zero-emission technologies. Compact cities can facilitate access to the same essential activities and goods demand, but reduced overall activity in both urban passenger and freight transport.

- **Reducing GHG emissions from transport requires incremental vehicle improvements (including engines), especially in the short to medium term.** In road transport, options include improved aerodynamics, lower rolling resistance and weight reductions to reduce energy needs, as well as technologies that improve the efficiency of internal combustion engines (ICEs), including exhaust heat recovery and hybridisation. Hybrid electric vehicles (HEVs) are also instrumental to enabling the transition from ICEs to electric cars, especially plug-in hybrid electric vehicles (PHEVs).
- **Electrification is crucial for short-distance vehicles (light-duty vehicles [LDVs] and 2- and 3- wheelers) and the rail sector, and needs to go hand in hand with decarbonising the electricity sector.** In the Beyond 2°C Scenario (B2DS), nearly all 2- and 3-wheelers and most passenger trains are electric by the mid-2040s, and around 90% of all cars on the road are plug-in electric by 2060. Electrification also offers an essential solution in both urban public transport modes and freight deliveries.
- **In the near term, reducing emissions from trucking will require systemic improvements (e.g. in supply chains, logistics and routing in the case of freight) and rapid exploitation of energy efficiency potential.** In the long term, decarbonising long-haul road freight will require major investment in infrastructure for alternative energy carriers. Electric road systems (ERS) and hydrogen come out as the most promising ultra-low or zero-emission options for heavy-duty trucks. Low-carbon gaseous and liquid fuels (advanced biodiesel and biomethane, complemented by power-to-X [PtX] synthetic fuels)¹ will also be necessary to deliver emissions reductions. Biomethane is especially relevant in fleets with hub-and-spoke operations, while liquid biofuels have greater potential in blends. By 2060, low-carbon fuels will account for 5.8 EJ (22% of road freight final energy) in road freight in the B2DS and will coexist with ultra-low or zero-emission technologies, complementing them. In the B2DS, zero-emission infrastructure will have to be rolled out not later than the coming decade: testing and demonstration of ultra-low or zero-emission technologies need to be started as soon as possible.
- **Shipping and aviation have limited fuel alternatives to fossil fuels, while demand for their services will increase substantially.** Both modes have to pursue highly ambitious efficiency improvements and need low-carbon fuels. Achieving the B2DS requires reductions of specific energy use by 2.5% per passenger kilometre in aviation and by 2.8% per tonne kilometre (tkm) in shipping each year between 2015 and 2060. In addition, in the B2DS, shipping and aviation largely shift to advanced biofuels to reduce GHG emissions further (by 50% in shipping and 69% in aviation in 2060). Hydrogen could also have a relevant role in the future of international shipping, either as direct use or as an intermediate product for the synthesis of PtX fuels. In aviation, improved intermodal integration also needs to lead to the substitution of intra-continental flights with distances of up to 1 000 kilometres (km) by high-speed rail.
- Even though the 2°C Scenario (2DS) and the B2DS require significant investment in infrastructure and technology development, the cumulative 2017-60 costs of transport (total expenditures on vehicles, infrastructure and fuels) in the RTS are 130 trillion United States dollars (USD) higher than those of the 2DS, and USD 110 trillion higher than those of the B2DS (in 2015 USD at purchasing power parity [PPP]).
- **Considerable uncertainty persists concerning the potential impact of various nascent and projected transformations of mobility.** The various elements of the “autonomous and connected vehicles, electrification, and sharing” (ACES) paradigm are beginning to penetrate mobility markets, particularly in major cities. Yet to date, the magnitude of their effects on, and even the likely direction of, mobility patterns, energy use and emissions can only be speculated on.

1. PtX synthetic fuels combine hydrogen produced from low-cost and low-carbon electricity (e.g. excess electricity from variable renewables or other low-carbon sources) with renewables-based carbon streams to produce gaseous or liquid fuels.

Opportunities for policy action

- **The removal of fossil fuel subsidies from all transport fuels and modes is a prerequisite to carbon taxation of transport fuels, one of the pillars needed to stimulate the decarbonisation of transport.** In the B2DS, CO₂ taxes that take into account the life-cycle performance of energy carriers increase over time and reach USD 540 per tonne of CO₂ (tCO₂) by 2060, in line with the estimations developed for energy supply. CO₂ taxation partly offsets lower fossil fuel prices occurring due to lower demand.
- **Even with effective CO₂ taxation, regulations on the energy use and life-cycle GHG emissions of vehicles are necessary to address market failures, particularly the underestimation of fuel savings in purchase decisions, and to spur the rapid adoption of electric vehicles (EVs) and other low-carbon vehicle technologies.** Regulatory measures need to be combined with differentiated vehicle taxation, based on energy and emissions performance (i.e. feebates) to stimulate rapid market shifts.
- **Supporting the transition to ultra-low or zero-emission mobility will also require a transition in the way transportation is taxed,** complementing and partly shifting the fuel tax component aiming at the recovery of infrastructure construction and maintenance costs with charges reflecting road usage, vehicle travel (i.e. vehicle kilometres) and local air pollutant emissions. Increasing prices of passenger goods and movements may increase government revenues in the short- to midterm. On the other hand, fuel tax revenues are clearly destined to shrink as vehicles electrify. Road pricing is also relevant to manage rebound effects of improved efficiency.
- **Local policies, including regulatory measures such as congestion charging (to be implemented coherently with other road pricing measures), low-emissions zones, access regulations, parking fees and restrictions, and also strategic investment in well-sited public charging points for plug-in electric vehicles (PEVs), can support national-level policies** to achieve the rapid deployment of zero-emission vehicles in urban areas. These measures can also help reduce the need to rely on individual transport vehicles for urban mobility, e.g. providing funding for the support of public transport services.²
- **Cities are also important test beds for advanced technologies and can serve as pilot projects where the real-world impacts of potential transformations to mobility services can be investigated.** Policy makers should support innovation in novel mobility services in metropolitan areas, as they could enable faster switches to fuel saving technologies and zero-emission technologies. They must be prepared to learn from successes and failures to design policies that do not compromise accessibility to goods and services, to improve standards and quality of lives, but also to steer new mobility paradigms so that they contribute to GHG reductions. In particular, policies regulating mobility as a service need to ensure that these services are well integrated with high-capacity public transport, complementing it rather than competing with it.
- **Considerable uncertainty remains regarding the relative efficacy and cost-effectiveness of various policies.** Since the relative efficacy of measures is likely to vary in different contexts (e.g. as a result of urban patterns, geography, income level and distribution, and culture and preferences), it is advisable for policy makers to deploy a portfolio of policies and to carefully monitor and compare their cost-effectiveness using data-driven metrics. In this manner, policy priorities can be realigned to maximise their impact.
- **While international shipping and aviation are outside national and regional jurisdictions, the global nature of their activity provides opportunities and necessities for worldwide collaboration and regulation.** For both modes, existing efficiency standards must be ratcheted up significantly. The price of carbon-intensive fuels will need to increase to improve the competitiveness of low-carbon fuels. Both sectors currently benefit from fuel tax benefits and exemptions in several regions (e.g. the United States [US] and European Union [EU]). Abolition of these benefits in the short term followed by the introduction of an ambitious carbon pricing mechanism is essential.

2. These points are further developed in IEA (2016a), which focuses on urban energy systems.

Overview

This chapter considers actions that can be taken to accelerate the transition to a low-carbon transport sector that is sustainable and delivers the needed services to move people and goods. The analysis derives from three scenarios looking at the period to 2060.

- The **RTS** takes into account transport policies on energy efficiency, energy diversification, air quality and decarbonisation that have been announced or are under consideration.³ It incorporates technology improvements in logistics, energy efficiency and modal choices that support achievement of this policy ambition.
- The **2DS** is consistent with 50% probability to limit the expected global average temperature increase to 2°C. In transport, this reflects clear policy choices favouring less energy-intensive modes, the rapid uptake of all cost-effective energy efficiency opportunities and the transition towards a much higher reliance on low-carbon energy carriers by 2060.
- The **B2DS** falls within the Paris Agreement range of ambition, and corresponds to a 50% probability of limiting the increase of the global average temperature to 1.75°C. In transport, this requires even greater reliance on the most efficient modes, a very rapid deployment of zero-carbon vehicle technologies and energy carriers to shift away from fossil fuels, and needs to be accompanied by effective near-term accelerated and ambitious policy changes.

Transport accounts for 28% of global final energy demand and 23% of global CO₂ emissions from fuel combustion. In 2014, the transport sector consumed 65% of global oil final energy demand. Moreover, with 92% of transport final energy demand consisting of oil products, the transport sector is the least diversified energy end-use sector.

The contribution of transport technologies and policies towards reducing GHG emissions is conceptualised in this chapter by applying the "avoid, shift and improve" paradigm. "Avoid" refers to a reduction of energy consumption primarily derived from a decline in activity (passenger kilometre or tonne kilometre), for example through reducing demand for travel or trip length. "Shift" refers to abatement of emissions through modal shift, for example by shifting to a transport mode that uses lower emissions to achieve the same level of travel. "Improve" strategies include vehicle efficiency gains as delivered by a wide range of improvements to the engine, drivetrain, vehicle system, auxiliaries and material substitution resulting in light-weighting. They also encompass shifts to low-carbon fuels, i.e. away from fossil fuels to advanced and low-GHG-intensity biofuels or even to electricity-based energy carriers (PtX). The chapter discusses the contributions of "avoid, shift, and improve" measures needed to pursue the B2DS objectives.

The decarbonisation challenge for transport

Future impact of current ambitions: Transport sector in the RTS

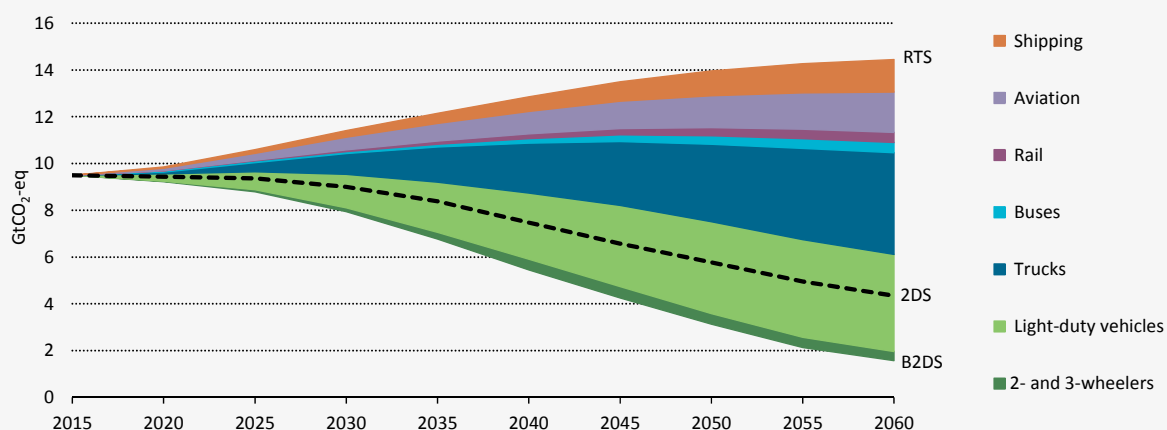
In the RTS, total transportation final energy consumption grows from 113 exajoules (EJ) in 2015 to 165 EJ in 2060. In 2060, most of the demand (36%) comes from road freight vehicles (LCVs and trucks), followed by PLDVs (28%). Energy use increases most in long-distance transport modes (rail, air, shipping and road freight) between 2015 and 2060. Well-to-wheel⁴ (WTW) GHG emissions from transport increase from 9.5 gigatonnes of CO₂ equivalent (GtCO₂-eq) in 2015 to 14.4 GtCO₂-eq in 2060 (Figure 5.1).⁵

3. With respect to decarbonisation, the RTS broadly reflects the ambition of climate mitigation pledges of the Paris Agreement.

4. This chapter distinguishes between GHG emissions from production and distribution of transport fuels – from the extraction of primary feedstocks to the delivery to the final site of distribution to the end user (well-to-tank) – and emissions occurring during the combustion of

Figure

5.1. WTW GHG emissions reductions by transport mode and scenario, 2015-60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

WTW GHG emissions from transport are 83% lower in 2060 than in 2015 in the B2DS, while in the 2DS they decline by 54% over the same period.

Decarbonising transport

In the B2DS, WTW GHG emissions from transport are 83% lower in 2060 than in 2015. Between 2015 and 2060, the share of passenger transport energy use decreases from 60% to 48%, while the share of freight transport increases from 40% to 52%, reflecting the relative difficulty of decarbonising freight modes. LDVs and trucks, which accounted for the majority (68%) of energy use in transport in 2015, are responsible for the largest share of GHG emissions reductions. In the RTS, total transportation final energy consumption grows from 113 exajoules (EJ) in 2015 to 165 EJ in 2060. In 2060, most of the demand (36%) comes from road freight vehicles (LCVs and trucks), followed by PLDVs (28%). Energy use increases most in long-distance transport modes (rail, air, shipping and road freight) between 2015 and 2060. Well-to-wheel (WTW) GHG emissions from transport increase from 9.5 gigatonnes of CO₂-equivalent (GtCO₂-eq) in 2015 to 14.4 GtCO₂-eq in 2060 (Figure 5.1). Yet, in the B2DS, 2- and 3-wheelers and rail are the only sectors to decarbonise fully by 2060 (Table 5.1). The share of rail in total transport energy demand quadruples between 2015 and 2060.

the fuels by vehicles (tank-to-wheel). Together these two elements make up WTW GHG emissions. This does not include emissions from vehicle or battery manufacturing, or those offset by material recycling, among others.

5. Well-to-tank emissions for fossil fuel-derived fuels and biofuels are largely based on data from the Joint Research Centre, EUCAR and CONCAWE and do not include indirect land-use change factors (JEC, 2014a).

Table

5.1. Total WTW GHG emissions reductions by mode in the 2DS and B2DS relative to RTS, 2060

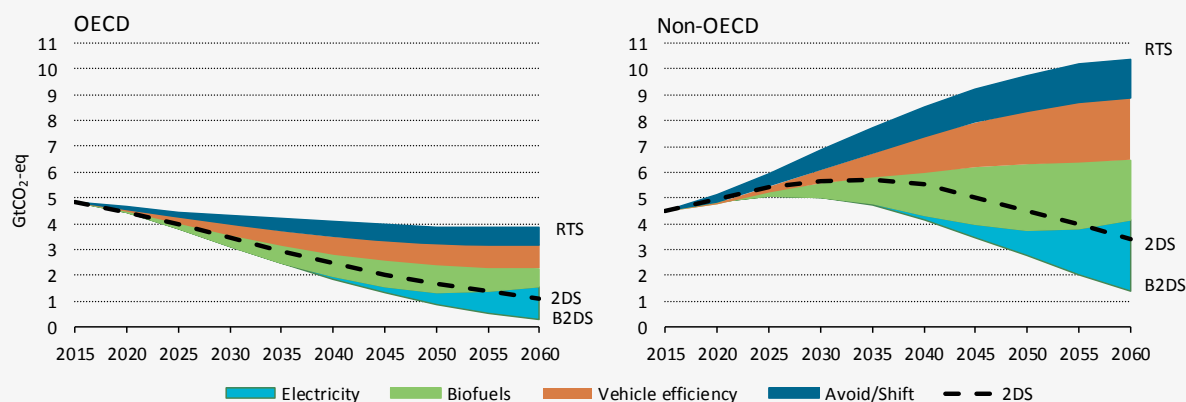
Transport mode	2DS	B2DS
2- and 3-wheelers	99%	>100%
LDVs	73%	92%
Trucks	70%	91%
Bus	65%	93%
Rail	87%	>100%
Aviation	69%	85%
Shipping	54%	71%

Note: In the B2DS, WTW emissions of some modes are reduced by more than 100% in 2060, relative to the RTS. This happens in modes relying largely on energy carriers with negative WTW emissions (primarily electricity from bioenergy with carbon capture and storage [CCS]).

Total WTW GHG emissions of member countries of the Organisation for Economic Co-operation and Development (OECD) have already peaked, but emissions of non-OECD countries are set to more than double from 2015 levels in the RTS by 2060 (Figure 5.2). Achieving an emissions trajectory in line with 2DS targets would require that OECD countries achieve deep cuts through 2060, reducing emissions by more than 75% from 2015 levels. Meanwhile, roughly equal policy effort would be required to rein in transport emissions across non-OECD countries by 2060 to a level 29% lower than that in 2015. The B2DS would require even more aggressive policy and technology actions to realise deep cuts in transport emissions in both the OECD (95%) and non-OECD (72%) countries from 2015 levels by 2060.

Figure

5.2. WTW GHG emissions in OECD and non-OECD countries by scenario, 2015-60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

Achieving the B2DS target requires OECD countries to reduce WTW GHG emissions by 95% and non-OECD countries by 72% from 2015 levels by 2060.

Low-carbon opportunities for each transport mode

Meeting the GHG emissions reductions goals for the deep decarbonisation scenarios, 2DS and B2DS, requires major transformations that alter the nature of each transport mode. The pace of decarbonisation is the main difference between the 2DS and B2DS: WTW emissions in 2DS fall to 4.4 gigatonnes (Gt) in 2DS in 2060, but they need to be reduced below 1.6 Gt in the B2DS (Figure 5.1).

To achieve this, the B2DS requires widespread adoption of today's most advanced technologies by 2060 and calls for even more stringent policies to reduce activity in carbon-intensive modes and shift to more efficient ones than in the 2DS. Short-distance transport modes – including 2- and 3-wheelers, LDVs and public transport (both bus and rail) – largely rely on ultra-low or zero-emission technologies by 2060, when they use primarily electricity, and potentially hydrogen, as an energy carrier. Long-distance transport modes, i.e. international shipping and aviation, are more difficult to electrify and must therefore decarbonise by means of strong efficiency improvements coupled with a shift to low-carbon energy carriers. These are the modes where biofuels are best placed to replace fossil-derived high-energy-density liquid fuels. Trucks include both short- and long-distance transport modes. By 2060, they will need to shift to a mix of low-carbon gaseous and liquid biofuels, electricity, hydrogen, or other forms of electricity-based fuels (PtX synthetic fuels). A sizeable shift from carbon-intensive modes (LDVs, aviation and trucks) to more efficient modes (rail and public transport) also is needed.

Electrification emerges as the major low-carbon pathway in the B2DS, especially in short-distance modes. Battery performance and cost will need to continue along the recent impressive trajectories they have charted, and will need to attain energy density and cost improvements consistent with targets announced by various automakers and government departments (e.g. EV Obsession [2015] on GM target; HybridCARS [2015] and Tesla [2016] on Tesla target; and US DOE [2012]). Significant research, development and demonstration (RD&D) improvements on battery technology (also driven by the wide application of battery storage in consumer electronics) provide encouraging signs in this respect. However, unless technology developments significantly outpace optimistic expectations on energy density improvements, durability and cost reductions, electrification is not likely to happen without policy support.

Advanced low-carbon fuels must complement electrification. Global sustainable bioenergy availability is limited to about 75 EJ of final energy by 2060 (see Chapter 8). The need for biomass use across sectors, and the importance of bioenergy with carbon capture and storage (BECCS) technologies, especially in power generation but also in the refining industry, to sequester carbon as a means of offsetting emissions across end-use sectors leave around 24 EJ in the B2DS and 30 EJ in the 2DS for the transport sector in 2060. The limited availability of biomass implies that biomass use in transport must be prioritised on modes where other decarbonisation pathways have the highest cost. This is why biomass use in transport in the B2DS is primarily allocated to long-distance transport modes (aviation, shipping and trucks).

PtX synthetic fuels combine hydrogen produced from low-cost and low-carbon electricity (e.g. excess electricity from variable renewables or other low-carbon sources) with renewables-based carbon streams to produce gaseous or liquid fuels. PtX can also lead to the production of ammonia (from hydrogen and nitrogen) as an energy carrier. Like other biofuels, PtX technologies using renewables-based carbon streams are limited by the sustainable supply of primary biomass. All PtX technologies face additional constraints due to the limited availability of low-cost electricity supply and the narrow geographical scope for renewables-based and very low-cost electricity over sufficiently long periods. Such conditions are met only when solar and wind installations

operate in regions with high solar and/or wind potential.⁶ Given their favourable performance in terms of WTW emissions, but also accounting for the limitations mentioned, PtX technologies are considered here as an option that could complement other low-carbon biofuel production pathways, helping to achieve the B2DS decarbonisation target, but do not account for a large fraction of the low-carbon fuel demand, even in this scenario. In the integrated results developed for the characterisation of the low-carbon scenarios, most of the liquid and gaseous low-carbon fuels originate from hydrotreated oils or thermochemical or biochemical conversion processes.⁷

Hydrogen may play a role in contributing to GHG emissions reductions and energy security. Driving ranges attainable by fuel cell vehicle technologies and compressed hydrogen storage are comparable to those available in today's ICE road vehicles. In addition, the possibility to produce low-carbon hydrogen using CCS or low-carbon primary energy sources makes it a promising low-carbon energy carrier (see for instance Miller, 2016). Technical assessments further suggest that there is significant potential to bring down the costs of fuel cells: continued technology improvements and other benefits derived from fuel cell vehicles are expected to reduce the total cost of ownership (Papageorgopoulos, 2016). Despite this potential, hydrogen faces greater deployment challenges than other low-carbon energy carriers. For hydrogen produced from low-cost electricity from variable renewables, the economic case is hampered by the low capacity utilisation of electrolyzers. Additional economic challenges are posed by the lower thermodynamic efficiency of hydrogen-based electricity storage when compared with competing technologies with higher efficiency, including supercapacitors, flywheels, pumped-storage hydropower, compressed air energy storage and batteries. Centralised hydrogen production technologies have the capacity to generate hydrogen at low cost, but also face tougher barriers than decentralised production due to the segmented nature of the investment required for the development of hydrogen transmission and distribution infrastructure, especially if hydrogen demand does not emerge across all end uses.⁸ These barriers may delay or slow the development of vehicle technologies, retarding technology learning and reducing the possibility to benefit from the economies of scale that could drive cost reductions for fuel cells and storage tanks. For these reasons, hydrogen contributes only a small fraction of the energy demand in the central projections developed in *Energy Technology Perspectives (ETP) 2017* in the low-carbon scenarios. Larger contributions to the 2DS and B2DS are discussed primarily as an alternative, an addition or a complement to electrification, with a primary focus on road freight transport. Hydrogen and PtX are also considered as additional possibilities to decarbonise international shipping beyond the 2DS and B2DS results.⁹

6. In addition to the cases mentioned, PtX technologies may also use CO₂ streams from industrial processes or air capture. CO₂ streams from industrial processes are subject to limitations in terms of available volumes and, if they are to deliver emissions reductions, depend on the availability of primary biomass. Air capture is likely to be characterised by low thermodynamic efficiency and therefore high costs, and it has not been assessed for this publication.

7. Additional work is needed to improve the assessment of these technologies against biofuel production from hydrotreated oils and thermochemical and biochemical routes.

8. The magnitude of the total investment required for the deployment of a hydrogen retail infrastructure for LDVs has been estimated to be similar to the investment needs required for electrification (see for instance Melaina, Sun and Bush, 2014). The key challenges for hydrogen include the size of upfront investment, which limits the possibility to share investment risks across small stakeholders; and the limited opportunities to mitigate risks by ensuring that part of the demand required to pay back infrastructure investment is secured up front, which could be mitigated by the emergence of large-scale hydrogen demand in buildings and industry. Financing of natural gas pipelines also requires large, stable and long-term demand, e.g. power plants, to ensure reliable payback streams. For considerations on the need for centralised production for high hydrogen demand volumes, even in the presence of high shares of variable renewables, see IEA, 2015.

9. Given the need for ultra-low or zero-emission technologies to achieve deep decarbonisation of the transport sector, efforts to achieve cost reductions and demonstrate the economic viability of hydrogen-based solutions (including PtX synthetic fuels) should be encouraged. This is particularly important in light of the uncertainties to achieve cost-effective reductions via other pathways, e.g. feedstock availability and cost issues for low-carbon biofuels, technology risks and limitations for the uptake of electrification in long-distance modes, suggesting a potential for hydrogen and fuel cells to be competitive in these applications.

When looking at costs, the cumulative 2017-60 costs of transport (total expenditures on vehicles, infrastructure and fuels) in the RTS are 130 trillion United States dollars (USD) higher than those of the 2DS, and USD 110 trillion higher than those of the B2DS (in 2015 USD PPP). (Figure 5.16). Fuels savings make up the majority of the savings in the decarbonisation policy scenarios: cumulative expenditures of about USD 220 trillion on fuels in the RTS can be cut by 41% in the 2DS and by 48% in the B2DS. Additional savings accrue from a reduction in total road vehicle purchases and from reduced road and parking infrastructure investments.

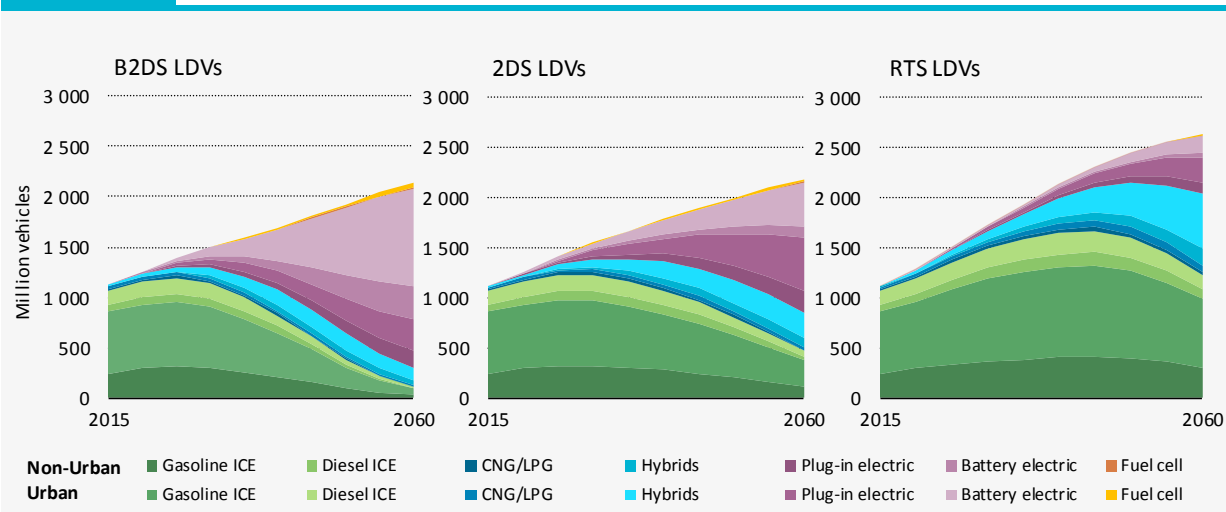
LDVs

Achieving the B2DS targets requires the LDV fleet to minimise GHG emissions through technology transformations, which occur on top of large contributions from the "avoid" and modal "shift" components in the B2DS (see the sections on public transport and on 2- and 3-wheelers that follow). In the case of the LDV fleet, which includes PLDVs and LCVs, substantial improvements in fuel economy would be needed in the short to medium term, in parallel with actions that enable the sector's transition towards ultra-low or zero-emission technologies in the long term. In the B2DS, technologies delivering fuel economy improvements and ultra-low or zero-emission solutions require a rapid scale-up:

- By 2020, 2.3% of all PLDVs on the road have ultra-low or zero-emission powertrains of three types: 0.9% PHEVs, 1.3% battery-electric vehicles (BEVs) and 0.05% fuel cell electric vehicles (FCEVs).
- By 2040, less than half of all PLDVs on the road have conventional combustion engines: 39% are PEVs¹⁰ and 1.2% are FCEVs. The remaining shares (around 10%) are conventional HEVs¹¹ or natural gas vehicles.

Figure

5.3. Global technology penetrations in LDV stock by scenario, 2015–60



Note: CNG = compressed natural gas; LPG = liquid petroleum gas.

Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

By 2060, the share of alternative powertrain vehicles in the global LDV stock will reach 94% in the B2DS and 77% in the 2DS.

10. Including BEVs and PHEVs.

11. HEVs exclude start-and-stop technologies and refer to serial or parallel hybrid powertrain architectures combining ICEs and electric propulsion.

This development contributes to the achievement of net-zero GHG emissions for the energy sector as a whole by around 2060 (see Chapter 1) and is enabled by the wide availability of zero-carbon electricity in the 2060 timeframe. The strong shift to ultra-low and zero-emission technologies for LDVs matches increased pressure for decarbonisation for short-distance modes (such as 2- and 3-wheelers and LDVs), dictated by larger decarbonisation costs occurring in long-distance transport.

Technology prospects

A large part of the LDV decarbonisation challenge will fall to improvements in ICEs (gasoline and diesel), especially in the short to medium term. ICE technologies excluding plug-in hybrids still represent over half of the global LDV market share in 2035 in the B2DS trajectory and account for a stock of 1.2 billion vehicles – thereafter, sales and stock shares of these vehicles begins to fall. The average fuel consumption of gasoline cars would need to decline by 37% and that of diesel cars would need to decline by 32% over the next 20 years, leveraging on improved aerodynamics, lower rolling resistance and weight reductions to reduce energy needs, as well as technologies that improve ICE efficiency. The latter include solutions that apply solely to the ICE (such as variable valve lift and timing, direct fuel injection, engine downsizing and homogeneous combustion, and the use of thermodynamic cycles with a compression ratio that is smaller than the expansion ratio), and technologies that recover energy at the exhaust. These will be supplemented by technologies that reduce energy losses in the transmission as well as improved lubricants.

Short- to medium-term improvements also include hybridisation technologies, combining ICE improvements with the support of an electric or hydraulic motor. HEVs are also instrumental to enable the transition from ICEs to electric cars. In the B2DS, hybrid vehicles therefore primarily use electric technologies. HEVs are increasingly deployed until 2030, with a peak of an 11% global market share (as they are deployed earlier in developed markets, the market share of hybrids in the OECD reaches 16% in 2030). From 2030 onwards, HEVs are progressively phased out, alongside conventional ICEs (Figure 5.3).

In the B2DS, most long-term emissions reductions come from ultra-low or zero-emission technologies. These include electrification (emerging as the most promising long-term path towards net-zero GHG emissions on LDVs, provided that it goes hand in hand with decarbonisation of the electricity grid), low-carbon fuels (including biofuels produced from hydrotreated oils, biochemical or thermochemical routes, and PtX synthetic fuels) and FCEVs using low-carbon hydrogen.

The limited availability of biomass-based fuels (including PtX) and the need to prioritise their use in transport for long-distance modes narrows the potential to use substantial portions of biomass resources for LDVs. The investment risks in building large hydrogen production plants and the adequate infrastructure necessary to supply hydrogen as demand increases inform the low uptake projections for FCEVs, despite substantial cost reduction potentials for fuel cell technologies. As a result, most of the ultra-low or zero-emission vehicles entering the LDV fleet in the B2DS are expected to be PEVs, including both PHEVs and BEVs.¹²

The technology deployment rates required under the B2DS trajectory are very ambitious. This is the case for phasing in fuel economy improvements and alternative powertrains, but also for phasing out ICEs and the use of fossil fuels. The technology shift required by the B2DS requires a substantial increase in policy ambition on a global level. A taste of the ambition required by the B2DS can be understood from the following considerations, which outpace any previous transformations of the transport sector.

- Fuel economies of new vehicles entering the market will reach 4 litres per 100 km (when measured according to the Worldwide harmonised Light vehicles Test Procedure

12. PEVs are also subject to infrastructure-related barriers, requiring investment for chargers and solutions to address the stability of the grid. These investments, however, have a much lower risk profile than those required for a large-scale hydrogen deployment, because they do not need to be largely available up front and involve a broad array of stakeholders.

[WLTP]) by 2030 in the B2DS, exceeding by 10% the 2030 target of the Global Fuel Economy Initiative (GFEI), which aims to halve new PLDV average fuel economy relative to 2005 levels.

- The ultra-low or zero-emission vehicle stock in the B2DS reaches 200 million by 2030, double the fleet targets announced in the Paris Declaration on Electro-Mobility and Climate Change and Call to Action (Paris Declaration), released shortly before the Paris Agreement was finalised. The 40% share of new ultra-low or zero-emission vehicle sales for all road transport modes combined (2- and 3-wheelers, PLDVs, LCVs, trucks and buses) projected in the B2DS by 2030 also exceeds the target of the 35% announced in the Paris Declaration for that year.

The global share of ultra-low or zero-emission vehicles projected in the B2DS is broadly consistent with the ambition of the 30@30 campaign redefining the ambition of the Electric Vehicles Initiative (EVI)¹³ established under the Clean Energy Ministerial, but exceeds this ambition when looking only at EVI countries.

Scaling up electric mobility will also require a significant transformation in terms of industrial production capacity. This transformation needs time to materialise. The Tesla “gigafactory”, designed to support a production of half a million electric cars per year, for instance, got started in 2014 and will not be fully operational before 2018. Currently, the global vehicle market totals 89 million vehicles and it will likely reach 93 million by 2025. Shifting to BEVs for about a tenth of the production, as projected in the B2DS for shortly after 2025, would require building about 17 gigafactories within in the next decade. Three more would be necessary to produce enough batteries for all PHEVs deployed in the B2DS in the same time frame. Assuming four years for construction means that roughly 40% of this production capacity should now be under construction and in different phases of development. In that case, transport would be the sector accounting for most of the technology learning in battery technology.

Focus on electric cars

The major shift towards electric mobility projected in the B2DS is the catalyst of global sales-weighted average fuel consumption for PLDVs reaching 2.0 litres of gasoline equivalent (Lge) per 100 km, and per-kilometre emissions approach zero by 2060.¹⁴ Electrification is necessary because improvement of conventional or even hybridised ICE vehicles would not allow reducing fuel consumption per kilometre beyond half of its current value.

In 2016, there were 2 million PEVs in circulation, representing 0.2% of the global car stock. The B2DS implies a very steep adoption rate of PEVs, representing 13% of new LDV sales on average in OECD countries and the People’s Republic of China (hereafter, “China”) by 2020 and 32% in the same regions by 2030, compared with 12% in OECD and 26% in China in the 2DS.

Urban areas of OECD countries and China will likely host nearly 70% of all the PEVs in circulation by 2020. The larger share of PEVs in cities matches the fact that cities are often at the forefront of innovation. In the case of vehicle electrification, cities have already begun deploying charging infrastructure and enacting low-emission zones that favour ultra-low or zero-emission technologies. Urban cars also tend to be smaller and to have more frequent short-distance usage patterns than cars primarily used outside of cities. Both these features can also favour the adoption of BEVs over PHEVs.

In the B2DS, PHEVs contribute to electrification by representing over 10% of worldwide rural LDV sales by 2030 and a sales volume of 11 million LDVs globally, including 3 million vehicle sales in regions outside OECD countries and China. Also in 2030, the share of PHEVs in the global car stock peaks and PHEV sales shares stabilise, even as

13. For more on the EVI, see www.cleanenergyministerial.org/Our-Work/Initiatives/Electric-Vehicles.

14. For the LDV fleet as a whole, the global sales-weighted average fuel consumption reaches 2.4 litres of gasoline equivalent per 100 km.

BEV market shares increase thanks to cheaper batteries allowing higher driving ranges, higher fossil fuel prices and better access to charging infrastructure.

In order to reach technology adoption rates dictated by the B2DS, 73% of all energy use in LDV transportation relies on electricity in 2060. To achieve this, PHEVs would need to be designed and used in a way that significantly increases the share of travel on the vehicle's electric battery. Electric driving shares for PHEVs in the B2DS increase to 50% by 2020 and stabilise at 80% as early as 2030. This reflects stronger requirements for electric driving in urban areas (to reduce both local air pollution and GHG emissions) and is facilitated by the fact that average daily travel distances are fully within the ranges over which a PHEV can operate in urban environments in all-electric mode. On the policy side, this must be favoured by local measures requiring electric driving in urban environments (such as low-emission zones) and increasing fuel taxation to reflect a price of carbon that is aligned with the estimations developed for energy supply and that, by 2060, reaches USD 540/tCO₂.

To deploy the number of PEVs in the 2DS and the B2DS, battery cost and performance trends of the past decade would need to be sustained in the future; in 2015, a PHEV battery cost close to USD 270 per kilowatt hour (kWh), a BEV battery about USD 210/kWh and battery energy density ranged at about 300 watt hours per litre (Wh/L). These parameters have shown about a fourfold improvement since 2008 and are expected to continue to improve through research, innovation and economies of scale as PEV sales continue to expand.

With the B2DS PEV adoption rate, cumulative battery production for PEVs would reach nearly 3 billion battery packs in 2060. This would enable progression along a learning curve,¹⁵ ultimately reaching costs of USD 100/kWh for PHEVs and USD 80/kWh for BEVs. The latter are aligned with current estimates of the potential foreseen from RD&D results (Howell et al., 2016; Howell, 2017). Meeting these targets is currently expected to require the adoption of technologies with greater energy density, such as lithium metal and lithium air. Since batteries constitute the major powertrain cost component in PEVs today and are the main reason for the cost gap between PEVs and LDVs powered by ICEs, achieving such cost reductions, and especially narrowing the cost gap between PEVs and conventional vehicles, will be instrumental for a widespread introduction of PEVs on the market (Figure 5.4).

In all three *ETP 2017* scenarios, the total cost of ownership (TCO)^{16,17} of ICE LDVs tends to increase while the TCO of PEVs decreases. In the case of ICEs, the TCO increase observed in the scenarios is attributable to rising fuel expenditures over the use of the vehicle lifetime, as liquid fossil fuels are subject to increasing taxes and to the cost of engine improvements to meet fuel economy as well as GHG and air pollution emissions regulations.

In the United States and China, for example, although distances driven decrease and fuel economy improves under the B2DS trajectory, taxes on petroleum gasoline increase from 11% (USD 0.07/Lge) in the United States and 50% (USD 0.30 /Lge) in China in 2015 to more than 200% (USD 1.70/Lge) in both regions by 2060, primarily reflecting a rising carbon price. This results in the TCO of a gasoline ICE vehicle, calculated over 3.5 years of use, increasing by close to 40% over its 2015 level by 2060 in the United States and by almost 80% in China. Over the same timeframe, BEVs benefit from technology learning that reduces battery costs by 60% in 2060, even though vehicle range doubles from 200 km in 2015. Energy costs of BEVs also decrease, as electricity prices do not experience the same

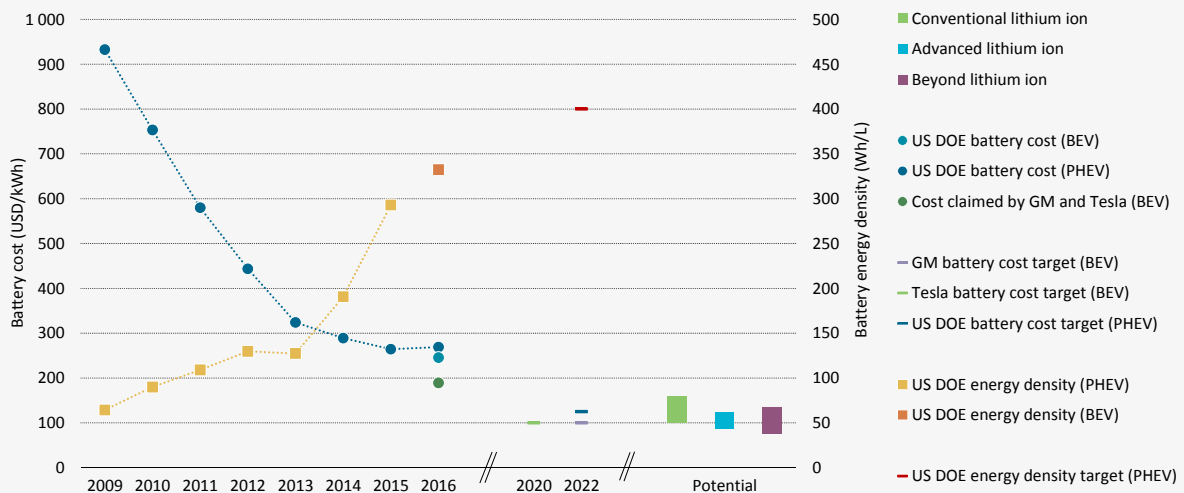
15. The learning rate assumed for this assessment is 20%.

16. Fuel prices used for the evaluation of the TCO of different technologies include CO₂ prices as in the analysis of power generation technologies. In 2060, the CO₂ price is assumed to reach USD 540/tCO₂. The oil price assumptions (in 2015 constant USD) used for this assessment are USD 50 per barrel (bbl) in 2015, USD 140/bbl in the RTS and USD 75/bbl in the B2DS. Fuel taxes reflect the assumptions outlined in this chapter.

17. In this assessment, calculation of the TCO accounts for fuel taxes in each region, using a short use time (3.5 years) and taking into account the powertrain cost after 60% depreciation and a uniform 20% purchase tax, assuming similar durability characteristics for different powertrain technologies. This primarily aims to highlight key dynamics between powertrain investment and operating costs to identify major points of interest for policy developments. Despite shortcomings due to the lack of a full inclusion of insurance and maintenance costs, as well as uncertainties related to technology performance, it broadly reflects the cost differentials faced by a first vehicle buyer.

increases observed for fossil fuels. The TCO of PHEVs does not undergo such striking changes over time, as increasing costs on the ICE side are offset by decreasing costs on the electric side. However, the narrowing cost gap with conventional ICEs also improves the cost-competitiveness of PHEVs over time. By 2060, the TCO of BEVs over 3.5 years of vehicle life is similar to that of comparable sized gasoline and gasoline hybrid vehicles, and becomes significantly lower than conventional and hybrid models when calculated over longer timeframe (e.g. five or ten years of vehicle life).

Figure 5.4. Evolution of battery cost and energy density, 2009-15



Note: US DOE = US Department of Energy.
Source: IEA (2017b), *Global EV Outlook 2017*.

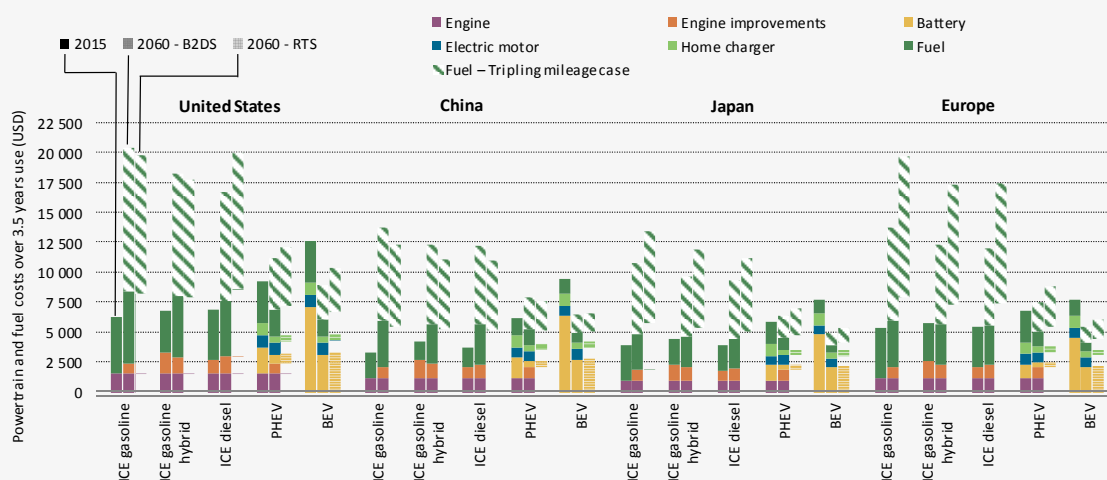
Key point *Prospects for future cost reductions from the main families of battery technologies confirm the encouraging signs in cost and performance improvements observed over the past decade.*

The evolution of the TCO of competing technologies at different points in time in the B2DS also suggests that cost-competitiveness of electric cars cannot take place overnight. In 2030, the year when the global electric LDV stock attains 200 million units, the TCO of BEVs over 3.5 years is still 84% higher than the TCO of gasoline cars in China, and 22% greater in Europe, the region moving fastest towards cost-parity due to fuel tax regimes higher than those in any other region. Even if PHEVs have a lower TCO than BEVs in 2030 (this is no longer the case in 2060), they are also between 18% and 38% more expensive than their ICE counterparts.

In addition, it is also important to underline that TCO levels for BEVs and PHEVs in the RTS by 2060 do not radically differ from B2DS levels, as battery costs approach an asymptote in the long-term in both cases (Figure 5.5). The major difference in the two scenarios is embedded in the TCO increase of ICEs (due to technology improvements required to improve fuel economy and reduce emissions of local pollutants), which is faster under the B2DS and thus more quickly narrows the cost gap between ICE and electric technologies than in the RTS trajectory.

Figure

5.5. Comparative cost of PLDV technologies by country/region in the RTS and B2DS, 2015 and 2060



Notes: Vehicle travel per year, powertrain costs and fuel costs reflect assumptions of IEA (2017a).

Key assumptions on PLDV costs are:

Vehicles: 2015 powertrain investment costs for European vehicle characteristics range from USD 2 600 for gasoline ICE, USD 4 400 for diesel ICE, USD 5 500 for gasoline ICE hybrid, USD 7 800 for PHEV to USD 12 400 for BEV. In Europe, powertrain investment costs in 2060 range from USD 4 400 for gasoline ICE, USD 5 000 for gasoline ICE hybrid to USD 6 700 for PHEV, and USD 6 800 in the B2DS to USD 7 100 in the RTS for BEV.

Powertrain costs in other countries are adapted to domestic vehicle characteristics. Results shown also reflect 60% depreciation and a uniform assumption of a 20% tax on vehicle purchase. Insurance and maintenance costs are not included.

Home charger: USD 1 000 cost for the installation of a home charger is included in the TCO of PHEV and BEV in 2015. By 2060, this cost drops to USD 500.

“Fuel – tripling mileage case” refers to the fuel cost increment imputable to a tripling of the average mileages considered in the B2DS.

Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

PEVs (including PHEVs and BEVs) become increasingly competitive with conventional technologies over time in the four regions in both scenarios. The TCO differential in favour of PEVs occurs sooner and is more substantial for vehicles that are driven more than average distances.

Policy needs

The considerations outlined for PEVs, and in particular the converging TCO once learning, resource cost and carbon taxes are factored in, suggest that technologies with quite different GHG potential impacts will have similar costs for consumers. This is an encouraging sign, as it suggests that reducing CO₂ emissions in LDVs could take place with CO₂ prices that are similar in magnitude to those required for the decarbonisation of power generation.

On the policy front, this convergence underlines the importance of fuel taxes that embed carbon prices reflecting life-cycle GHG emission intensities of fuel production.¹⁸ Provided that the revenue is effectively and transparently used, differentiated vehicle taxes or feebates, i.e. the combination of fees and rebates, applicable to both vehicle registration and circulation, have proven to be an effective and popular means of accelerating the

18. If the fuel production industry is subject to CO₂ taxes for the fossil fuels it uses (tank-to-wheel component) and transport fuels are subject to taxes only on well-to-tank CO₂ emissions, the total taxation reflected in end-user prices is equivalent to the application of taxes on WTW CO₂ emissions. This is also valid if the WTW concept is broadened to include the whole life cycle of the fuels, also accounting for GHG emissions embedded in goods and services needed for their production.

deployment of energy-efficient vehicle technologies.¹⁹ Feebates based on CO₂ emissions performance of vehicles are highly effective at accelerating the uptake of low-carbon technologies, thereby reducing fleet average GHG emissions (Brand, Annable and Tran, 2013). A brief review of successes, failures and lessons learned on differentiated vehicle taxes is summarised in Box 5.1. It also discusses differentiated vehicle taxation practices that aim to enhance the long-term competitiveness of ultra-low or zero-emission technologies.

Box

5.1. Differentiated vehicle taxation – success, failure and lessons learned

Many countries, including 20 EU member states (ACEA, 2016), Brazil, Canada, China and South Africa (GFEI, 2017), impose differentiated taxes on vehicle registration and/or circulation, based on their fuel economy or CO₂ emissions performance. Some countries have designed systems that not only tax inefficient and highly emitting vehicles, but also use the revenues collected from these taxes to subsidise the purchase of cars with superior fuel economy performance relative to the average car sold. “Feebate” systems – the combination of fees and rebates – may be based on CO₂ emissions performance and/or other vehicle attributes and metrics. Registration taxes may consider CO₂ and local pollutant emissions (Norway), engine power or size (Portugal), vehicle weight, and even vehicle length (Malta). Sales price is another commonly used factor, also factored in through value-added tax (VAT).

France was one of the early adopters of a nationwide feebate system underpinned by vehicle CO₂ emissions per kilometre, and its “bonus-malus” scheme has been instrumental to France having one of the European Union’s most efficient passenger vehicle fleets (EEA, 2017).

Differentiated vehicle taxation is also widely applied in the Scandinavian countries, where vehicle taxes tend to be quite high and where rebates do not accompany fees. For instance, in Finland vehicle registration taxes range from 5% to 50% of the initial (untaxed) vehicle purchase price. In Denmark, vehicle taxes total more than the purchase price of the average vehicle (ACEA, 2016). Norway’s registration tax employs a graduated and strict fee (and no rebate) based on CO₂ and oxides of nitrogen (NO_x) emissions, vehicle weight, and engine size – the average registration tax level for a medium-sized car including VAT was close to USD 20 000 in 2015 (IEA, 2016b; Tietge et al., 2016). In Norway, BEVs are exempted from both VAT and registration taxes, and PHEVs are exempt from the registration tax. The strong, clear price signal provided by feebates at the time of vehicle purchase, together with their impact on payback periods (particularly in cases of additional waivers or exceptions for ultra-low or zero-emission vehicles), provide effective mechanisms for accelerating the adoption of efficient technology in new vehicle registrations (Gallagher and Muehlegger, 2011; Bareit, 2016). In the case of Norway, the vehicle taxation system is recognised as one of the pillars leading that country’s EV sales to world-record shares.

Differentiated taxation has also proven effective when applied to imports of second-hand vehicles. Since 2010, Sri Lanka has introduced substantial tax reductions for used imports of hybrid cars and in 2015 included PEVs. By the end of 2015, this led to the import of about 80 000 hybrid vehicles and 2 400 PEVs, representing more than 15% of the country’s LDV stock (UNEP, 2015).

Fiscal incentives aiming to boost ultra-low and zero-emission sales volumes are already in place in countries leading the PEV market in various forms: direct purchase subsidies, VAT breaks or exemptions, or differentiated vehicle purchase and/or circulation taxes that favour low-emission vehicles and in particular PEVs. Maintaining fiscal incentives commonly

19. Taxation on individual vehicles can also be effectively used for the development of public transport networks for the promotion of access to low-emissions mobility to all portions of the population (IEA, 2016a).

observed today (around USD 5 000 for BEVs and two-thirds of that for PHEVs) would already make BEVs cost-competitive with conventional ICEs and PHEVs in Europe by 2020, and significantly narrow the cost gap with conventional gasoline cars over the next ten years elsewhere, supporting PEV market uptake. Establishing these incentives in countries that have not yet introduced them would help to achieve greater sales volumes, speeding up this process. The convergence of the TCO for competing vehicle technologies also suggests that cost reductions alone will not be sufficient for PEVs to reach the market shares required by the B2DS: such a shift will be possible only with clear indications that ultra-low or zero-emission vehicles provide better value for consumers than alternatives. At the same time, as technology uptake accelerates, subsidies will need to be phased out.

Ideally, differentiated vehicle taxation and feebate schedules should directly target performance outcomes, including CO₂ or local pollutant emissions, or both, rather than vehicle weight, engine size or other vehicle characteristics. Further, feebates should avoid giving preference to one technology over another. Whenever possible, feebates should be imposed as a continuous function (such as a linear increase per gramme of CO₂ per kilometre) to prevent the use of loopholes by automakers (which is witnessed when discrete thresholds are used to group vehicles).

As TCO parity cannot be reached without substantial reductions in battery costs, incentives for PEVs will remain essential, at least in the next few years, to stimulate technology adoption and support technology learning. The justification for this lies in the stronger cost reduction opportunities resulting from learning in the initial phase of technology deployment, when learning and economies of scale lead to the greatest cuts in battery costs. Incentives for ultra-low and zero-emission vehicles are best conceived based on life-cycle GHG emissions mitigation performance, which should also apply to FCEVs. The logic applied for performance-based incentives is the same already applied in several global regions using differentiated vehicle taxes based on specific CO₂ emissions. In cases where fee reductions, credits or exemptions are granted to specific technologies such as PEVs and FCEVs to stimulate cost reductions, a clear schedule for revising and ultimately eliminating these technology-specific measures should also be laid out in advance (and subsequently amended as little as possible thereafter), benchmarking the phase-out of specific incentives against cost reduction targets.

Fiscal incentives for vehicle technologies having the capacity to enable ultra-low or zero emissions (PEVs and FCEVs) can be justified even when the production of electricity and hydrogen is not yet decarbonised, provided that adequate measures are also enacted in the energy transformation and power sectors to ensure the rapid and progressive decarbonisation of these energy carriers.

Ultimately, should feebates and other measures to reduce the specific emissions of cars prove successful, policies such as pricing based on vehicle kilometre will need to be phased in to maintain revenues, prevent rebound and provide price signals that reflect the other externalities, such as congestion, road wear and other environmental impacts.

The shift to ultra-low and zero-emission vehicles needed in the B2DS will also require other policy instruments.

- Zero-emission vehicle mandates (ZEV mandates), i.e. regulatory requirements (now based on a system of tradable credits) for automakers to sell a set portion of ultra-low or zero-emission vehicles, aiming to complement RD&D efforts to market ultra-low and zero-emission vehicles. ZEV mandates were pioneered by California (CARB, 2017), are enforced in several other US states (UCS, 2016) as well as Canada's Quebec province, and are now being considered in China (Electrek, 2016).
- The progressive tightening of fuel economy regulations, beyond the efficiency potential available from improved ICEs and hybrids. Regulatory limits on the average emissions per kilometre are likely to be one of the main policy drivers enabling the transition, given that no

other policy instrument (including vehicle and fuel taxation) can act directly on this key vehicle design parameter. The lack of a regulatory framework for specific fuel economy/GHG emissions would add uncertainties and risks for original equipment manufacturers (OEMs), something that is likely to delay action.

- Local policies, including access restrictions on ICE vehicles, differentiated road pricing and parking fees, and other measures targeting local air pollution have the capacity to increase the value proposition of ultra-low or zero-emission vehicles. Restrictions on the operation of vehicles that emit high volumes of local pollutants have already been widely adopted in Europe. Air pollution concerns have also led seven major Chinese cities to enact policies restricting the availability of licence plates that include waivers for low-emission vehicles.

Supporting the adoption of ultra-low and zero-emission vehicles also requires the deployment of charging and refuelling infrastructure.

- For PEVs, this takes the form of home, work or public charging points and is likely to require grid reinforcements to deal with capacity limitations to handle demand peaks. Since the availability of charging infrastructure emerged as one of the key factors that are positively correlated with the growth of PEV market shares, public support for the deployment of charging infrastructure is currently a policy priority. The main mechanisms available for this purpose include direct incentives or fiscal advantages (e.g. tax breaks) for the installation of charging outlets. Infrastructure installation approaches prioritising private charging over public chargers and, for public chargers, matching charging outlets with PEV owner demand are well placed to mobilise private investment and ensure cost minimisation (see for instance Vertelman and Bardok, 2016).
- Developing the infrastructure necessary for the successful introduction of FCEVs requires action to manage investment risks. This requires a co-ordinated effort across industries to resolve the market mismatch between infrastructure deployment (refuelling stations) and demand for hydrogen. Car manufacturers; fuel cell and electrolyser producers; oil, gas and power suppliers; and transport service providers have created common initiatives, such as the German Mobility Coalition and the California Fuel Cell Partnership, aiming at the joint deployment of an initial network of refuelling stations (Hydrogen Council, 2017).
- Low-carbon liquid biofuels and PtX synthetic fuels need to take the form of drop-in fuel to maximise the possibility to rely on existing infrastructure.

The transition to ultra-low or zero-emission mobility could also be facilitated by changes in the traditional model of car ownership, moving away from an individual ownership paradigm towards a usage-based model (i.e. “mobility as a service”). Such a shift would result in higher vehicle utilisation, thereby enabling rapid amortisation of capital costs and faster vehicle turnover, accelerating the adoption of innovations in the vehicle stock. It would also require fewer cars to satisfy the same travel demand and would be favoured by the success of shared mobility services, such as electric, and potentially even autonomous and electric shared mobility services (Box 5.2). This effect is clearly shown in Figure 5.5: the cost advantage of PEVs in terms of TCO clearly rises under a tripling of the average mileages considered in the B2DS (in this case, the increment in fuel expenditures is represented by dashed columns).

Box**5.2. ACES – automated, connected electric and shared vehicles**

The advent of new technologies and business models enabled by digitalisation may lead to a disruptive transformation in the transport sector. The differences in how mobility services are provided are captured neatly by the ACES paradigm – automated, connected, electric and shared. Given the nascent stage of these developments, questions of how fast these changes will come, and how deeply they will impact not only patterns of moving people and goods but by the energy needed to do so, are far from answered. Nevertheless, growing literature is beginning to identify and explore the key technology, policy and behavioural drivers, as well as likely impacts under different development scenarios.

Automated vehicles (AVs) and connected and automated vehicles (CAVs) promise greater safety and less congestion, making commutes and other trips both faster and more pleasant in the short term. Driverless AVs also promise substantive cost reductions for on-demand and shared mobility services, i.e. services offered by app-based car-sharing, ride- and vehicle-sharing, and sourcing platforms.

The innovative potential of AVs led to significant investments in the recent past. Some of the major OEMs have targeted introduction of highly autonomous (levels 4-5)²⁰ vehicles as early as the beginning of the coming decade. Investments in vehicle automation technology are now growing at a rapid clip. Yet many technical, legal and regulatory hurdles stand in the way of fully automated self-driving cars. This suggests that automation technologies are likely to be introduced in progressive steps over the next decades, with highly autonomous vehicles currently expected to be ready for deployment in the 2025-40 timeframe (IHS Automotive, 2014; Milakis et al., 2015; Wadud, MacKenzie and Leiby, 2016).

The impact of AVs on the transportation system could be significant. A lower perceived inconvenience and time costs of driving with AVs may favour urban sprawl. The cost reductions that driverless AVs could deliver to mobility services are also likely to increase their appeal and use, possibly displacing mobility that would otherwise take place on public transport and in personal vehicles, and potentially moving the transport system away from the current paradigm of vehicle ownership, towards the provision of mobility as a service.

Overall, vehicle automation and sharing are likely to lead to increased vehicle use. This pressure would give more relevance to the costs of operating vehicles, favouring efficient technologies. EVs such as BEVs and FCEVs may stand to benefit significantly from the growth of mobility as a service, as they may become the most cost-effective vehicle platform for dynamic ride-sourcing. As operations (and fuel) costs exceed vehicle capital costs because of high utilisation rates, shared vehicles could also spur more rapid vehicle (and fleet) turnover, thereby accelerating the uptake of highly efficient technologies. A dispatchable and roving fleet could further enable right-sizing of vehicles to trip purpose and capacity required.

The potential upsides of a new mobility paradigm are undeniable – these new systems have the potential to improve safety for car users and pedestrians alike, optimise vehicle performance, and thereby reduce specific (per kilometre) emissions, making more destinations cheaply and easily accessible for more people. At the same time, such improvements in access and convenience could drive up demand for trips. With true self-driving cars, not only might previously under- and unserved populations (e.g. children, teenagers, the blind and physically disabled) be able to ride unaccompanied and with unprecedented ease, but on-demand delivery could culminate in roving urban fleets providing traditionally location-based services such as groceries, restaurant food and even health care. The ACES paradigm is likely to drive down costs and substantially improve service efficiency in freight as well, with similarly ambiguous potential implications for total energy use and emissions.

While experts differ on their expectations of the timing and extent of the impacts of ACES technologies and mobility patterns, some consensus on likely ramifications for vehicle activity exists, with several studies suggesting an increase. A report sponsored by the BMW-funded Institute for Mobility Research (Ifmo, 2016) explores scenarios in which fully autonomous cars penetrate the German and US automobile fleets. In a baseline scenario, stock shares of AVs in these countries reach 11-17% by 2035, while in a “technology breakthrough” scenario, AVs make up 32-42% of the passenger car fleet. The impacts on total travel (vehicle kilometres) projected across the scenarios are modest: from 3% in the baseline to 9% in the scenario

20. Various classifications of levels of vehicle automation exist. The US National Highway Traffic Safety Administration has levels 0–4, while the widely accepted schemes devised by IHS Automotive (IHS Automotive, 2014) and the Society for Automotive Engineers International (SAE, 2014) have levels 0–5. Levels 4 and 5 designate “high” and “full” autonomy. The radical transformations considered here would become possible from level 4, according to all schemes.

where zero-passenger trips and trips by unaccompanied ten-year-olds are made legal. Another study explores the impacts of connected and AV technologies entering the Dutch market within the 2025-45 timeframe (Milakis et al., 2015). The authors expect AV penetration to lead to substantial increases in total activity, and depending on key technology, behaviour and policy drivers, the upper bound estimated increase in vehicle kilometres grows from 3% in 2030 to 27% by 2050, despite the assumption that the Dutch government would adopt policies to limit travel activity growth. Another study examines the impacts of shared AVs operating in a typical European city, under the assumption that these services supplant car and bus trips (ITF, 2015). This study finds that eight to nine out of every ten cars could be removed from European cities; up to 80% of off-street parking space could be relegated to other purposes. At the same time, the study finds the potential for vehicle kilometres to increase by 6-89% if the paradigm of urban mobility transforms to the extent modelled. Particularly in a scenario where conventional private cars and autonomous shared fleets operate simultaneously, the potential impacts on congestion and emissions are considerable.

Contrary to vehicle activity, there is no consensus on the consequences of ACES on energy and emissions. The range of uncertainty in projecting activity and energy use impacts is wide – depending on assumptions of behavioural response, policy intervention, and the speed and degree of adoption of efficient and appropriately sized vehicles. Various studies set wide brackets for estimated potential impacts. Analyses of extreme scenarios developed for the US DOE find that AVs could reduce fuel consumption by 90% (Greenblatt and Saxena, 2015) or triple (Brown, Gonder and Repac, 2014), under a “perfect storm” of behavioural response. However, recent studies (Greenblatt and Shaheen, 2015; Wadud, MacKenzie and Leiby, 2016) are broadly optimistic on the prospects of ACES to confer energy use and GHG and pollutant emissions reductions, particularly if policy makers and planners are flexible and proactive in steering the development. Indeed, many studies that model behavioural rebound responses, and consider revenue impacts, recommend gradual introduction of distance- and congestion-based pricing to offset the reductions in the monetary cost of trips and to address externalities resulting from increased travel.

Fiscal incentives directed at early ultra-low and zero-emission vehicle adoption lead to direct expenses for governments. The resources needed to finance the uptake of BEVs, PHEVs, HEVs and FCEVs in the B2DS amount to roughly 15% of total PLDV sales tax revenues over 2020-30 in the regions that account for most of their deployment (OECD and China). This estimate is based on purchase subsidies of USD 5 000 for BEVs, USD 3 300 for PHEVs and USD 1 100 for HEVs until 2020, reduced gradually to half their initial level by 2025 (and to zero for HEVs), and is benchmarked against an average tax rate of 30% applied to all vehicle purchases worldwide in the B2DS trajectory.

As ultra-low and zero-emission vehicles gradually gain market share and displace ICEs, revenues collected from conventional fuel taxes will also shrink. For example, despite growing taxes on liquid transport fuels adopted in the B2DS (which are based on the WTW GHG intensity of the fuels), US fuel tax revenues could drop by two-thirds in 2060 relative to 2015. The decline can reach 95% in regions that apply fairly high fuel taxes today, such as the European Union and Japan. These declining revenues will need to be compensated to maintain road infrastructure, to finance the new energy infrastructure required in the B2DS and to address externalities caused by vehicles and congestion.

Ultra-low and zero-emission vehicles will need to contribute to alternative taxation schemes.²¹ Moving towards direct road pricing, applying taxes based on the number of

21. For PEVs, this could take the form of a tax on the electricity used, embedding a component of differentiated tax rates depending on the life-cycle GHG performance of transport fuels. Given the wide diffusion of low-carbon electricity in the B2DS and the much lower demand for electricity from PLDVs (compared with ICE fuel demand) owing to the much better fuel efficiency of electric motors, revenues

vehicle kilometres travelled rather than the fuel used is likely to be the most suitable alternative. Charging vehicles for their usage in terms of vehicle kilometre would also be an accurate way to account for their contribution to infrastructure use, local pollution and congestion. Advanced road pricing schemes can also be geographically and temporally differentiated to incorporate, for example, a higher fee for vehicles circulating at peak traffic periods in densely populated urban centres. Maintaining governmental revenues currently derived from fuel taxes will also require a progressive shift towards charges applied on a vehicle–kilometre basis. This could be partially reduced by the lower health expenditures in cities induced by a shift to ultra–low and zero–emission mobility.

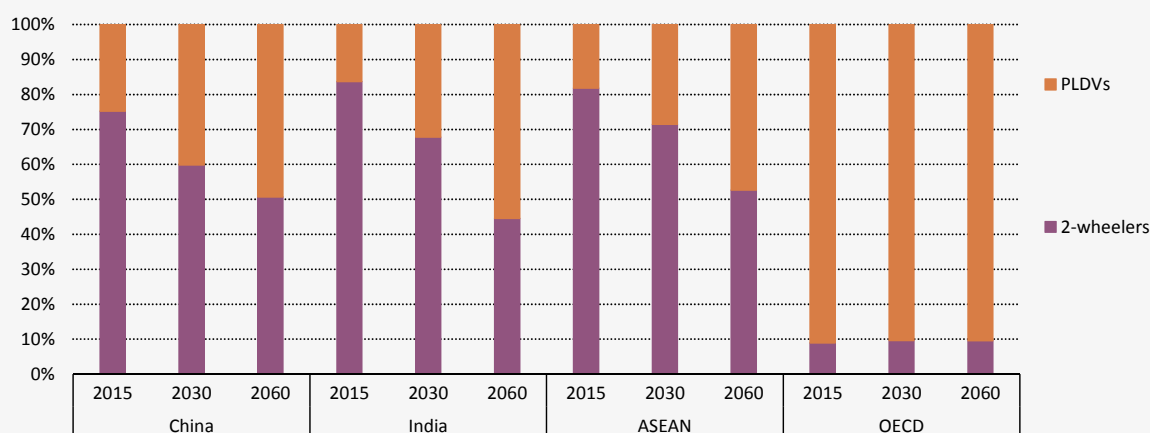
The analysis of fuel taxation revenues in key vehicle markets such as China, the European Union, Japan and the United States helps to grasp the magnitude of road taxes needed to maintain taxation revenues roughly equivalent to what would be reaped by fossil fuel taxation in 2020–30. Post-2030 (i.e. once fuel taxation revenues begin to fall significantly) the vehicle–kilometre fee, applicable to all cars in circulation and capable of maintaining revenues equal to those raised by fuel taxes in 2015, would need to range from USD 0.01/km in the United States and China, to USD 0.08/km in the European Union and Japan.

2- and 3-wheelers

Global activity of motorised 2- and 3-wheelers tripled from 2.8 trillion pkm in 2000 to 8.5 trillion pkm in 2015, nearly twice the rate of activity growth for cars. Most of this growth took place in Asia. Motorised 2-wheelers have major relevance in India and in the Association of Southeast Asian Nations (ASEAN) region, where they outnumber personal cars by a ratio of more than five to one, as well as in China, where the ratio between 2- and 3-wheelers over PLDVs exceeds a factor of three (Figure 5.6). In the OECD, motorised 2- and 3-wheelers currently account for less than 10% of all personal vehicles. Two- and 3-wheeler ownership rates have always been far lower in the OECD (one–third or less, even in the case of Italy, the OECD country with the highest level of motorcycle ownership) than the levels currently observed in China and the ASEAN region.

Figure

5.6. Share of 2-wheelers in major Asian regions and the OECD average in the B2DS, 2015–60



Source: IEA, (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

With rising average income levels, ownership levels of 2-wheelers in China, India and ASEAN countries decrease and ownership levels of PLDVs increase over time.

from this taxation system would not to compensate for the fall in revenues from liquid fuels unless tax rates are extremely high. Similar considerations can be extended to FCEVs and hydrogen.

Activity projections

In each of the *ETP 2017* scenarios, 2- and 3-wheeler ownership declines with rising incomes in favour of PLDVs. In the B2DS, 2- and 3-wheeler ownership declines faster than in the RTS and the 2DS, thanks to stronger policies that promote the competitiveness and appeal of public transportation over PLDVs and 2- and 3-wheelers alike. Given the high numbers registered in 2015, 2- and 3-wheeler ownership levels in the ASEAN, China, India and other developing Asia regions remain well above the levels reached in all other world regions. This assumption is grounded on historical differences between Asia and the rest of the world and consistent with expectations for more frequent decisions in Asian households (with respect to households located in other global regions) not to buy a personal car (or a second or third car, as the case may be). For instance, surveys in Chinese cities show that electric 2-wheelers provide a means of fast and affordable transport in car-centric urban landscapes that do not successfully integrate walking, cycling or public transit (Weinert, 2006; Cherry et al., 2016). Survey evidence also points to electric bikes (e-bikes) providing a viable substitute for car travel. More than 40% of Chinese e-bike riders interviewed in 2012 had access to a car, but still used their e-bikes for some trips. Others may be forestalling the purchase of a household car, or else not buying a car, due to their satisfaction with mobility services provided by their e-bike (Cherry et al., 2016).

When looking at future developments of mobility, it is important to emphasise that the evolution of 2- and 3-wheeler ownership can have major consequences on the development of aggregate transport energy demand. A faster transition from 2-wheelers (3-wheelers are primarily used as taxis and for light freight) towards more energy-intensive PLDVs in Asia, in particular, would increase global energy demand and considerably hinder efforts to limit energy demand growth and mitigate CO₂ emissions. This is especially important if a faster shift from 2-wheelers to PLDVs ends up occurring in highly populated and rapidly developing regions in Asia, given the high relevance of 2- and 3-wheelers in the region today. The magnitude of this effect can be captured by a simple calculation: if 10% of the passenger kilometres currently taking place on 2- and 3-wheelers in Asia were to shift to PLDVs, global energy demand in transport would increase by roughly 1%. Given that Asia will account for a growing share of total passenger kilometres from road modes (54% in 2060 relative to 41% in 2015), this effect is destined to grow over time.

The way Asia will transition from 2- and 3-wheelers to PLDVs will have major importance in the depth of modal shifts and the technology transition to ultra-low or zero-emission vehicles necessary to meet the goals of the B2DS.

Technology prospects

Electric 2- and 3-wheelers provide inexpensive motorised mobility with environmental performance superior to conventional cars: due to their light weight and the efficiency of electric drivetrains, they can use as little as 1.8 kWh/100 km of electricity, or about one-tenth the energy of an electric car (Ji et al., 2012). Projections of technology choices for 2- and 3-wheelers include rapid changes in the B2DS, where these modes become entirely electrified (99%) by 2045. Two- and 3-wheelers are indeed the most straightforward to decarbonise, which explains the progressive shift towards electric 2- and 3-wheelers occurring even in the RTS.

The basis for the rapid and full electrification of 2- and 3-wheelers that occurs in the B2DS is their low weight and short range, combined with the high efficiencies of electric motors. The energy requirements of electric 2-wheelers are 80% lower for similar gasoline-powered versions. This makes them the most suitable candidates for battery electric propulsion, with zero tailpipe emissions. This limits the battery storage capacity required on 2- and 3-wheelers, which cuts both costs for the most expensive component of EVs, as well as battery weight, therefore allowing easy battery removal for recharging purposes. Low energy requirements for 2-wheelers also facilitate battery charging from conventional electricity outlets over relatively short time spans (a few hours for a full recharge).

Many of these advantages are well represented by the case of China, the world leader in electric mobility for 2- and 3-wheelers. China has more than 200 million electric 2-wheelers in circulation, about 40% of the world's total 2-wheeler fleet (IEA, 2017a). With prices ranging from around 400 Yuan renminbi (RMB) to RMB 4 000 (USD 60 to USD 600), and

with the most popular models selling for around RMB 2 000 (USD 300), Chinese electric 2-wheelers have already reached cost parity with conventional 2-wheelers and are now one of the mainstream technologies used for 2- and 3-wheeled mobility (Cherry, 2010).

Policy needs

Stimulating the shift towards the electrification of 2- and 3-wheelers could follow some of the steps already adopted in China since the early 2000s. The main driver of the transition that occurred in China was restrictions on the ownership and operation of gasoline motorcycles in urban cores. Other measures having the capacity to stimulate the market penetration of electric 2-wheelers include:

- Tightening regulatory requirements for 2- and 3-wheelers on the emissions of local pollutants.
- Introducing regulatory limits on the GHG emissions of 2- and 3-wheelers and progressively tightening them.
- Adopting differentiated taxes for the registration and circulation of 2- and 3-wheelers, providing incentives for those offering the best performance.

The market uptake of electric 2- and 3-wheelers could also be strengthened by waivers, for ultra-low or zero-emission vehicles or from regulatory measures limiting access to specific urban areas, and/or by the exemption from pricing policies such as congestion charging.

As electric 2-wheelers have already achieved cost competitiveness in China, import taxes on electric 2-wheelers should also be reduced or eliminated.

Importantly, encouragement of (electric) 2- and 3-wheelers in the B2DS must go hand in hand with increased safety measures. Today, 90% of deaths that result from road traffic injuries occur in low- and middle-income countries, and motorcyclists are among the most vulnerable road users (WHO, 2016). In China and India, 2- and 3-wheelers represent the largest road-user category among traffic fatalities, with users of 2-wheelers making up 35% of total traffic deaths and those of 3-wheelers making up 32% (WHO, 2013). Measures to improve road safety include the adoption of vehicle regulations on minimum standards, the promotion of vehicle design ensuring greater safety features for drivers and pedestrians, reducing speed, reducing drinking and driving, increasing helmet use, and increasing the use of child restraints (WHO, 2016). The reallocation of road space accommodating changes in the urban vehicle mix, for instance replacing conventional lanes with dedicated lanes for 2-wheelers (along the lines of measures aiming to encourage walking and cycling) are also likely to have positive safety implications.²²

In China, not requiring licensing and registration permitted electric 2-wheelers to travel in bicycle lanes. This advantage of reduced congestion for e-bike users has contributed to their success, but has also led to safety concerns as electric 2-wheelers made motorised travel available to a growing share of the population. The increased use of bike lanes by electric 2-wheelers led some Chinese cities to ban e-bikes over the past few years. This underlines the importance of the definitions and regulations classifying electric 2-wheelers, as well as the need to conceive urban transport infrastructure in a way that can accompany an ordered transition to 2-wheeled electric mobility. This will require a timely match between the supply of road space and the evolution of modal shares, especially in rapidly developing economies.

Bus and rail

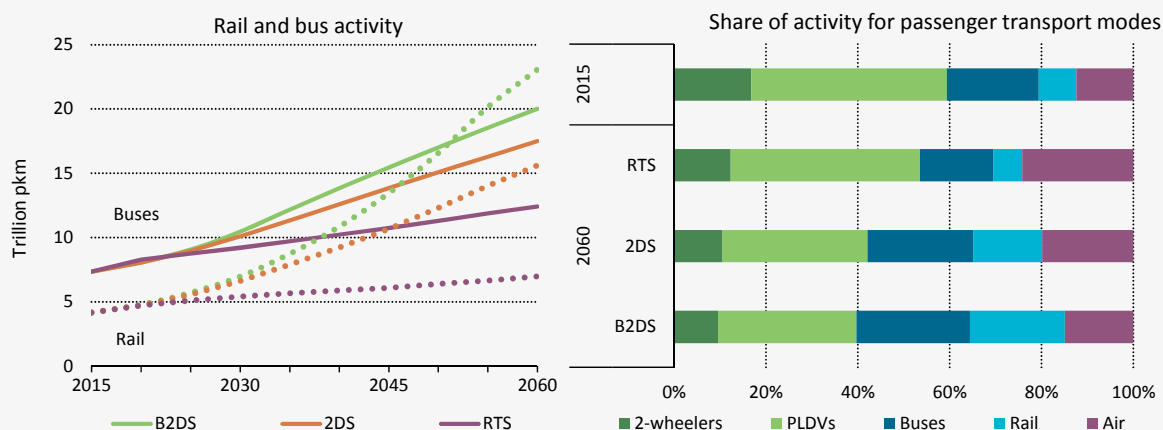
In the RTS, passenger rail activity increases from 4.2 trillion pkm in 2015 to 7.0 trillion pkm in 2060. Passenger travel on buses increases from 7.3 trillion pkm to 12.4 trillion pkm over the same period. Yet the share of public transport activity (rail and bus) out of total passenger activity decreases in the RTS from 2015 to 2060, shifting to private passenger

22. This change in modal mix may be encouraged by a variety of measures; for instance, by restrictions on parking availability for PLDVs, parking fees, and those that promote electric 2- and 3-wheelers.

transport (PLDVs and 2- and 3-wheelers) as a result of rising average incomes, particularly in the emerging and developing economies (Figure 5.7).

Figure

5.7. Bus and rail activity by scenario and passenger transport activity by mode, 2015–60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

National-, regional- and local-level policies would be needed to promote major shifts from private cars to public transport in order to reduce the energy intensity of passenger transport services.

On the contrary, policies constrain this shift in the 2DS and B2DS, encouraging the opposite shift from carbon-intensive transport modes (PLDVs and aviation) to public transport. This shift is stronger in the B2DS than in the 2DS (Figure 5.8).

In addition, in the B2DS (and in the 2DS) a strong shift in activity from aviation to high-speed rail (HSR) takes place (see Figure 5.13). Today, rail is 91% more energy efficient per passenger kilometre than aviation, and with limited alternatives to fossil-derived fuels available to the aviation sector, this strong shift to HSR is essential for meeting B2DS targets. Lower unit costs enabled by population density translate to greater utilisation rates of, and more activity in, HSR in regions with higher population densities.

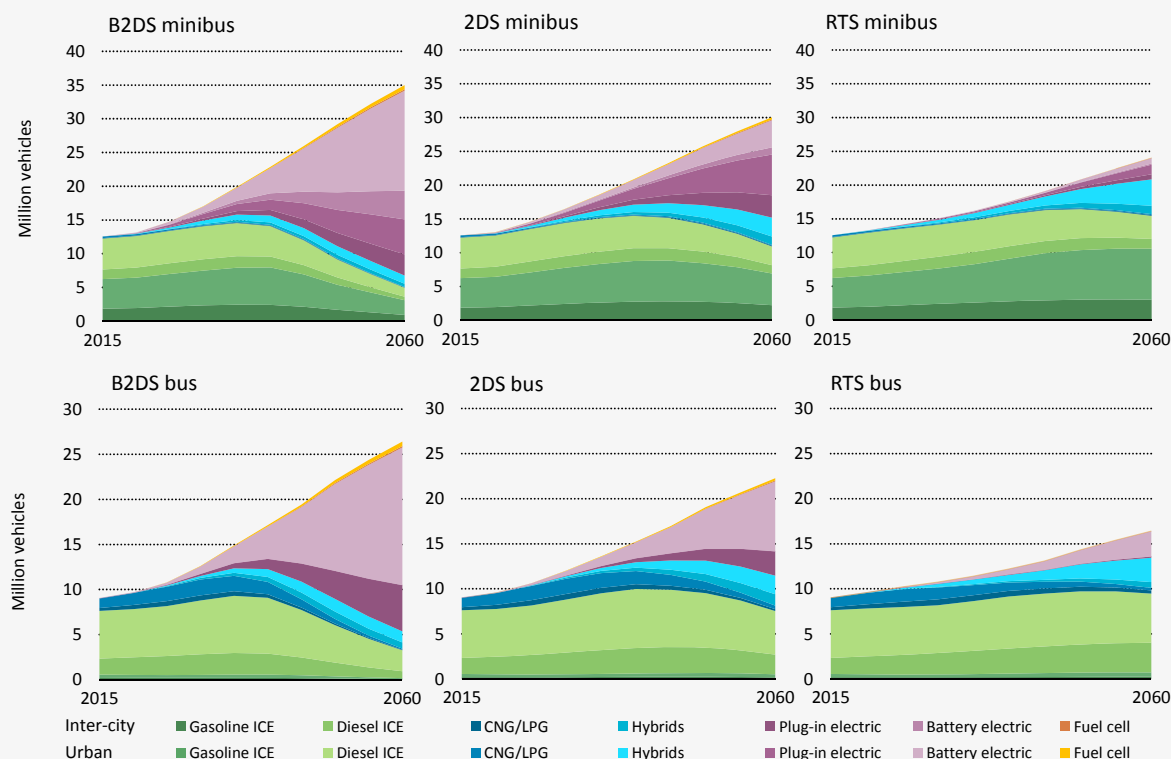
The share of transport activity avoided or shifted from LDVs to buses is greater in urban than in non-urban regions: urban vehicle kilometres in PLDVs can be reduced by 29% in the B2DS, relative to the RTS, versus a 24% reduction in non-urban vehicle kilometres.

Low-carbon fuel and vehicle technologies

In the B2DS, the primary technological development in rail is electrification. Although electrification requires installation of overhead lines, which is relatively more costly in sparsely populated regions, diesel trains need to be phased out completely for the sector to decarbonise. By 2060 the entire rail sector is fully electrified (Table 5.1). Full decarbonisation of the sector might favour hydrogen as an alternative to diesel trains.

Figure

5.8. Technology penetration in urban and intercity bus and minibus stocks worldwide by scenario, 2015–60



Source: IEA, (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

A partial shift from conventional to alternative powertrains takes place in the decarbonisation scenarios, with electric and hybrid technologies experiencing the largest growth.

There is considerable near-term potential to shift to vehicle efficiency technologies that pay for themselves in reduced fuel costs over the lifetime of bus operations (Figure 5.8). This is particularly true for urban buses, where advanced engine technologies, low rolling resistance tyres and series electric hybridisation can reduce emissions by an estimated 43%, at negative user costs (i.e. with net savings with respect to total cost of ownership) over the vehicle's lifetime (Schroten, Warringa and Bles, 2012). In the case of intercity buses, other measures such as predictive cruise control, reducing friction in the transmission, low rolling resistance tyres and vehicle streamlining could reduce fuel use and emissions by 25%, also reducing the TCO over the vehicle lifetime (Schroten, Warringa and Bles, 2012). This estimate of the potential for negative cost GHG reductions for both urban and intercity buses is robust to reasonable ranges in assumptions of fuel prices and technology costs. Given their transient usage, with frequent stops, light-weighting alone could improve bus fuel economy by an estimated 17% by 2050 (Ricardo-AEA, 2015).

In the RTS, the fuel economy of the urban bus fleet is about 20% more efficient in 2035 than in 2015 and about 50% more efficient by 2060. As urban bus fleets are often purchased by municipalities, and given the substantial societal savings of co-benefits of consuming less diesel (and thereby emitting less NO_x and particulate matter) in urban regions, investments in these near-term efficiency technologies should be prioritised. In the case of non-urban and sparsely populated areas, regulatory legislation, fiscal incentives or green financing schemes all may be effective means of allowing infrastructure to be built

(especially HSR infrastructure in the case of rail and impelling private coach operators in the case of buses) to invest up front in fuel-saving technologies.

Efficiency improvements in the intercity bus fleet are more marginal and improve by only 32% by 2060 in the RTS. In the B2DS, a rapid shift to electric buses translates to an efficiency improvement of 80% for urban and 47% for intercity bus fleets by 2060. Buses are also suitable for FCEV and hydrogen technologies, given the advantage provided by fixed routes and the possibility to minimise risks for the development of refuelling infrastructure. The speed of hybridisation and electrification for urban and intercity minibuses is roughly on par with that of large cars, while the penetration of electric drive technologies in urban and intercity buses slightly anticipates the rollout of these technologies in medium-freight trucks (MFTs), due to more rapid cost-competitiveness on a TCO basis in buses than in MFTs. In addition, catenary lines (overhead electric lines) on key freight corridors could provide power to hybrid and electric buses. (A more comprehensive discussion of the costs and energy-savings potential of advanced vehicle and fuel technologies in the heavy-duty road sector is in the road freight section.)

Policy needs

The B2DS requires an unprecedented pace and push of measures needed to shift passenger activity from personal cars and aviation to more energy-efficient modes (rail and bus). In the B2DS, these measures take the form of fuel taxes reflecting the WTW GHG intensity of the transport fuel and growing in all global regions to the level of USD 1.5 per litre of gasoline (in 2015 USD) by 2060, reflecting a carbon price of USD 540/tCO₂ in the same year.

To facilitate a shift to public transport in urban settings, a gradual phase-in of congestion and distance-based pricing would be needed to offset the decline in government revenues as LDV fleets electrify, and as reduced fuel purchases result in lower fuel tax revenues. These revenues would be required not only to maintain existing road infrastructure, but also to fund the infrastructure components dictated by the ambition of the B2DS, notably including (high-speed) rail and urban rail/metro infrastructure, public charging stations, public transit, and walking and cycling infrastructure.

Large investments are needed to develop the public transport infrastructure systems to facilitate the shift observed in the B2DS. This might be more costly in sparsely populated regions, but is nonetheless required to facilitate the large activity shift to public transport in the B2DS.

The 2016 edition of *ETP* explored the potential for urban policies to avoid and shift private passenger vehicle activity to public and non-motorised transport modes (IEA, 2016a). Quantitative assessment in *ETP* transport modelling is based on an extensive literature review of city-level case studies, as well as travel demand modelling and economic assessments of the impacts of national and local policies, spanning from fuel and vehicle taxes to congestion charging and public transit fare reductions. The modelling incorporates conservative estimates of the potential for policy actions to deliver across three broad categories of measures. These comprise both national-level vehicle and fuel taxation and various city-level policies:

- travel demand management (TDM) policies, both fiscal (such as congestion and parking pricing) and regulatory (such as zero-emission zones)
- policies promoting densification and altering urban form to reduce trip frequencies and distances
- investment in public and non-motorised transport.

The stringency and rate of adoption of the city-level TDM policies driving avoid-shift is greater in the revised RTS than in *ETP 2016*. It attempts to reflect commitments of local and regional actors to national climate pledges and assumes that subnational actors will respond to the call to realise these goals. In addition to local measures, regions that continue to subsidise fossil fuels will need to phase them out by 2025 in the RTS.

Cities need to adopt TDM policies, both regulatory and fiscal, on an ambitious timeline in the B2DS. By 2060, all major world cities have in place affordable and attractive high-capacity public transit networks, regulatory or monetary restrictions on parking and vehicle operations and urban designs that reduce the frequency and length of trips (such as densification, mixed use and transit-oriented development). The B2DS pace of roll-out of these policies and their realisation ensures that by 2060 they are on par with current best practices. The majority of smaller cities (i.e. those with more than 500 000 but fewer than 2 million inhabitants) would also need to commit to a portfolio of progressively more ambitious TDM measures and invest in alternatives to private cars such as public transit, walking and cycling to achieve the B2DS.

A commitment to providing a diversity of personal mobility options is particularly important if BEVs succeed in largely displacing the ICE in urban settings. The diffusion of electric cars will bring about radical reductions in the costs of vehicle operation. If coupled with an increasing uptake of AVs, this could lead to increases in mobility demand resulting from conventional rebound effects, and even greater surges in the demand for mobility from shared vehicles (Box 5.2). The cost reductions that driverless AVs could deliver to mobility services could also end up displacing mobility that would otherwise take place on public transport, changing the nature of transit services feeding major trunks of high-capacity transit systems.

Trucks

Globally in 2015, MFTs and heavy-freight trucks (HFTs) consumed just under one-quarter (24%) of the petroleum-derived transport fuels and emitted the same share of total transport GHG emissions (2.2 GtCO₂-eq).²³ Without co-ordinated efforts by shippers, logistics service providers and carriers, together with regulations and incentives to improve truck fuel efficiency and to spur improvements in operations, routing and logistics, this share could grow to upwards of one-third by 2060. Road freight as a whole could surpass passenger vehicles by as early as 2030 as the largest GHG emitting subsector within transport.²⁴

Economic and population growth are the ultimate drivers of the projected strong growth in road freight activity over the coming half-century. Trucking activity is expected to rise with the growth of East and Southeast Asian economies. Collectively in 2015, China, India and the ASEAN countries constituted 30% of tonne kilometres moved by road worldwide. By 2060, their share of global trucking activity grows to 46%. Growth in trucking activity on the African continent will likely lag behind Asia, but by the end of the century the 2015 activity share (6% of global activity) in Africa is likely to double.

In the RTS, despite the combined deployment of logistics improvements, vehicle efficiency technologies and low-carbon fuels, WTW emissions from the road freight sector nearly double (increasing by 90%) between 2015 and 2060, even while total activity in tonne kilometres grows by nearly fourfold. This emissions growth is far larger than the 52% increase in WTW emissions that occurs for transport as a whole. The B2DS would require reining in road freight emissions, but the 78% reduction in WTW emissions by 2060 that could be achieved in the road freight subsector still lags behind the reduction in total transport direct emissions of 83%.

Improved logistics

Many external drivers are likely to influence the decarbonisation of road freight logistics over the coming half-century. Among these, improved road quality, expansion and improved capacity of sustainable logistics initiatives, and collaborations among companies driven by policies and market forces (including shipping industry consolidation, which tends to accompany economic development to some degree) are likely to work in favour of efforts to

23. MFTs range from 3.5 tonnes to 15.5 tonnes gross vehicle weight (GVW). HFTs include trucks above 15.5 tonnes GVW. The road freight sector also includes LCVs (trucks below 3.5 tonnes GVW).

24. The results outlined here benefit from a significant revision and update of data and projections of road freight activity in our *Mobility Model* (IEA, 2017a). The methods and results of this revision will be outlined in a forthcoming IEA report on the road freight sector's historical evolution and its role in oil consumption, energy use and local pollutant emissions.

decarbonise (McKinnon, 2016). On the other hand, various trends may impede decarbonisation; growing congestion, structural shifts from rail to road that tend to accompany economic development, and growing demand for just-in-time delivery all may render such efforts more difficult (McKinnon, 2016).

In recognition of the need to address trends in which road freight continues to consume greater shares of petroleum-based transport fuels, and hence constitutes an increasing share of GHG emissions in transport, the RTS considers gradual but consistent improvements in logistics and systemic efficiency. This development is consistent only under the assumption of concerted efforts to translate national mitigation pledges related to the Paris Agreement into concrete actions by policy makers and industry to improve freight efficiency.²⁵

Hence, the RTS incorporates the potential for the road freight sector gradually to exploit about half of the available potential from cost-effective and relatively easily realisable logistics improvements between now and 2060. The measures realised in the RTS that have low technical, political and institutional barriers are summarised in Table 5.2. Individually, each of these improvements has the potential to reduce energy use and direct emissions by 1-5% and in some cases more. The mechanisms by which efficiencies are realised vary by measure, but most require consistent data collection by retailers, shippers and their logistics providers and carriers.

Furthermore, continued development and utilisation of ICTs, as well as vehicle automation and communication technologies, would enable shippers to tap the full potential of systemic improvements. Regulatory regimes and developments could also hinder or enable many of these systemic changes. For instance, shifting from weight and size limits for vehicles operating on various truck roads and highways to more flexible and sensible regulations – known as performance-based standards – that target specific outcomes (such as ensuring safety and preventing degradation of road, bridge and tunnel infrastructure) could aid the phasing in of HCVs, with substantial potential efficiency gains.

In the RTS, moderate uptake across all these measures leads to energy demand reductions from LCVs, MFTs and HFTs estimated at 7.6% in 2060. The modest estimate of the combined potential of these measures reflects the overlapping nature of many of the contributions (as in the case of improved vehicle utilisation and backhauling), non-additive contribution when the measures are combined, and some degree of rebound in activity stemming from reduced operational (fuel) costs.

Realisation of the systemic efficiency improvements at a minimum will require a co-ordinated public and private collaborative effort to collect basic data on freight operations as a means of understanding current systemic inefficiencies as well as best practices. Steps towards making such benchmarking common practice have been taken in some countries. There are promising initiatives to extend technology and vehicle operation benchmarking programmes, such as the US Environmental Protection Agency's SmartWay to incorporate a wider array of logistics practices (US EPA, 2017).

25. Only 13% of the Nationally Determined Contributions – the building blocks of the Paris Agreement – specified measures that aim to reduce road freight emissions. The assumption in the *ETP* decarbonisation scenarios is that these pledges will be translated into concrete actions and future efforts.

Table

5.2. Measures to improve efficiency in road freight systems with low implementation barriers

Category	Enablers	Barriers	Potential energy savings	Examples/notes
Enabling high-capacity vehicles (HCVs)	Performance-based standards.	Concerns with safety and road infrastructure impacts; potential for “reverse” mode shift; increased demand for just-in-time delivery.	Direct savings may be upwards of 20%, but actual savings may be lower, depending on activity rebound and modal shift from rail.	Regulations allow for operation of HCVs at the national or regional level in Canada, Mexico, South Africa, Sweden and Finland.
Optimised routing	Real-time routing data based on geographic information systems (GIS). Easing of delivery time constraints.	Increased demand for just-in-time delivery.	From 5-10% for intra-city trucking, but only about 1% for long-haul missions.	United Parcel Service (UPS) ORION, which in 2017 began its global roll-out.
Platooning²⁶	Vehicle communication and automation technologies.	Traffic congestion. Need to ensure safety.	From 5–15% for three-truck platooning travelling at 80 km/hour (depending on gap distance).	The European Commission’s Safe Road Trains for the Environment (SARTRE) project.
Improved vehicle utilisation	Better data collection (enabled by information and communication technology [ICT]). Collaboration and alliances among carriers and logistics companies.	Legal frameworks that restrict anti-competitive behaviour (which impede co-ordination among carriers, shippers and logistics companies). Lack of industry consolidation among carriers.	Substantial, but difficult to quantify. Better tracking of basic freight operational parameters and adopting industry best practices in logistics enable savings. Collaborations and online exchanges increase this potential.	The EU’s CO3 Project (Collaborative Concepts for Co-Modality) on horizontal supply chain collaboration. Alliances are quite common in Germany and Italy. Online freight exchanges co-ordinate a large fraction of road freight movements in the United States and United Kingdom.
Backhauling	Collaboration and alliances among carriers and logistics companies (through freight exchanges).	Legal frameworks that restrict anti-competitive behaviour. Lack of industry consolidation.	Substantial, but difficult to quantify. Highest potential in emerging markets, e.g. China and India.	Return trips formerly run without cargo are used to transport goods, thereby reducing trips.
Last-mile efficiency measures	Allocation and prediction of dynamic demand to prepare for demand peaks. Increased competition, including market entry of freight service providers.	Increased demand for just-in-time delivery. Urban traffic congestion.	Likely in the range of 1-5%.	Delivery Service Plans developed by TFL (London); Binnenstadt service in 11 towns in the Netherlands.
Re-timing urban deliveries	Incentives to shipment receivers to accept the insurance and logistical impacts of shifting to early-morning and off-hour deliveries.	Local citizen concerns with noise. Customer concerns with product quality and condition. Constraints imposed by just-in-time delivery.	Very difficult to estimate and generalise. Across the urban truck fleet as a whole, fuel and GHG emissions reductions are estimated at 5–10%.	A complete shift to off-hour deliveries led to a reduction in local pollutants in the 45–67% range in New York City, Bogotá and São Paulo.

Sources: Carbon War Room, 2012 for optimised routing; Tsugawa (2013), cited in Wadud, MacKenzie and Leiby, 2016 and SARTRE (2017) for platooning; Wallenburg and Raue (2011) and McKinnon (2016) for improved vehicle utilisation; Holguín-Veras et al. (2016), for re-timing urban deliveries.

26. Platooning refers to the practice of driving heavy-duty trucks (primarily tractor-trailers or rigid trucks) in a single line with small gaps between them to reduce drag and thereby save fuel during highway operations. Vehicle-to-vehicle and vehicle-to-infrastructure (V2V and V2I) communication technologies can enable trucks to drive in very close proximity without sacrificing safety or manoeuvrability.

In the B2DS, the full potential of the measures in Table 5.2 is realised by 2060. Measures that require closer collaboration, including sharing of assets and services between and among companies (“horizontal collaboration”) and more radical re-envisioning of how logistics systems operate, including a move towards the “physical internet”, are also included in the B2DS. Policies that reward efficiency and collaboration, as well as regulations and/or pricing to discourage “just-in-time” and same- or next-day deliveries and similar practices, drive radical changes leading to a reduced GHG footprint for road freight. Additional measures to reduce emissions in the B2DS are shown in Table 5.3.

The complete realisation of all measures shown in Tables 5.2 and 5.3 in the B2DS leads to a reduction in road freight activity (tkm) of 14.1% and a decline in vehicle activity (vkm) of 26% in 2060, relative to the RTS. The difference between these two reductions is a measure of the impact of improved vehicle utilisation (or equivalently, of higher load factors, as expressed in tkm/vkm) that can be realised by all of the above measures.

Table

5.3. Measures to improve efficiency in road freight systems with high implementation barriers

Category	Enablers	Barriers	Potential energy savings	Examples/notes
Urban consolidation centres (UCCs)	City regulatory policies to reduce congestion and promote air quality.	Design is highly specific to individual cities, making dissemination of best practices difficult.	Vehicle activity, fuel use and CO ₂ emissions within urban centres can be reduced by 20-50%.	UCCs group shipments from multiple shippers and consolidate these onto a single truck for delivery to a given geographic region. Various world cities, mostly in Europe, and a few in Japan.
Co-loading	Legal and regulatory frameworks to promote energy savings while protecting companies' intellectual property rights.	Just-in-time delivery. Lack of industry consolidation among shippers and carriers.	Estimated at 5–10%.	Co-loading uses supply chain collaboration within a company and/or across firms to increase vehicle load on outbound operations.
Physical internet²⁷	Legal and regulatory frameworks. ICT to collect, process and protect proprietary data.	Anti-trust or other non-harmonised national legislative frameworks.	Work to date on this concept suggests a potential 20% systems-wide efficiency improvement.	The realisation of complete collaboration across shippers and carriers to maximise vehicle utilisation, it is an open, shared system of all physical resources (e.g. ports, warehouses) associated with goods delivery.

Sources: Browne, Allen and Leonardi, 2011; Wiki4City, 2014 for UCCs; Van Lier et al., 2010 for co-loading.

Energy-efficient technologies

In addition to logistics measures, fuel economy of new MFTs improves by 20% and that of new HFTs by 23% in the RTS between 2015 and 2035. This helps to realise vehicle efficiency improvements with negative marginal costs of carbon abatement, including many with very short payback periods (less than one year in many cases).

27. The “physical internet” is a concept for an open, global logistics system in contrast to the proprietary or closed systems that are common today. It is based on the idea of a delivery process that resembles a relay race, based on the handoff of physical packages – consisting of modular containers of standard sizes that allow their stacking and combination – in logistical nodes. The process is enabled by shared and real-time information on the origin and destination of each package and would require open and connected data collection and software systems, and by network hauling services that interconnect the logistical nodes (Treiblcock, 2012).

Some investments in vehicle efficiency both reduce energy consumption and can be cost-effective. These include those with a short payback period (i.e. within three years), which corresponds to the upper boundary of the typical time horizon for investment decisions of truck fleet operators,²⁸ as well as others that may pay back only over the period of ownership for a truck's first owner. Other investments pay for themselves only when costs are assessed over the lifetime of the technical measure or of the entire vehicle (typically 7 to 15 or more years). Ranges of potential for technical and operational efficiency investments that pay for themselves within three years over the 2015-30 timeframe range from around 20% to 23%, while those that pay for themselves over the entire lifetime of the technology fall close to 30% (Schroten, Warringa and Bles, 2012, based on Law, Jackson and Michael, 2011; AEA/Ricardo, 2011), with greater potential for savings in HFTs than in MFTs.²⁹

The efficiency of new truck sales improves in the 2DS by 35% between 2015 and 2035, meeting the recently announced GFEI fuel economy improvement goals (GFEI, 2017). Indeed, greater improvements have been proved technically possible using best-in-class technologies, as demonstrated by the US DOE's SuperTruck challenge, which targeted a 50% energy efficiency improvement in prototype class 8 trucks (US DOE, 2015). The challenge led to separate contracts with four truck OEMs, all of which met and exceeded the targeted efficiency gains, each resorting to independent technical solutions. Among these were engine downsizing, common rail fuel injection, turbo compounding, mild hybridisation and waste heat recovery (Daimler, 2012; Volvo, 2016). The US DOE has also announced the goal of building upon the first programme with SuperTruck II, which aims to be both more ambitious and more easily applicable to real-world conditions than its predecessor. Further, SuperTruck II will measure and assess solutions based on their cost-effectiveness as well as efficiency gains.

Vehicle design improvements that reduce energy needs include improvements in aerodynamics, reduced rolling resistance for tyres and truck weight reduction. Enhanced powertrain efficiency can be realised via improvements to the engine transmission and drivetrain – powertrain controllers that integrate transmission and engine controls can bring additional fuel savings. Parallel hydraulic hybridisation (combining an hydraulic compressor/pump and compressed gas storage with internal combustion engines) may be the most cost-effective near-term technology option for municipal utility vehicles, while electric hybridisation tends to be the best option for most other vehicle and mission profiles (Schroten, Warringa and Bles, 2012). Battery-powered electric auxiliary power units can provide on-demand power for climate control and other cabin devices while saving fuel. Other cost-effective measures to reduce energy demand include investments in driver training and installation of feedback devices that monitor and reward more fuel-efficient driving, as well as predictive cruise control. In the European Union, the use of speed governors to limit highway speeds are mandatory, and even in countries where they are not, large trucking companies often install such devices to save fuel and reduce operating costs. Table 5.4 summarises the vehicle efficiency measures with the greatest potential for near-term cost and fuel savings.

The actual efficiency improvements, cost and CO₂ savings vary significantly across regions with differing fleet structures and baseline technology penetrations, and depend not only on the composition of the truck fleet but also on the mission types and other variable conditions of actual operations (e.g. road quality, road grades, speed limits and congestion profiles). The presence or absence of fuel economy regulations also influences the remaining near-term cost-effective potential.

28. Typical payback periods range from as short as six months in the case of owner/operators of individual trucks to three years in the case of large fleets. Most carriers will invest only in efficiency technologies that have a clear and proven payback period of less than 1.5 years.

29. This cost assessment figure is for a representative truck based on the total cost of ownership over three years or over the full vehicle lifetime (which ranges from 8–19 years by vehicle type) and uses a 4% discount rate.

Table

5.4. Near-term vehicle efficiency measures with net savings over the vehicle lifetime

Measure	Description	Potential energy savings	Source
Aerodynamics	A wide range of aerodynamic fittings (e.g. aft box tapers, aerodynamic tractor bodies, mud flats, trailer tails, box skirts, cab/box gap fairings) can reduce the drag coefficient, thereby reducing road load.	Individual vehicle components reduce fuel use by 0.5-3%, depending on truck type and aerodynamic retrofit. Trailer device packages considered in the US heavy-duty vehicle (HDV) GHG Phase 2 regulations may reduce fuel use by 5-14%.	Schroten, Warringa and Bles, 2012; US EPA/NHTSA, 2016.
Low rolling resistance tyres and tyre pressure systems	Low rolling resistance tyres can be designed with various specifications, including dual tyres or wide-base single tyres with aluminium wheels and next-generation variants of these designs.	Potential ranges from about 0.5% to 12% in the tractor-trailer market. Tyre pressure systems alone could reduce fuel use by 0.5-2%.	Schroten, Warringa and Bles, 2012; Meszler, Lutsey and Delgado, 2015; US EPA/NHTSA, 2016.
Light-weighting	Broadly, all HDV types except utility trucks could cost-effectively reduce weight by upwards of 7% within the next ten years.	CO ₂ savings potential is about 1% to 2020, 2-3% by 2030 and 2.7-5% by 2050.	Ricardo-AEA, 2015.
Transmission and drivetrain	Moving from manual to automatic/automated manual transmissions can greatly improve efficiency. Adding gears, reducing transmission friction and aggressive shift logic in manual automated or fully automated transmissions can also improve drivetrain efficiency.	Automatic/automated transmissions reduce fuel consumption by 1-8%, depending on truck type; other improvements lead to fuel savings of about 0.5-2.5%.	Schroten, Warringa and Bles, 2012.
Engine efficiency	Engine improvements include increasing injection and cylinder pressures, both of which typically improve incrementally on an annual basis.	Improvements in the coming decade could lead to fuel savings of approximately 4% (in service/delivery vehicles) to 18% (in long-haul trucks).	Schroten, Warringa and Bles, 2012.
Hybridisation	Parallel hydraulic hybridisation may be the most cost-effective near-term technology option for municipal utility vehicles (e.g. garbage or street cleaning trucks), while electric hybridisation tends to be the best hybridisation option for most other mission profiles.	Dual-mode hybrid: 8-30%. Parallel hybrid: 25-35%. Parallel hydraulic hybrid: 20-25% – all ranges depend on vehicle type; gains are lowest on long-haul vehicles operating at constant highway speeds.	Law, Jackson and Michael, 2011; Schroten, Warringa and Bles, 2012.

Note: Potential energy savings cited are near-term (i.e. over the coming decade) technologies and measures that reduce the total cost of ownership over the vehicle or measure lifetime.

Fuel switching and zero-emission technologies

In the short to medium term, bioethanol, renewable biodiesel³⁰ and biomethane can substitute for petroleum-derived gasoline and diesel fuels, thereby serving to reduce GHG emissions of conventional ICE LCVs, MFTs and HFTs. Other liquid or gaseous energy

30. Renewable biodiesel, also referred to as hydrotreated vegetable oil, includes diesel produced from a range of feedstocks, including vegetable oils, used cooking oil and animal fat wastes.

carriers produced with renewable electricity (PtX) can complement this in the longer term.³¹ The main limitations on the volume of biofuels available for the decarbonisation of land-based modes are the limited availability of sustainable biomass resources and the need to prioritise their use for aviation and shipping (and, more broadly, for bioenergy with CCS), where the potential to electrify is limited to very targeted applications. Box 5.3 provides details on the reasons CNG and liquefied natural gas (LNG) vehicles are included in the B2DS only when they use biomethane.

Box

5.3. Why are CNG and LNG vehicles included in the B2DS only when they use biomethane?

Switching trucks and buses to natural gas has clear benefits in terms of local air quality and energy diversification. However, despite its lower carbon intensity compared with diesel, switching to natural gas trucks results in only minor reductions in WTW GHG emissions, when issues related to methane are considered. These include methane's high global warming potential (particularly in the near term) and pervasive leakage issues in production, processing, transmission and distribution. On the vehicle side, the lower efficiency of most heavy-duty engines running on natural gas relative to diesel, as well as persistent issues with methane slip,³² counterbalance somewhat the potential benefits of the lower carbon intensity of natural gas. Various sources quote conflicting ranges of WTW GHG emissions reduction potential for natural gas relative to diesel. These range from a reduction of as much as 20% when looking purely at fuel properties (JEC, 2014a; Muller-Syring G. et al. (2016); Dominguez-Faus, 2016) to no net benefits when also accounting for engine performance (JEC, 2014b; IEA-AMF, 2016), to near-term climate damages due to the higher short-term radiative forcing of natural gas (Camuzeaux et al., 2015). Ultimately, the range of results reflects variability in natural gas production and upstream leakage, as well as in engine technologies. Even with a rapid roll-out of the factors that minimise the life-cycle emissions of natural gas, the limited GHG emissions savings achievable from switching to natural gas rule it out as a contributor to decarbonisation in the B2DS.

On the other hand, vehicles that can run on CNG and LNG can be fuelled by biomethane, which is chemically and physically identical to fossil natural gas, but, when produced from high-moisture-content organic wastes such as the organic fraction of municipal solid waste, wastewater treatment sludge, agricultural residues and manure, leads to very low life-cycle GHG emissions. These characteristics include biomethane among the few promising near-term options for decarbonising fuel for road freight and make it particularly attractive from an economic perspective if captive fleets operate near biomethane production sites. Nevertheless, while biomethane remains an attractive near- to medium-term cost-competitive option for decarbonising captive urban fleets, and may be among the first fuel pathways to benefit from life-cycle GHG pricing of transport fuels in the B2DS, feedstock volumes are limited to around 3 EJ to 4 EJ of final energy.

Given the limited availability of sustainable biomass resources, and notwithstanding substantial use of low-carbon biofuels for road freight in the B2DS (8.3 EJ in 2060, representing 35% of the total demand of low-carbon biofuels in transport), long-term GHG emissions reductions need to come from ultra-low and zero-emission technologies. As in the case of LDVs, these include electricity use in transportation vehicles using electric motors or hydrogen requiring the use of fuel cells.

While biofuels will be an important component of the strategy to decarbonise road freight for as long as trucks using ICEs (including hybrids) are on the road, in the longer term, only two

31. See, for instance, the study on renewable power-to-gas (IEA-RETD, 2016).

32. Methane slip occurs as a result of incomplete combustion of methane, which then escapes into the atmosphere.

options are capable of supplying the full capacity of energy demanded by rising truck activity in general and by long-haul operations in particular: electricity (used in ERS) and hydrogen.

ERS rely on vehicles that can receive electricity from power transfer installations along the road. Furthermore, the vehicles can be hybrid or battery electric and have the ability to conduct normal driving operations, such as overtaking and driving autonomously outside of the electrical roads. The two main infrastructure concepts for ERS are:

- catenary (overhead) lines that require the installation of an overhead retractable pantograph on trucks
- inductive transfer of power that requires the installation of coils that generate an electromagnetic field in the road as well as receiving coils for electricity generation on the vehicle.

High investment costs for building out the energy supply infrastructure characterise all these options, but targeting infrastructure development on motorways and major trunk roads could help limit investment requirements, while also covering most of the heavy-duty traffic.³³

The installation of catenary lines along roadways is starting to be demonstrated in pilot applications in Sweden, the United States and Germany (Siemens, 2016). Installation costs are on the order of USD 2 million per kilometre (in both directions) or more (Den Boer et al., 2013; Mottschall, 2016), and may fall to half that in the long term, approaching magnitudes that characterise rail electrification infrastructure upgrades (Network Rail, 2009). The technology builds upon a mainstream commercialised technology that has been adopted in many cities for buses.

Inductive charging has a number of advantages over conductive charging,³⁴ but also several disadvantages, including lower efficiency,³⁵ higher material requirements per lane kilometre, more invasive changes to the existing infrastructure and more complex components and higher cost per kilometre of infrastructure. Until a need for electric road systems beyond HDVs (i.e. for LDVs) is identified and a solution designed capable of providing both vehicle classes with the necessary electrical power, inductive charging is also likely to require higher investment per vehicle than overhead catenary systems.

Benefits of hydrogen include the fact that, once produced, it can be easily stored, and hence may be an option for storage of excess renewable electricity, for easing energy imports in regions where (seasonal) demand for low-carbon energy exceeds local electricity production capacity, and for use as a flexible energy carrier across all end-use sectors. Trucks powered by hydrogen fuel cells also have longer driving ranges than plug-in hybrid trucks, thanks to the far higher capacity to store energy of compressed or liquefied hydrogen in comparison with batteries. Promoted by regional policies, demonstration projects have begun to test the use of hydrogen in trucks in California (Fuel Cells Bulletin, 2015) and Norway (Scania, 2016), as well as in Germany, France and the United Kingdom (Green Car Congress, 2017).

Hydrogen uptake is subject to two main barriers:

- The low thermodynamic efficiency of hydrogen production and usage pathways. Hydrogen use is penalised by the losses taking place in several steps of its manufacturing and distribution – including production (via electrolysis or steam reforming), transportation and refuelling – and during the use in fuel cells applications, even if they have a good tank-to-wheel efficiency.

33. In England, for example, the Strategic Road Network, made up of the motorways and major trunk roads, accounted for 2.4% of the total road network and for about two-thirds of the heavy-duty goods vehicle traffic in 2014 (DfT, 2015). A GIS-based cost minimisation model found that between 2.9% and 4.3% of the existing global road network would need to be equipped with catenary lines to cover 78% of HDV operations (Singh, 2016). In Germany, 60% of all tonne kilometres shipped by trucks occurs on the most heavily trafficked 3 966 km of the Bundesautobahnen (Verkehr in Zahlen, 2012; TREMOD, 2012), or roughly 2% of the total road network and 32% of the main highway network.

34. The main advantages include convenience due to the wireless charging, lower risk of electrical shock, no limitations on the number of devices that can be charged and low maintenance costs due to the lack of wear and tear of components.

35. The efficiency of inductive power transmission is competitive with wired solutions only when the induction coils have comparable size (less than 50% difference) and are in close proximity (less than 10% of the size of the largest induction coil). The proximity requirement is very difficult to comply with in the case of dynamic charging, and therefore very likely to pose structural limits to actual efficiency potential.

- The high cost of fuel cells and hydrogen storage tanks. Even if there are good prospects for cost reductions in technical assessments (US DOE, 2017), asymptotic costs and learning rates³⁶ for heavy-duty transport applications are subject to significant uncertainties, and actual cost reductions will depend on the extent to which these technologies will be adopted. This, in turn, depends on the likelihood to see hydrogen picked up across the energy system.

In an energy system that will strive to reduce costs by exploiting demand management opportunities to minimise the overcapacity needed to handle variable renewable energy sources, hydrogen is also exposed to investment risks. These risks remain limited if hydrogen production takes place in decentralised electrolyzers, especially if electricity from renewables becomes increasingly available at low costs (results shown in Figure 5.9 refer to this case). However, these risks increase significantly if hydrogen production needs to be scaled up in centralised production facilities, even if they allow for lower cost of production, because they require the development of capital-intensive upfront investment to deploy a hydrogen transportation and distribution infrastructure. The high co-ordination and investment risks of deploying upstream hydrogen infrastructure also could be mitigated for heavy-duty fleets by the concentration of most of the heavy-duty traffic on small portions of the road network, as this is more compatible with a smaller number of refuelling points than for LDVs. Centralised (or hub-based) fuelling networks used on specific fleets also offer additional opportunities in this respect.

Figure 5.9 illustrates costs per kilometre for HDVs operating in various world regions and under a range of vehicle technology, fuel and infrastructure costs, and taking into account a time horizon of five years of use and including the effect of carbon taxes. The analysis compares conventional ICE diesel vehicles, diesel hybrids, trucks fuelled with natural gas, battery and hybrid electric hybrids operating over the majority of their vehicle kilometres connected to catenary-based ERS (CAT-ERS) and hybrid electric hydrogen trucks. BEVs and plug-in hybrid vehicles are excluded from the figure for simplicity, given its focus on long-haul mission profiles.

The results for 2060 reflect a range of different assumptions on possible cost reductions, in a deliberate attempt to account for both fairly optimistic and pessimistic assessments. Figure 5.9 also includes infrastructure costs for natural gas, hydrogen and ERS. The assumptions used for the estimation of 2060 costs aim to evaluate the long-term cost of all technologies systems once the infrastructure they require is highly utilised (see figure notes for details on the assumptions used for the infrastructure cost assessment).

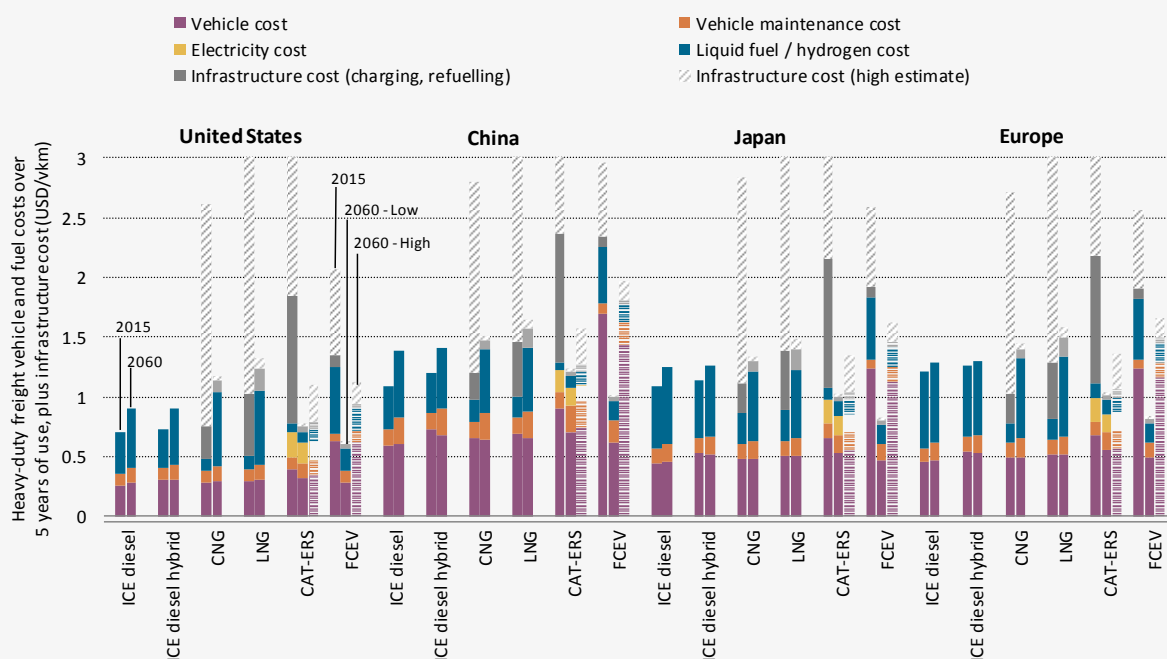
Hybridisation of diesel HFTs may prove an attractive option, with a relatively fast payback in the near term in many regions. In certain regions such as the United States, China and Europe, LNG trucks are also competitive to diesel ICE vehicles in the near term. In the B2DS, catenary CAT-ERS and hybrid electric hydrogen trucks emerge as viable only under the assumption of co-ordinated and planned infrastructure investments and carbon taxes on transport fuels. Under the most optimistic scenarios of technology cost and performance development, hydrogen emerges as an attractive option in the long term in relation to catenary lines. This reflects the importance of cost reductions for fuel cell systems, one of the most uncertain technical assumptions. Hydrogen production from electrolysis also comes with lower infrastructure cost than catenary lines (CAT-ERS systems), essentially imputable to compressors, storage and refuelling systems.³⁷

36. Learning curves are often defined on the basis of a learning rate, which is a unit-less parameter indicating the cost reduction per doubling of production volume.

37. If hydrogen is produced at centralised facilities, then production costs decline but transmission and distribution costs increase significantly. The increase reflects the need to transport hydrogen in compressed or liquefied form on trucks, and, when volumes increase, the cost of developing a transportation infrastructure via pipelines. The long-term cost balance between electrolyzers and centralised production will depend on the availability of low-cost electricity generation technologies and of low-cost electricity availability over long periods. Low availability of low-cost electricity would favour centralised production pathways, as it would increase the importance of electrolyser costs per unit of hydrogen produced. Widespread availability of low-cost electricity would favour electrolysis, as it would increase the utilisation rate of the electrolyzers. The inclusion of results that assume hydrogen production from electrolyzers in Figure 5.9 matches a positive outlook for low-cost power generation technologies from renewable sources and reflects the much higher risks affecting centralised production pathways.

Figure

5.9. Heavy-duty freight vehicle and fuel costs over five years of use, including infrastructure cost, 2015 and 2060



Notes: The figure shows high and low cost assumption and infrastructure utilisation ranges.

Key assumptions on HDV costs and infrastructure are:

Vehicles: 2015 vehicle investment costs range from USD 120 000 for diesel ICE, USD 160 000 for diesel ICE hybrid, USD 145 000 for natural gas vehicles and USD 220 000 for CAT-ERS to USD 510 000 for FCEV. Vehicle investment costs in 2060 range from USD 126 000 for diesel ICE, USD 150 000 for diesel ICE hybrid, USD 145 000 for natural gas vehicles, USD 165 000 (low) to USD 180 000 (high) for CAT-ERS, and USD 150 000 (low) to 440 000 (high) for FCEV. Current and future gasoline, diesel and electricity prices are from the IEA Mobility Model and the electricity price is USD 0.17/kWh in all regions and cases. Carbon taxes in 2060 are USD 540/tCO₂-eq (based on WTW emissions).

Depreciation is assumed to be the same for all technologies. After 5 years, the residual value of truck is 42% of the purchase value.

ERS: 2060 electric road system infrastructure costs are based on investment requirement of USD 0.6 million/km, a 35-year lifetime of the system, and usage rates ranging between 30 and 260 vehicles/hour. These values are used, respectively, for the top of the high cost estimate (striped grey bar on right column for CAT-ERS) and for the bottom of the low cost estimate (grey bar on central column for CAT-ERS). The higher value of this range is close to 260 vehicles/hour (DfT, 2015). 2015 costs are based on USD 1.6 million/km and a frequency of use of 30 vehicles per hour or less (as cost estimates are very sensitive to the frequency of usage: using low frequencies leads to major increases in unit cost per km for CAT-ERS in 2015).

Hydrogen: 2015 hydrogen costs are evaluated using an electricity price of USD 0.01/kWh (and hence assuming that hydrogen is generated during periods when electricity supply is far in excess of demand); electrolyser cost of USD 78 per gigajoule (GJ); operating and maintenance costs of USD 8/GJ; an electrolyser usage rate of 7% across the year; a lifetime of 15 years and costs for the storage and refuelling system of USD 5.2/GJ of hydrogen delivery capacity. The 2015 cost estimates also account for a capacity utilisation of the refuelling system ranging from 33% (captive fleet case, grey shading in the figure) to 4% (higher estimate in the figure). The 2060 hydrogen costs account for large availability of electricity produced from renewables at an average cost of USD 0.07/kWh and a large capacity utilisation factor for electrolyzers, leading to a 50% overall capacity utilisation rate. Storage and refuelling system costs equal USD 5.0/GJ of hydrogen delivery capacity. The capacity utilisation rate of the refuelling system ranges from 10% (top of the high cost estimate – striped grey bar on right column for FCEVs) to 50% (minimum infrastructure costs in the low cost estimate – grey bar on central column for FCEVs).

Source: Vehicle travel per year, vehicle costs and fuel costs reflects assumptions used in the characterisation in the IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

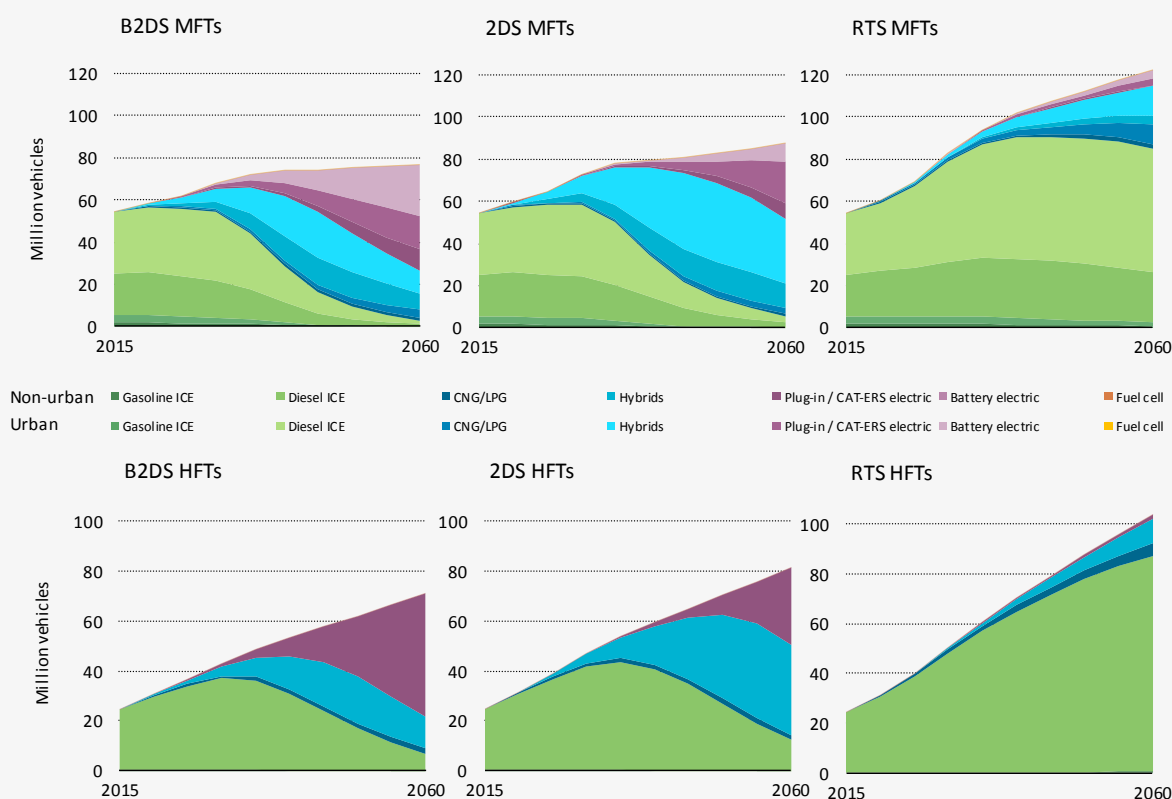
Depending on driving distances and fuel costs, current hybridisation and natural gas technologies can reduce costs compared with conventional diesel trucks over five years of use. In the longer term, carbon taxes would be needed to make ultra-low and zero-carbon technologies competitive.

Under moderate to conservative assumptions of technology cost developments (for batteries and fuel cells, as well as for other vehicle components, including electric motors and storage tanks), ERS emerge as the most cost-competitive (and resilient to variations in the range of cost assumptions for vehicle technologies) long-term option in terms of cost

per kilometre, especially in regions with lower mileages. As with any technology, ERS infrastructure costs are dependent on the frequency of use. First commercial applications are therefore likely in shuttle-like traffic situations, such as port-hinterland connections or mining trucks. Initial deployment phases on long-distance highways are likely to come with low usage rates, requiring major investments for limited benefits. Once the system is widely adopted, however, it offers good opportunities to enable low-carbon road freight transportation for long-haul heavy-duty applications at lower costs than conventional ICE and hybrid technologies, even when taking into account fuel savings due to vehicle efficiency improvements, provided that carbon taxes are in place.

Figure

5.10. Global technology penetrations in truck stock by scenario, 2015–60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

Ultra-low and ultimately zero-carbon technologies would need to rapidly penetrate the truck fleet to achieve the B2DS emissions reduction targets. Current modelling assumptions privilege the adoption of electric road systems among zero-emission technologies, but hydrogen may well emerge as a viable alternative.

Figure 5.10 shows the penetration of vehicle technologies in the three scenarios. In the RTS, natural gas penetrates first in captive urban MFT fleets, and later to a lesser extent in non-urban MFTs. A fraction of LNG HFTs also penetrates that fleet at roughly the same rate as non-urban MFTs, at a rate proportional to the national or regional share of natural gas in total final energy and to an extent dictated by the regional cost gap between diesel and natural gas. Shares of conventional hybrids grow most quickly in urban MFTs and finally in HFTs. Penetration of zero-emission technologies (i.e. BEVs and PHEVs, as well as hydrogen trucks) in the RTS is marginal and occurs in the second half of the century, and is

limited to operations with mission profiles that accommodate pure battery electrics. Further, low- and zero-emission vehicle technology penetration in the RTS occurs primarily in regions where regulatory incentives, e.g. local air quality standards, and/or fiscal incentives, e.g. purchase subsidies or green financing mechanisms, promote their uptake.

The uptake of zero-emission technologies for MFTs and HFTs proceeds much faster in the 2DS and B2DS. Pure BEV vehicles would penetrate most extensively in urban MFT fleets. Current modelling assumptions privilege the adoption of ERS among zero-emission technologies in long-haul operations. This is due to the higher uncertainties in the extent to which fuel cell costs can be reduced and the much greater thermodynamic efficiency of ERS over hydrogen, consistent with the attention given to energy efficiency throughout the *ETP* analysis. Nevertheless, uncertainty in future technology and cost developments, the availability of promising opportunities to manage investment risks for long-haul trucks fuelled by hydrogen and the large potential for cost savings in fuel cell technologies have the potential to alter this balance.

In order to achieve long-term cost-competitiveness, zero-emission infrastructure build-out will need to proceed first along the most heavily trafficked corridors and gradually extend to all major trunk roads. Indeed, hydrogen could emerge as a viable option, especially in regions with low population density where the major roads service low frequencies of heavy-duty truck operations.

Policy needs

Heavy-duty fuel efficiency (or fuel economy) standards have only recently entered into force in four of the world's major truck markets: Japan, China, Canada and the United States. These countries account for about half of the world's HDV sales.

As with many investments in energy efficiency technologies, the upfront costs of purchasing a more efficient truck pay for themselves in reduced fuel costs over subsequent years of operation. The range of viable efficiency investments (including retrofits) that reduce fuel use substantially and pay for themselves within less than three years points to a case of market failure. The root causes are many and include a lack of adequate financing opportunities for carriers, as well as to a lack of sufficient and precise information on the fuel savings of various available technologies (and their ability to reduce costs).³⁸ These issues are exacerbated by the fact that many truck owner/operators have only a single truck or a few trucks and hence are capital constrained – this is particularly true in developing and emerging countries.

The portion of the global truck market covered by fuel economy standards will need to expand. Given the diverse vehicle segmentation with respect to size and mission profiles, regulating fuel economy for trucks has a greater complexity than in the case of LDVs. Action should focus first on the vehicle types that dominate fuel consumption in each market (namely tractor-trailers, rigid trucks and delivery trucks). Further regulatory developments should rely on simulation tools that allow benchmarking wider ranges of vehicles and missions. In order to speed up policy adoption, regulatory limits on the fuel economy of trucks should leverage the key tools (including test cycles and simulation models) available in countries that have already developed regulations. Given the relevance of EU regulation for global adoption in the framework of the United Nations World Forum for Harmonization of Vehicle Regulations, the rapid finalisation of the policy process in the European Union is important to speed up global mobilisation.

Differentiated vehicle taxation could help significantly to improve payback times. Penalising taxation for commercial vehicles with poor energy efficiency and rebates or lower taxes for the best in class would be especially helpful to address market failures that do not allow the full exploitation of the available cost-effective energy efficiency potential. This could also add to the market appeal of energy-saving technologies that have payback times longer than just a few years, widen their deployment on trucks that

38. Further evidence for market failures, discussion on their causes and means by which to address them will be among the topics discussed in the upcoming IEA report on the road freight sector. See for instance Roeth et al. (2013), Klemick et al. (2015), and Vernon and Meier (2012).

are used on a range of different mission profiles and reduce technological costs due to improved economies of scale. Differentiated taxation can also help to ensure in the coming two decades that the GHG emissions saving per kilometre for new trucks matches or exceeds the 35% reduction in fuel use recently announced as a GFEI target.

Governments and other public and private entities can play a role by intervening to stimulate the deployment and uptake of fuel-efficient technologies. Financing institutions, such as development banks, need to complement this with green procurement and financing mechanisms that favour the acquisition of commercial vehicles with lower GHG emissions, particularly for capital-constrained individual owner/operators and small fleets, and particularly in developing countries. These schemes should incorporate co-benefits. Chief among these are that reduced emissions of particulate matter, NO_x and other local pollutants will lead directly to health benefits, thereby reducing public health care expenditure. Given the regional and structural differences in national truck fleets, determining the fuel savings potential of various technology and logistical improvements will require concerted and comprehensive data collection.

Vehicle technologies alone will not be sufficient to achieve the B2DS. Systemic improvements in shipping operations efficiency will require a transformation in operations across logistic supply chains. The missing element in the near term is a lack of data. Data on road freight practices are not sufficiently detailed, comprehensive or accurate. Better data collection would allow companies to learn from one another's practices, aid policy makers to design standards and incentives appropriate to the national and regional context, and facilitate collaboration across the supply chain. The Global Logistics Emissions Council, led by the Smart Freight Centre, has created the first harmonised method for calculating emissions across the global logistics supply chain (GLEC, 2016). Green freight initiatives, such as SmartWay in the United States, Lean and Green in many European countries and Green Freight Asia, are effective fora for gathering baseline data and encouraging shippers and carriers to adopt best practices. In addition, public authorities should mandate that all logistics operators report basic minimal data, or provide incentives for companies that provide data and make reporting as easy as possible.

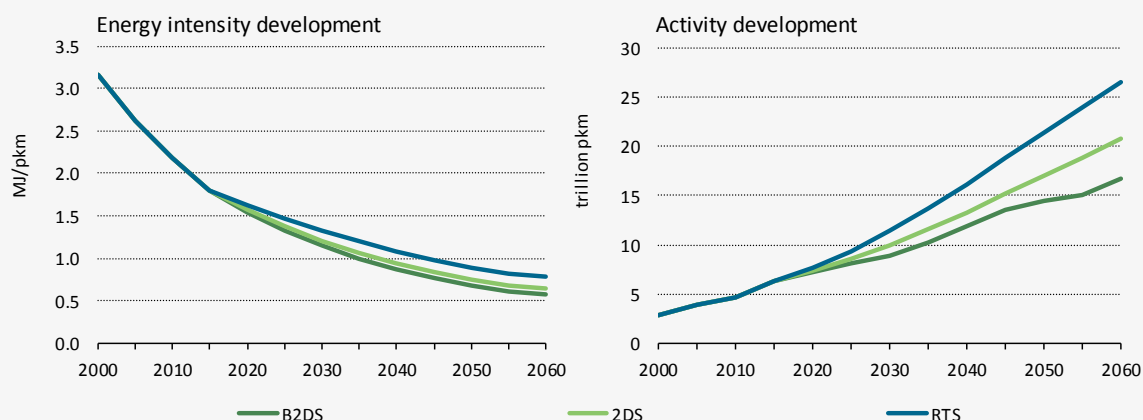
Given the need to decarbonise the energy system by 2060, the pace of infrastructure build-out and electrification or a shift to hydrogen trucks called for in the B2DS is also extremely rapid. Extensive demonstrations of ERS and hydrogen truck operations would be needed in the coming decade to gain experience in operations and to evaluate costs and benefits. A shift to the commercial scale for one of these options would be needed in the coming decade in developed countries and on key road freight routes globally before 2030.

Beyond pilots on commercial shuttle applications, the high initial costs emerging from low utilisation rate of zero-emission technologies such as ERS or hydrogen (except for captive fleets) in the early deployment phase indicates that the transition to zero-carbon freight is very likely to require public support for infrastructure investment. This is particularly true for infrastructure to serve long-haul trucking. The application of road pricing schemes would allow investment costs to be spread across the commercial vehicle fleet. Such schemes would be well suited to finance the build-out of the requisite infrastructure by levying an infrastructure development fee applicable to all commercial vehicles operating on major trunk roads. Such an approach could leverage existing systems for the recovery of infrastructure costs, such as the Eurovignettes and other taxes already levied on HDV operations in place on European motorways.

Aviation

Between 2000 and 2015, the growth of passenger activity in the aviation sector doubled, reaching USD 6.3 trillion revenue passenger kilometres (RPK) in 2015 (ICAO, 2016). Over those 15 years, aviation also made significant progress in efficiency: energy use per passenger kilometre declined at an average annual rate of 3.7% (Figure 5.11). As a result, aviation energy use increased by less than 25% over that fifteen-year period, less than the aggregate energy use increase across all passenger transport modes combined since 2000 (42%).

Figure 5.11. Energy intensity improvements in global aviation by scenario



Note: MJ/pkm = megajoules per passenger kilometre (or megajoules per RPK).

Key point *International aviation experiences strong activity growth and continuously improves fuel economy of the fleet in each scenario.*

In the RTS, activity in the aviation sector will continue to grow rapidly through 2060. The annual growth rate of RPK between 2015 and 2060 is 3.2% and total RPK reaches 26.5 trillion in 2060. GHG emissions rise by 1.6% per year across the same time span, continuing to benefit from sizeable improvements in energy efficiency. Much of the difference between the rate of activity and emissions growth is explained by the 2% annual improvement in fuel efficiency indicated by the aviation industry and the International Civil Aviation Organization (ICAO) as their aspirational goal to move towards a reduction of aviation's GHG emissions.

In the B2DS, annual WTW GHG emissions from aviation decline to 0.3 GtCO₂-eq in 2060, compared with 1.0 GtCO₂-eq emissions in 2015. This meets the goal of the Air Transport Action Group (ATAG) to halve net aviation carbon emissions (compared with 2005) in 2050, without carbon offsets.³⁹

In order to achieve this target without offsets from other sectors of the economy:

- Aviation needs to achieve significant operational and technical efficiency improvements.
- Activity growth in aviation has to be significantly reduced compared with the level in the RTS.

³⁹ In 2016, the international aviation sector adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA aims to offset an increase of absolute CO₂ emissions from selected routes as of 2020. Member countries can enter voluntarily from 2021, while this becomes compulsory as of 2027 for most countries. All flights departing and arriving in participating countries are included. Carbon offsets are to be achieved through offset credits from crediting mechanisms or allowances from emission trading systems (ICAO, 2013).

Although CORSIA acknowledges the need for climate change mitigation, the B2DS does not include a shift from aviation through offsets. Reducing global emissions in line with the B2DS carbon budget could not be achieved without a direct reduction of CO₂ emissions from the aviation sector. This carbon budget already takes into account GHG reductions from measures taken outside the energy sector, including effects of land use, land-use change and forestry (LULUCF), which eliminates the possibility of using offsets.

- Unless major technology breakthroughs open opportunities for electric flights or hydrogen storage, aviation needs to switch a substantial share of its fuel mix to advanced biofuels (6.6 EJ in 2060, around 70% of aviation energy demand).⁴⁰

Meeting the ATAG goal without carbon offsets is possible if the average energy intensity of flying falls to a level of 0.6 megajoules per RPK by 2060, 68% below today's average. Attaining this level of improvement is technologically possible with major changes in aircraft design, engine conception and material choices, as well as a transformation of air traffic management delivering strong operational improvements (ANL, 2013; IATA, 2013). It also requires a level of ambition that goes well beyond the levels implied by the ICAO fuel efficiency standards or ICAO's improvement ambition of 2% per year (Box 5.4).

Box

5.4. Gaps between ICAO fuel efficiency standards, its efficiency goals and the B2DS

- In 2017, the ICAO adopted its first binding CO₂ standard for new aircraft (ICAO, 2017). The standard is applicable to new types of aircraft design as of 2020 and to new aircraft of currently existing designs as of 2028, with a transition period starting in 2023. A cut-off date of 2028 for aircraft that do not comply with the standard was included. Recent estimates suggest that the standards will require a 4% reduction in the cruise fuel consumption of new aircraft starting in 2028 compared with 2015 models, with the actual reductions ranging from zero to 11%, depending on the maximum take-off mass of the aircraft (ICCT, 2016).
- Even the higher values in this range are in stark contrast with the much greater ambition represented by the ICAO commitment and aspirational goal for a 2% annual improvement in energy intensity (after 2020) (ICAO, 2013), which translates to an approximate 30% improvement over the period 2013–30. This is the case even if the 2% annual improvement in fuel burn per tonne kilometre refers to the average of existing planes and includes savings occurring from their operations.
- In the B2DS, the gap between the existing fuel economy standards and the need to deploy energy-efficient technologies widens even more, given that the global aircraft fleet becomes 35% more efficient between 2015 and 2030.

Due to the limited potential for aviation to move away from fossil fuels, measures that limit activity growth and encourage a shift to high-speed rail are also essential to meet the emissions reductions required by the B2DS. In this scenario, strong policies are needed to stimulate investments in HSR, which, combined with carbon prices leads to reduced activity of 37% in 2060 compared with the RTS⁴¹.

In addition to the vast efficiency improvements and activity shifts adopted in the B2DS, a pronounced shift to biofuels is also needed to cut aviation emissions more than half of 2005 levels, as indicated by the ATAG goal. By 2060, the aviation subsector consumes 6.6 EJ of advanced biofuels per year, which accounts for 70% of the aviation fuel mix. Should the levels of efficiency improvements and the extension of activity shifts indicated fail to materialise, meeting the goal to halve aviation emissions by 2050 relative to 2005 would require even higher shares of advanced biofuels.

40. Advanced biofuels are sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

41. Region-specific taxation measures, including the removal of the exemption of VAT for intra-European flight tickets, would also contribute to limiting activity growth.

Improving aviation efficiency

Achieving the 68% efficiency improvement needed to meet the B2DS will require the rapid adoption of improvements that have recently started to enter aviation technologies, as well as a radical departure from conventional aircraft configuration (IATA, 2013; Airbus, 2016):

- Cabin interior designs will need to allow for increased load capacity.
- Lightweight materials, and in particular composite structures, will need to be progressively used for the construction of wings and fuselages.
- Advanced engine concepts, ranging from geared turbofans to open rotors and hybrid-electric propulsion systems, will need to be adopted.
- Electric assistance will need to be universally used in ground level operations, including during taxi.
- Improvements in air traffic management will need to optimise routing, minimise flight distances and cut aircraft waiting times.
- Continued increases in the aircraft load factors, along the line of the developments observed in the recent past, will need to take place.
- A departure from the conventional aircraft configuration towards blended wing body aircraft architecture will need to become mainstream (Figure 5.12).

Blended wing body aircraft are the most radical change needed to cut fuel burn to the extent required in the B2DS. The advantages of this architecture are well known by aircraft manufacturers, but the risks of making such a switch today are too large. Shifting to blended wing body aircraft requires major design changes, bears significant risks associated with consumer perception of flights and necessitates significant investment to adjust ground-level infrastructure (e.g. the gate space at airports).

Figure 5.12. Concept of a blended wing body aircraft



Source: NASA, 2007.

Key point

A departure from the conventional aircraft configuration, towards blended wing body aircraft architecture, will contribute to meeting the B2DS targets.

Electric propulsion is also being considered as a possible future commercial aircraft technology (IATA, 2013). However, electric propulsion is not considered in the B2DS due to the major breakthroughs that would be required in battery energy density (a tenfold increase in energy per unit weight) and cost reductions to attract interest (Hepperle, 2012).

Should the efficiency improvements not materialise to the extent projected in the B2DS, the reduction of cruising speed could become necessary to meet GHG emissions mitigation goals: as aerodynamic drag depends on the square of speed, a 5% reduction in speed would result in 10% lower fuel burn.

Shifting aviation activity to HSR

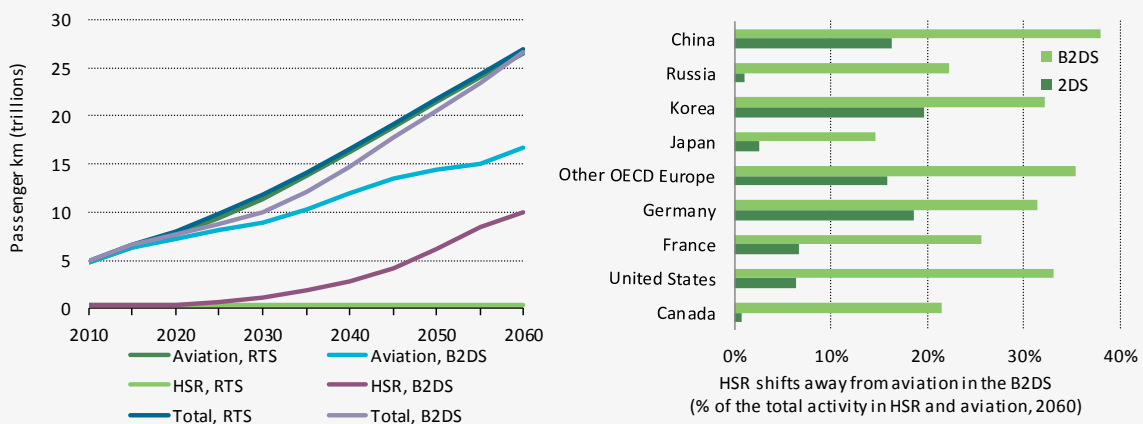
The energy use per passenger kilometre of HSR is around 90% lower than in aviation, and remains more efficient even when factoring in the major improvements included in the B2DS. As power generation is decarbonised, HSR can provide rapid mobility over short to medium intercity distances (up to 1 000 km) at virtually zero GHG emissions.

Limited availability of sustainable biomass and increasing competition for bioenergy feedstocks, as well as the major efforts required to improve aircraft efficiency, strengthen the case to constrain aviation activity via shifts to HSR. While building HSR infrastructure requires substantial investment, it can help to offset GHG emissions from aviation where decarbonisation options are more costly and technologically challenging.

The B2DS includes a significant shift from aviation to HSR, with stronger uptake in regions with higher population levels, as density enables lower unit costs and higher usage rates of the rail network. Today, Japan has the world's largest share of HSR, accounting for about 40% of total HSR and aviation activity. In the B2DS, the upper bound of the shifts to HSR activity achieved by 2060 is projected at 55% in regions that have population densities similar to the current level in Japan. In this scenario, the share of HSR in transport activity is a sizeable proportion of total high-speed passenger kilometres even in regions with medium and low population densities. Shifting to HSR comes at a higher cost if there is only scope to substitute for long-distance flights (more than 1 000 km). This is a consequence of the strong pressure posed by two main factors:

- limited improvements in aircraft efficiency that remain in 2060 as all measures are assumed to have attained full potential
- limited biofuel availability as it is assumed that all sustainable biomass resources are exploited by the energy sector and that biofuel shares already account for more than two-thirds of total aviation fuels in 2060.

Figure 5.13. Modal shift from aviation to HSR, RTS and B2DS



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

Ambitious shifts from aviation to HSR are needed to reduce GHG emissions, as aviation is a highly carbon-intensive mode of transport.

Policy needs

The introduction and progressive strengthening of carbon taxes in a subsector that currently enjoys several tax exemptions would increase the cost of flying.⁴² Given that fuel costs are a major component of the cost of flying, carbon taxes would generate significant incentive to upgrade to aircraft using energy-efficient technologies, ultimately reducing fuel burn. Fuel taxes that account for WTW carbon intensity of fuels would also stimulate the uptake of low-carbon fuels.

In the B2DS, carbon prices reach USD 540/tCO₂ by 2060. This curbs aviation activity by roughly 10% in that year, even after accounting for the assumed major reductions in energy intensity and the subsequent rebound in high-speed travel demand.

Achieving aviation's 68% efficiency improvement in the B2DS also implies a step change in the ambition of the ICAO fuel efficiency standards. The current target would need to be ratcheted up to increase the level of ambition. The combination of clear price and regulatory signals would create incentives to help bridge the risks that inhibit investment for the development of major innovations such as blended wing body aircraft.

Increasing biofuel shares in the aviation fuel mix will require the mobilisation of large investments in research, development, demonstration and deployment (RDD&D), as few advanced biofuel production pathways today offer the capacity to generate advanced biofuels at competitive costs. Production pathways based on hydrotreatment of vegetable oils or animal fats are likely to be the first to materialise. This suggests that steps towards the B2DS will not come about without significant actions by aviation stakeholders to secure feedstocks suitable to the production of fuels with near zero life-cycle emissions. Biofuel production will need to take place in a way that reduces GHG emissions and, more broadly, achieves other sustainability targets. Regulatory developments are needed to define the criteria used to evaluate biofuel production pathways with respect to their capacity to mitigate GHG emissions and other natural resource and sustainability goals. The adoption of low-carbon fuel standards could complement fuel taxes to stimulate the uptake of advanced biofuels in aviation.

Major investments will also be necessary to enable the development of high-speed networks required by the B2DS. This task could be eased if revenues derived from the taxation of fossil fuels in aviation were earmarked to build HSR networks.

International shipping

International shipping offers the most energy-efficient means of transporting freight, if measured per tonne kilometre. Yet its share of transport GHG emissions is set to rise due to expected increase of demand for shipping services and the lack of regulation to constrain GHG emissions. While shipping is difficult to regulate as most activity takes place outside national and international jurisdictions, rapid GHG reductions are needed to achieve the 2DS and B2DS targets; GHG emissions per tonne kilometre must be 69% lower in the B2DS in 2060 compared with RTS projections for 2060, and 70% lower by 2060 relative to 2015 (Figure 5.14). The shipping sector has significant potential for efficiency improvements. The energy intensity per ship kilometre can be nearly halved thanks to technical and operational measures available today (IEA estimate based on Smith et al., 2016). As such, the most significant measures included in the B2DS to reduce GHG emissions in shipping are improving the fuel efficiency for new ship designs and retrofitting existing ships (including wind assistance), and by switching half of the marine fuel mix to advanced biofuels. Given the long lifetime of ships (around 25–30 years) and the need to reach net-zero GHG emissions for the energy system by 2060, failing to act swiftly in shipping may have significant consequences on the possibility to limit global temperature increase.

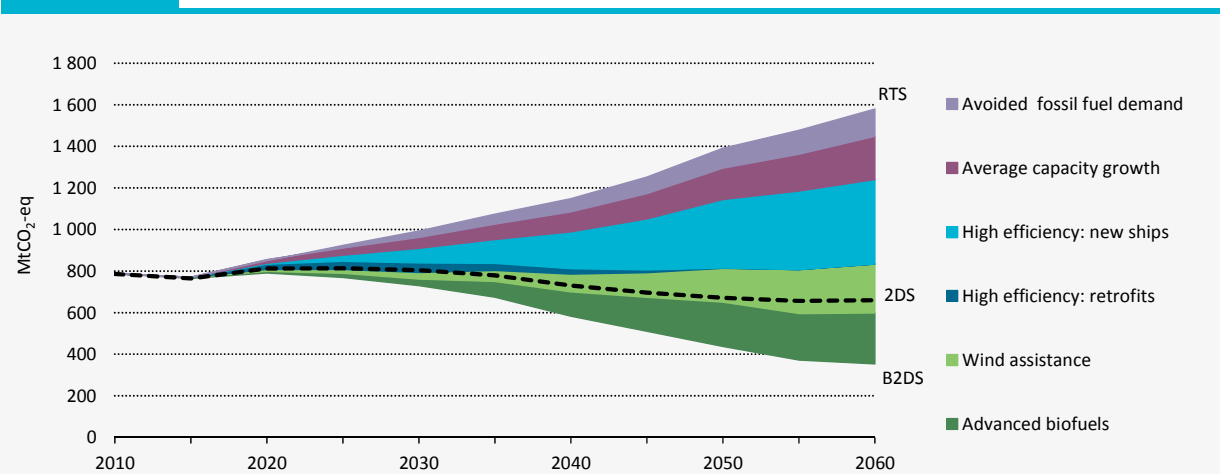
LNG is often mentioned as a solution for reducing local and GHG emissions in shipping, but it is not included in the B2DS. This is primarily due to its limited GHG abatement potential, especially when considering the risk of methane slip, in combination with the significant

42. In the European Union, for example, taxes on aviation fuels are not allowed and international aviation is exempt from VAT (Korteland and Faber, 2013).

costs required to develop a global LNG infrastructure. Developing such an infrastructure also risks locking in assets that may delay the adoption of more ambitious GHG emissions mitigation measures (Box 5.5).

Figure

5.14. WTW GHG emissions reductions in international shipping in the B2DS relative to RTS



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point

The largest share of GHG abatement in shipping results from operational and technological efficiency improvement combined with wind assistance in the B2DS.

Activity reduction

In the B2DS, some emissions are avoided as demand for international shipping services is lower than in the RTS projections. This is the result of lower demand for trade in fossil fuels, which currently accounts for about one-third of global maritime trade.⁴³ Demand for international maritime freight services grows significantly over time in all *ETP* scenarios, driven by population and gross domestic product growth. In the RTS, annual maritime freight activity grows from 99 trillion tkm in 2015 to 377 trillion tkm in 2060. In the B2DS, international maritime freight activity is reduced to 349 trillion tkm in 2060.

Efficiency improvements

In the B2DS, efficiency improvements per tonne kilometre are achieved from the increase of average ship size and utilisation rates, improved energy efficiency through vessel and engine design,⁴⁴ and more efficient operational practices. Reduced energy loads from auxiliary systems and wind assistance (relying on kites, sails or other solutions, such as Flettner rotors) are also required (Smith et al., 2016)⁴⁵.

Shipping's largest share of WTW GHG abatement in the B2DS is achieved from the combination of improved energy efficiency and wind assistance. Bulk carriers, tankers, general cargo ships and other types of ships improve energy efficiency 62% per ship

43. Some of the demand reduction could be compensated by increasing trade of advanced biofuels and the feedstock required for their production. These effects are not accounted for in the activity projections in the B2DS.

44. The solutions included in this category include trim and draught optimisation, contra-rotating propellers, superstructure mass reduction, improved aerodynamic design and air lubrication to reduce drag, and technologies for recovery of waste heat from engine operations.

45. The total efficiency potential from sails has been estimated at 20% and from kites at 5% (IEA estimate based on Smith et al., 2016).

kilometre by 2060 relative to 2010. Fuel savings are lower for container ships (53%) because of less potential for some of the wind assistance technologies. The B2DS also includes a reduction of the average speed of the global fleet, which can significantly reduce energy use per ship kilometre (Smith, Parker and Rehmatulla, 2011).

Due to the relatively long lifetime of ships, achieving the objectives of the B2DS will also require that part of the fleet be retrofitted with energy-saving technologies.⁴⁶ In the B2DS, fully retrofitted ships become 43–53% more fuel efficient, depending on the ship type. As shown in Figure 5.14, the contribution of retrofits to reducing GHG emissions is especially relevant in the coming 10–25 years, after which most of the older ships are scrapped and replaced by new ones.

Increasing the average size and thus carrying capacity of ships only partially increases the energy use per ship kilometre, while significantly reducing energy use per tonne kilometre (under the condition that load utilisation rates remain constant). The same is true for maximising utilisation rates. In recent years, the average size of ships, especially container ships, has increased. Between 2001 and 2009, the average ship size in the global container fleet increased at a cumulative annual rate of 1.9%, and between 2010 and 2015, it increased at an impressive 18.2% per year (UNCTAD, 2016). This was one of the main factors leading to a decline in energy use per tonne kilometre in international shipping in recent years. The B2DS assumes that average ship capacity continues to grow. Container ships are projected to grow fastest, at 0.9% per year until 2060. Bulk carriers grow at 0.4% per year until 2060, and general cargo ships grow at 0.6% annually until 2060. These increases will not be easy to achieve and will require the parallel development of port infrastructure and canal adjustments to accommodate larger ships.

Fuel switching

Unless nuclear use in shipping could be effectively unlocked (Box 5.6) or increasing demand in stationary or high-volume mobile applications would stimulate fuel cell and hydrogen use, advanced biofuels will remain the main alternative to fossil fuels in shipping.

Box

5.5. Why LNG is not included in the B2DS?

LNG is often seen as one of the solutions for meeting the recently announced International Maritime Organization (IMO) sulphur cap, primarily because of its lower unit cost compared with low-sulphur heavy fuel oil (HFO) or diesel fuel. When viewed from a perspective of potential to reduce GHG emissions, costs and risks clearly outweigh the benefits of the GHG abatement potential of LNG. LNG is a fuel that demands significantly different storage, handling and infrastructure and therefore gives rise to a number of challenges.

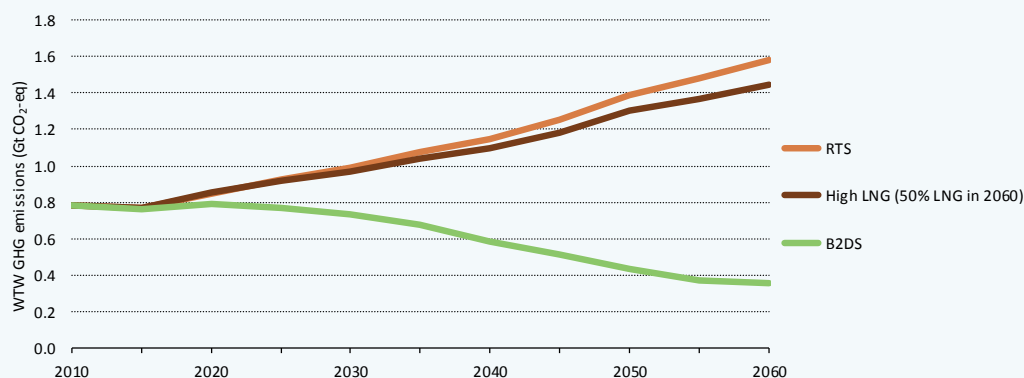
- The most striking of these is the development of bunkering infrastructure. Due to the global nature of shipping activity, LNG could be a viable substitute only once a global refuelling infrastructure network is developed. The size of this challenge is considerable. A first-order estimate suggests that building LNG bunkering facilities in the approximately 160 major global ports would require investments close to USD 11 billion. This estimate excludes the adaptation of all the upstream steps needed to deliver gas at the port facilities and to facilitate liquefaction processes.

46. Fuel-saving options suitable for retrofitting are trim and draught optimisation, contra-rotating propellers, hull coating, air lubrication, improved auxiliary systems in combination with solar power, improvement and substitution of engine components such as the fuel-injection system, technologies allowing the recovery of waste heat, variable speed control of pumps and fans, improved maintenance, and wind assistance.

- The containment of the fuel on board is also an issue for LNG. The tankage and other systems needed by LNG are more complex and larger than traditional bunker fuel components. This requires additional investments, including specialised labour forces and reduced space for payloads.
- Additional barriers to LNG are also posed by the need to develop new safety regulations.

Even if LNG has promising potential to reduce sulphur emissions, the GHG reduction potential of LNG is limited (Figure 5.15). The WTW CO₂ emissions intensity of LNG is 20% lower compared with HFO, disregarding side effects such as methane slip. If the shipping industry were to switch entirely to LNG, GHG emissions reductions would amount to only about one-third of what is required to meet the B2DS carbon mitigation needs. For these reasons, LNG is not included among the fuel supply options in the B2DS.

5.15. Figure: WTW GHG emissions reductions with a high LNG fuel mix relative to the RTS and B2DS, 2010–60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model www.iea.org/etp/etpmodel/transport/.

Key point: Even if LNG has promising potential to reduce sulphur emissions, the GHG reduction potential of LNG is small. Shifting 50% of the international shipping fleet to LNG would reduce GHG emissions by only 10%.

Biofuels for shipping could take the form of advanced biodiesel (and possibly biogas) for use in combustion engines and, if costs can be cut, methanol directly used in fuel cells. As in other transport modes, PtX technologies also have the capacity to deliver low-carbon liquid and gaseous fuels (Box 5.7).

Box

5.6. Why is nuclear not included in the B2DS?

On-board nuclear energy storage and power generation could be a clean and relatively cheap solution to decarbonise shipping. Nuclear propulsion is a proven technology for shipping applications: today about 200 reactors cruise the oceans on icebreakers (primarily operated in Russian Federation waters) and military vessels (Raeng, 2013). Operating these vessels

requires stringent crew selection, education and training regimes. Environmental hazards due to the use of radioactive fuel and decommissioning poses challenges, including finding safe storage space for spent nuclear fuel and on-board power plants. Decommissioning issues are similar to those faced in nuclear power generation, but environmental consequences could be far worse in the case of accidents occurring along inhabited coastlines. In addition to major changes to ship owning and operation infrastructure and practices, scaling up nuclear propulsion in ships would also require a complicated and sensitive regulatory framework that upholds strict precautionary measures and bi-lateral agreements. Environmental risks and the major regulatory barriers for the nuclear scale-up are the main reasons nuclear ships have not been included among the options in the B2DS.

In the B2DS, advanced biofuels are the main low-carbon fuel option contributing to the reduction of shipping's GHG emissions. In that scenario, 5 EJ of second-generation biofuels account for nearly half of the total final energy demand in international shipping in 2060. Marine biofuels take the form of advanced biodiesel for use in marine combustion engines.

Box**5.7. How is hydrogen for shipping addressed in the B2DS?**

Hydrogen could play a role in the future of international shipping, either as direct use or as an intermediate product for the synthesis of PtX fuels (Smith et al., 2016).

Fuel cells can be used for ship propulsion, with good experience gained in auxiliary and low-power propulsion machinery (Raeng, 2013). Stationary applications such as solid oxide and molten carbonate fuel cells could also be suitable for high-power marine propulsion. Proton exchange membrane fuel cells are more suitable for low-power applications. Costs are currently the main barrier to the deployment of fuel cell technologies.

Given the limited number of refuelling points, access to centralised production of low-carbon hydrogen could be easier in shipping than for road transport, making low-carbon hydrogen for maritime transport available at lower costs.

The main barrier for hydrogen use in shipping is the low market volume, which limits opportunities for technology learning and economies of scale, and therefore offers small contributions to cost reductions for fuel cells and on-board storage technologies. Opportunities for production in larger volumes are higher for road transport modes and stationary applications in the buildings and industry sectors. The successful deployment of hydrogen technologies in shipping is therefore likely to be affected by the dynamics of hydrogen deployment in other stationary and mobile applications. Given the limited prospects for hydrogen demand growth in industry and buildings in the B2DS and the barriers for hydrogen scale-up in other transport modes, hydrogen use in shipping is considered here only as an option that could provide GHG emissions reductions that are additional to the assessment made in the B2DS. Additional work will help to integrate them in the International Energy Agency (IEA) modelling tools to improve the understanding of opportunities for hydrogen technologies in shipping to contribute in low-carbon scenarios.

In addition, PtX technologies are assessed in this report only as a complementary option to other low-carbon biofuel production pathways. This is due to the limited availability of low-cost and low-carbon electricity in a system striving for the optimisation of electricity use (even in the presence of high variable renewable shares) and the constraints on the sustainable supply of primary biomass that have been taken into account for other biofuel production pathways. Additional work is necessary to improve the assessment of these technologies against biofuel production from hydrotreated oils or thermochemical or biochemical routes.

Given the need for ultra-low or zero-emission technologies to achieve the deep decarbonisation

of shipping, uncertainties on the possibility to achieve cost reductions for low-carbon biofuels and the limited potential of electrification in shipping (confined to short-distance trips), efforts to demonstrate the potential for the economic viability of hydrogen and fuel cells in shipping applications should be encouraged.

Policy needs

Between 2015 and 2025, the IMO Energy Efficiency Design Index (EEDI) mandates a 1% annual improvement in the energy intensity of the global fleet.⁴⁷ Getting on track with the B2DS requires an annual efficiency improvement of 2.3%, measured in megajoules per vehicle kilometre, and 2.6% in megajoules per tonne kilometre, between 2015 and 2025. From a policy perspective, this suggests that the first step to encourage efficiency improvement for new ships is to increase the ambition of the EEDI.

Expanding this framework to include operational efficiency standards for existing ships would significantly increase the impact of measures targeting energy efficiency because it would penalise inefficient ships in the existing fleet. Adequate collection of data along trading patterns of individual vessels is a prerequisite to allow operational performance monitoring and a prerequisite for the efficacy of other GHG emissions mitigation measures. Robust and transparent information on the energy use of ships also offers an opportunity to stimulate investment from shipowners to improve vessel efficiency, as it would improve the competitiveness of vessels with good GHG ratings to earn higher time charter rates than those with poor GHG ratings (Prakash et al., 2016). Currently, contractual arrangements between charterers and shipowners are such that charterers receive the benefits from efficient ships, rather than shipowners, but the latter are responsible for the investment in efficiency technologies. This constitutes an additional barrier to efficiency investments in shipping (Prakash et al., 2016).

Addressing these market barriers with increased transparency and accuracy of data is essential to ensure that CO₂ pricing based on life-cycle GHG emissions performance of fuels can become an effective lever to orient the shipping sector towards the efficiency improvements and fuel switching required by the B2DS trajectory (see for instance Farid et al., 2016).

Fuel quality regulations can also promote the adoption of high-quality low-carbon shipping fuels. The global sulphur cap announced by the IMO to take effect in 2020 offers opportunities to encourage low-carbon fuel technologies. The regulation requires conventional HFO (with an average of 2.5% sulphur content by mass), which accounted for 84% of marine bunker fuel in 2014, to be replaced with a fuel containing 0.5% (5 000 parts per million) sulphur. The compliance costs of switching to low-sulphur fuels have been estimated to lead to increases in fuel costs ranging from 20% to 85% (ITF, 2016). This upward price pressure is likely to benefit advanced biofuels, but may not be sufficient to bring them on par with conventional marine fuels. Biofuel mandates and regulations such as low-carbon fuel standards have the capacity to stimulate the adoption of low-carbon fuels, including PtX.

The case of low-sulphur diesel and LNG, both of which are viable alternatives to HFO for the reduction of sulphur emissions but clearly not sufficient to meet the B2DS GHG emissions mitigation targets, shows that investment decisions intended to comply with the IMO sulphur cap may result either in delayed action to reduce GHG emissions or heightened risk of becoming stranded assets. A clear signal from the IMO, starting from a sectoral emissions reduction target for international shipping, would be an effective means to reduce investment risks.

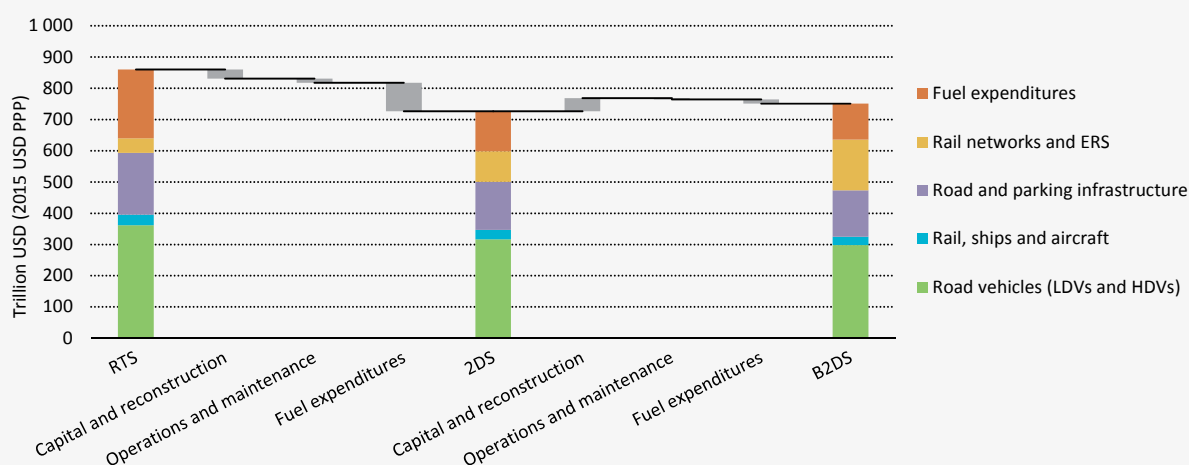
47. This effect is measured in megajoules per vehicle kilometre to exclude structural effects (i.e. increasing average ship size). The 1% improvement excludes the effect of an expected growth in average ship size and freight capacity.

Given the challenges posed by the need to reach a consensus decision in the IMO framework, unilateral action on GHG emissions reduction measures from major actors of global trade, such as the European Union and the United States, would provide effective opportunities to accelerate policy changes, as already demonstrated in the case of emissions of sulphur oxides and other local pollutants in Emission Control Areas. Such action, which includes the measures discussed such as CO₂ taxation and enhancements to data accuracy and monitoring, could be complemented by co-ordinated measures developed by major ports to provide incentives to ships with the best environmental performances. One example is provided by the Port of Rotterdam, which operates a scheme providing discounted fees for cleaner ships (Port of Rotterdam, 2017). The challenge is to create a common framework to which most ports agree and are willing to co-operate. Today such systems, where they exist, are voluntary initiatives.

Investment requirements

Scenario estimates of total expenditure on vehicles, infrastructure and fuels show that the cumulative 2017-60 costs of transport in the RTS are about USD 130 trillion (2015 USD PPP) higher than those of the 2DS, and USD 110 trillion higher than in the B2DS (Figure 5.16). Fuel savings make up the majority of the savings in the decarbonisation scenarios: cumulative expenditure of about USD 220 trillion on fuels in the RTS can be cut by 40% in the 2DS and by nearly 50% in the B2DS. Additional savings accrue from a reduction in total road vehicle purchases. By 2060, the avoid-shift policies in both passenger and freight result in a reduction in vehicle stocks of 17% in the 2DS and 19% in B2DS (not including 2- and 3-wheelers). Since these vehicles are equipped with advanced efficiency technologies, which makes them more expensive to purchase (but generally less expensive to operate over their lifetime), these aggregate stock reductions lead to cumulative 2017-60 savings of 12% in the 2DS and 17% in the B2DS.

Figure 5.16. Investment needs by scenario, 2017–60



Source: IEA (2017a), *Mobility Model*, March 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Decarbonising transport saves more than USD 100 trillion in the period to 2060, mostly from reduced expenditures on cars and fuel.*

Substantial savings in the decarbonisation scenarios also accrue from reduced road and parking infrastructure investment; the reduction in cumulative investment is in excess of 20% in both scenarios relative to the RTS. Infrastructure investment requirements, however, increase for other modes in order to enable a shift to ERS (or hydrogen) in long-distance road modes.⁴⁸ The majority of these costs are related to expanding and maintaining metro and intercity rail networks; these investments are about an order of magnitude greater than those of building and maintaining HSR and ERS (catenary lines). In the case of the 2DS, reduced outlays for road and parking infrastructure (about USD 45 trillion) are offset by the additional costs of these efficiency and low-carbon infrastructure investments (approximately USD 50 trillion). In the B2DS, the USD 50 trillion saved in roads and parking is overwhelmed by the additional investment, of about USD 115 trillion, needed for intercity, metro and HSR and catenary lines. The consequence of this difference is that the B2DS would require about USD 25 trillion more cumulative investment from 2017–60 than the 2DS.

Policy actions to realize comprehensive cuts in transport emissions

To realise the rapid and comprehensive cuts in transport GHG emissions required in the B2DS, policies and technologies must be effectively deployed to decouple emissions from passenger and goods movement across all modes. Policies will need to be promulgated and co-ordinated across all levels of governance (international, supranational, national, regional and local).

In both the 2DS and B2DS, policy actions must begin immediately. The main differences between the two scenarios are the magnitude of the necessary commitments and the pace of deployment of technologies. The B2DS would require a faster pace and more stringent regulatory and fiscal instruments, as well as more investments in low-carbon modes (e.g. public transit) and technologies underpinning low- and zero-carbon energy carriers, leading to higher total costs than those of the 2DS. Specific elements that characterise both the 2DS and B2DS, but are even more pressing in the B2DS, include:

- **Regulatory targets** need to be adopted on the energy intensity of vehicles across all modes and in all regions. These targets need to be benchmarked against the GHG emissions limits implied by the remaining cumulative GHG budget, defining key milestones to reach in future years. Regulatory limits for the emissions intensities need to be ratcheted up if the results underachieve the milestones. Accuracy, transparency and representativeness of test procedures need to be ensured and compliance strictly enforced. This is extremely important for modes that represent a large fraction of total transport emissions, such as LDVs and trucks, but also applies to transport modes that operate outside of regular jurisdictional zones (i.e. international shipping and aviation).
- **Regulatory policies** that mandate minimum performance need to be supported by economic instruments that incentivise the adoption of best available technologies (such as differentiated vehicle taxes, green financing mechanisms and low-carbon fuel standards).
- **Policies to transition to ultra-low and zero-emission technologies are needed.** Ultra-low or zero-emission vehicles will have a growing importance over time to achieve emissions reductions. Shifting the vehicle fleet to ultra-low or zero-emission technologies is unlikely to materialise in the absence of tight regulatory limits (including bans or usage restrictions for vehicles with the worse performance) and/or differentiated taxation that strongly favours vehicles with the best performances in terms of GHG emissions per km.
- **Public funding needs to support research, development, demonstration and deployment of crucial decarbonisation technologies and infrastructure.** Such technologies include hydrogen

48. Costs assessed here are for ERS, based on the assumption that about 5% of the road network worldwide would need to be equipped with catenary lines to enable road freight to electrify to the extent envisioned in the decarbonisation scenarios. The costs of a build-out of a hydrogen production, distribution and fuelling infrastructure are not explored in this analysis.

fuel cells, electric road systems, batteries and other energy storage technologies for the electrification of transport modes. Public support needs to target strategic infrastructure to encourage more sustainable and healthy passenger transport patterns, particularly in cities (such as high-quality public transit and non-motorised infrastructure investment), and the decarbonisation of long-haul road vehicles (e.g. ERS and/or hydrogen production and fuelling stations).

- **Fuel taxes that reflect life-cycle GHG emissions intensities** are needed to foster the competitiveness of ultra-low or zero-emission technologies. Regions that currently subsidise transport fuels must transition to taxation within the coming decade. Once ultra-low or zero-emission vehicles penetrate the road fleet, the taxation of transport needs to shift towards distance- and/or congestion-based pricing schemes. This will provide a revenue stream to finance infrastructure deployment as well as to maintain government revenues from taxing transport fuels.
- **Local policies**, including regulatory measures such as congestion charging, low-emissions zones, and access restrictions on vehicles with poor emissions performance, but also strategic investment in public transit and in well-sited public charging stations, are indispensable to modify urban transport systems to become lower emitting and more sustainable. The substantial health impacts of reducing local air pollution provide not only a pressing public policy justification but also a solid governance basis for implementing strict measures to limit local pollutant emissions from motor vehicles.

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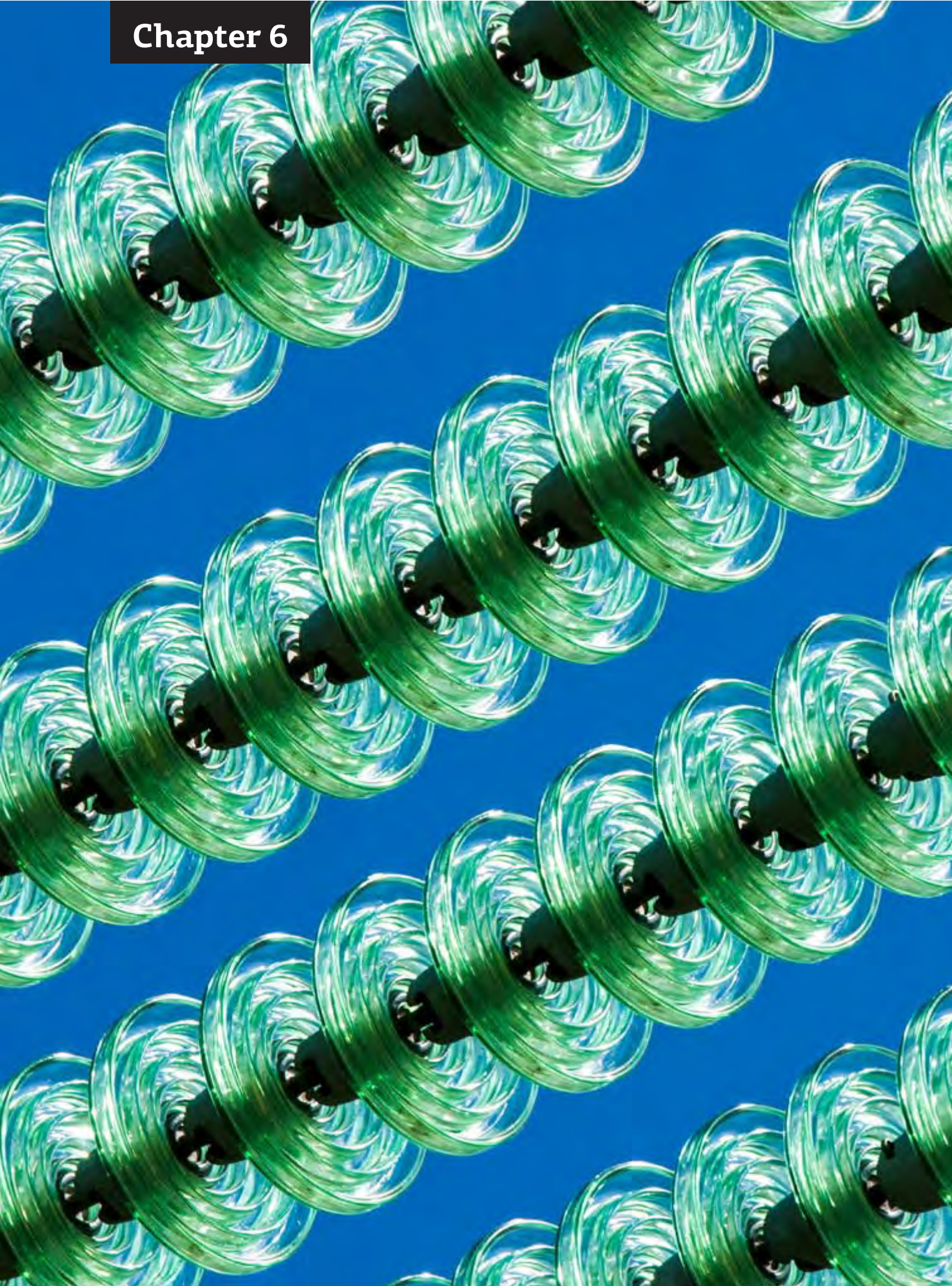
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Chapter 6



Transforming electricity systems

Deep and rapid emissions cuts in the power sector – the world’s largest emitter of carbon dioxide (CO₂) today – have to be central to any policy strategy aiming for a 2°C pathway and beyond. Once power systems are low carbon, electricity can also support the decarbonisation of heat and mobility. Through bioenergy-fired power plants with carbon capture and storage (CCS), the power sector is also capable of becoming a source of negative emissions to offset the more difficult task of mitigating emissions in other parts of the energy system.

Key findings

- **CO₂ emissions from the power sector are increasing rapidly.** Over the last decade, CO₂ emissions from the power sector, at 125 gigatonnes of CO₂ (GtCO₂), accounted for 30% of the sector’s cumulative emissions since 1900. Today, the power sector accounts for around 40% of total annual CO₂ emissions in the energy sector.
- **In the Reference Technology Scenario (RTS), global electricity demand more than doubles between today and 2060, while CO₂ emissions stabilise at a level of 15 GtCO₂ after 2030.** As a result, the CO₂ intensity of electricity is halved by 2060 relative to today.
- **In the 2°C Scenario (2DS), the global power sector reaches net-zero CO₂ emissions in 2060,** with 74% of generation from renewables (including 2% bioenergy with CCS [BECCS]), 15% from nuclear, 7% from fossil fuels equipped CCS, and the remainder from natural gas-fired generation without CCS.
- **The greater ambition in the Beyond 2°C Scenario (B2DS) will require accelerated power sector decarbonisation,** given that almost half of the sector’s cumulative CO₂ emissions in the 2DS between 2015 and 2060 are emitted before 2025.
- **Electrification of end uses is a key lever** in the 2DS and becomes even more important in the B2DS. The share of electricity in final energy demand¹ in buildings, industry, transport and agriculture increases from 18% today to 41% in 2060 under the B2DS (35% under the 2DS). This equates to 1 700 terawatt hours (TWh) more than in the 2DS, an amount corresponding to the combined electricity consumption of India and the Russian Federation (hereafter, “Russia”) today.

1. The definition of total final energy demand used in *Energy Technology Perspectives (ETP) 2017* deviates slightly from the one in International Energy Agency (IEA) energy statistics. In *ETP*, final energy demand for industry includes energy consumed in blast furnaces and coke ovens; in the transport sector, it excludes energy use for pipeline transport, which is accounted for in the transformation sector.

- **“Negative emissions” from the power sector with the use of BECCS are crucial for the overall energy system to attain the B2DS pathway.** This requires the global power sector to reach net-zero emissions by 2050 and to become net-negative, with emissions of -2.2 GtCO_2 , in 2060. BECCS in the power sector provides 6% (15 GtCO_2) of the necessary cumulative reductions in the period to 2060 across all sectors to progress from the 2DS to the B2DS.
- **Global electricity generation of 53 100 TWh in 2060 under the B2DS is from low-carbon technologies,** with renewables reaching a share of 78% in 2060 (22% in 2014), nuclear at 15% (11% in 2014) and fossil fuels with CCS at 7%.
- **Early retirement of coal-fired power plants before the end of their technical lifetime is unavoidable to reach the B2DS.** This is in the order of 1 330 gigawatts (GW), an amount corresponding to almost three-quarters of the world’s installed coal capacity in 2014. While CCS retrofits allow the continued operation of 170 GW of coal capacity that would otherwise be retired, even coal fitted with CCS becomes too carbon intensive in 2060 under the B2DS.
- **The accelerated deployment of variable renewable energy (VRE) sources in the B2DS, reaching a global share of 38% in 2060, will need to be facilitated by increased system flexibility.²**
- **The B2DS requires a significant expansion and upgrading of electricity grids.** In particular, annual investment needs to double by 2025 to enable large-scale deployment of VRE in later periods. Interconnection, in particular, emerges as a key option in the B2DS, with nearly 2 400 GW of capacity deployed to link power systems across the globe.
- **Accelerated deployment of storage is required to reach B2DS goals.** Despite the rapid ramp-up, materials availability is not likely to become a barrier. However, new technologies need to be developed, including higher-density nickel-based lithium batteries, lithium-sulphur batteries and lithium air batteries, as well as battery technologies with longer storage durations to cope with the deep decarbonisation of power grids.
- **An active demand side is a fundamental pillar of the B2DS.** Active demand response enables higher levels of low-cost flexibility to integrate the high shares of VRE and reduce overall costs. However, at present there is significant uncertainty as to the scalability of dynamic demand response business models, and the efficiency and flexibility they can afford.
- **The B2DS requires investment of 65 trillion United States dollars (USD) over the period 2017–60 in the power sector, with the additional investment relative to the RTS being almost 40% higher than that required under the 2DS.** Marginal abatement costs for CO_2 in the power sector increase from USD 240 per tonne of CO_2 (tCO_2) in 2060 in the 2DS to USD 565/ tCO_2 in the B2DS.
- **Delaying action to 2025 increases the B2DS cumulative investment needs of the power sector by 20%** and forces an additional 630 GW of fossil fuel-based generation capacity to be retired early, resulting in estimated lost revenues from electricity sales of around USD 8.3 trillion.

2. VRE sources are onshore and offshore wind, solar photovoltaic (PV), run-of-river hydropower, wave energy and tidal energy. The focus here is specific to the integration of wind and PV, so the discussion of VRE is limited to these two.

Opportunities for policy action

- **Approaches to technological innovation have to be tailored to the development status of specific low-carbon power technologies.** In addition, research, development and deployment (RD&D) has to take an integrated view of power systems in its design and operation, exploring stronger linkages among electricity, heat and mobility. This includes the double benefit of electrification by contributing to emissions reductions and increasing the potential for demand response measures to support VRE integration.
- **Strong carbon pricing policies are needed.** On their own, however, carbon prices are unlikely to be sufficient to deliver the necessary investment in time or at scale, particularly in the transition phase. Carbon prices should be complemented by technology support measures to reduce investment risks.
- **Renewables become the main source for electricity generation in the decarbonisation scenarios.** With both increased electrification and greater supply from VRE sources, opportunities to boost the flexibility and reliability of electricity systems should be explored and exploited. Assessment of the potential should be based on local conditions and roadmaps for implementation.
- **Development of natural gas-fired generation technology should focus on reducing capital costs, increasing flexibility and incorporating CCS.** While the 2DS and B2DS see natural gas as a transitional fuel in the power sector, with its global average share of generation (with and without capture) declining after 2025, gas-fired power plants can remain important to provide system services.
- **Coal-fired power generation without CCS becomes unsustainable in the 2DS and B2DS by 2040–45, increasing the risk that coal plants built in the near term become stranded assets.** At a minimum, new coal plants that are built should be CCS-ready. Fostering research for higher capture rates at coal-fired plants equipped with CCS may extend their use under more stringent climate targets.
- **BECCS in power generation needs to be demonstrated on a commercial scale to gain experience.** No large-scale plants are currently in operation. Given the infrastructural complexity of BECCS, which involves sourcing bioenergy and the transport and storage of CO₂, planning and deployment support from governments is necessary to mitigate multiple investment risks, at least in the initial deployment phase. RD&D for BECCS in the power sector should focus on improving the efficiency of smaller plants (compared with the size of fossil fuel plants with CCS), which are likely to be required due to constraints on bioenergy sourcing.

Overview

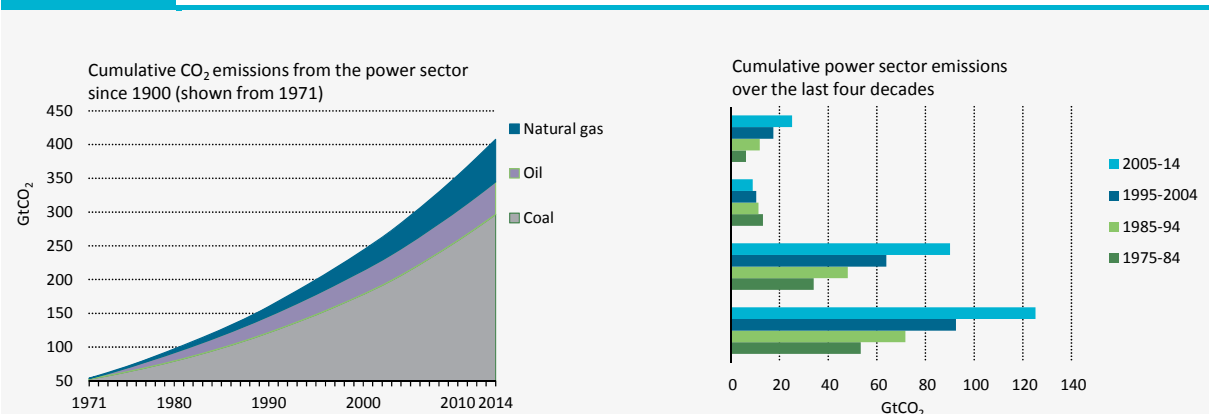
This chapter assesses the role of the power sector, and the technology options available to electricity systems, in the transition to a low-carbon energy future under three scenarios:³

- The RTS takes into account policy measures as currently implemented, and policies and targets that have been announced. The RTS leads to a stabilisation of CO₂ emissions in the global power sector at around 15 GtCO₂ in 2060. In this scenario, coal-fired electricity generation is almost flat after 2025, and increased power demand is provided from renewable energy technologies, natural gas and nuclear.
- The 2DS is consistent with a 50% probability of limiting the expected global average temperature increase to 2°C by 2100. In this scenario the global power sector reaches almost net-zero annual CO₂ emissions by 2060. The deployment of renewables, CCS and nuclear is drastically ramped up, while a proportion of fossil fuel power capacity without CCS has to be retired early to achieve this ambitious transition.
- The B2DS looks at the changes required to limit the global average temperature increase by the end of the century to 1.75°C. This scenario implies net-zero CO₂ emissions for the entire energy system by 2060, which, for the power sector, necessitates an even more accelerated deployment of low-carbon technologies. In addition, power systems must transition to negative emissions, for example with plants equipped with BECCS, in order to offset remaining CO₂ emissions in end-use sectors where decarbonisation may be more challenging, such as in long-distance transport.

Electricity is essential to peoples' daily lives and is a major component of economic and social development. Global average per capita electricity consumption has more than doubled over the last four decades, from 1 454 kilowatt hours (kWh) per capita in 1974 to 3 030 kWh per capita in 2014. Electricity already provides a broad range of services, from lighting, cooking, heating, and information and communication technologies (ICTs) to mechanical energy and industrial production. At a global level, electricity has been the fastest-growing final energy source (i.e. consumed in the end-use sectors), increasing at an average annual rate of 3.4% over the last four decades and overtaking natural gas in 2001 to become the second-largest final energy source, after oil. As a result, the share of electricity in global final energy consumption almost doubled from 10% in 1974 to 18% in 2014 (IEA, 2016a).

The prominent role of electricity in global economies makes power generation the largest source of CO₂ emissions in the global energy sector, accounting for 40% of energy- and process-related CO₂ emissions in 2014 and for 35% of the world's use of fossil fuels in primary energy use. Since 1900, the power sector has emitted 408 GtCO₂, of which 30% has been emitted in the last decade alone (Figure 6.1). Power generation is also a major source of air pollution in many countries (see *Energy and Air Pollution: World Energy Outlook Special Report* [IEA, 2016b]). Decarbonising the electricity system is a precondition for the transition to a sustainable energy future. Once decarbonised, low-carbon electricity can help to decarbonise the end-use sectors, e.g. by using heat pumps in buildings or electric vehicles (EVs) for transport. Currently, electricity serves about 30% of the energy demand in the buildings sector worldwide. With increased uptake of EVs, solar PV and onshore wind, as well as continued RD&D of opportunities to use electricity for heating and synthetic fuels, the signs of a new era of electrification are clear.

3. A full description of the scenarios can be found in Chapter 1, Box 1.1.

Figure 6.1. Cumulative CO₂ emissions from the power sector

Notes: the starting year for cumulative CO₂ emissions in the left graph is 1900; estimated emissions for the period 1900–70 are 50 GtCO₂. Sources: IEA (2016c), *CO₂ Emissions from Fuel Combustion* (database), www.iea.org/statistics/; Lenzen and Schaeffer (2012), *Historical and potential future contributions of power technologies to global warming*.

Key point *Cumulative CO₂ emissions from the power sector are increasing rapidly; emissions over the last decade alone accounted for 30% of the sector's cumulative emissions since 1900.*

Recent trends

Demand for electricity continues to increase. Except during the economic crisis in 2008–09, electricity generation has increased every year since 1971, reaching 23 816 TWh in 2014, a 2% increase compared with the previous year. Over the last decade, electricity generation has grown by 36%, with non-member countries of the Organisation for Economic Co-operation and Development (OECD) accounting for more than 90% of the increase (the People's Republic of China [hereafter China] alone was responsible for 55% of the global rise).

In 2016, 161 GW of renewables-based capacity was added, for the second year in a row an amount that was higher than capacity additions of fossil-fired and nuclear power plants combined. About 70% of this renewables capacity was installed in non-OECD countries. Renewables accounted for 23% of the global power generation mix in 2015. Of these, hydropower accounted for about 16%, wind for 3.4% and PV for 0.9%. Wind and PV capacity additions are on an upswing due to notable cost reductions. Indicative global onshore generation costs for new installations have dropped by around one-third, on average, between 2008 and 2015, while wind power generation more than doubled (IEA, 2016d). Generation costs for solar PV fell by two-thirds, while solar PV generation increased sevenfold between 2010 and 2015.

Nuclear provides around 10% of global electricity demand. It saw moderate growth in capacity from 408 GW in 2015 to 418 GW in 2016. Additional nuclear power capacity of the order of 10 GW was connected to grids in 2015 and 2016, the highest rate over the last 25 years. However, new construction in 2016 was 3.2 GW lower than the 8.8 GW seen in the previous year. China dominates the new capacity additions, accounting for five out of the ten new reactors connected to the grid in 2016.

Despite the progress in the deployment of these low-carbon technologies, the global electricity generation mix continues to be dominated by fossil fuels, with a share of 67% in 2014. Reductions in the global average CO₂ intensity of electricity have been moderate. Over the last decade CO₂ intensity has fallen by only 4%, to 519 grammes of CO₂ per kilowatt hour (gCO₂/kWh), a value roughly in the middle between the CO₂ intensities of a new ultra-supercritical coal power plant (730 gCO₂/kWh)⁴ and a new combined-cycle gas

4. Gross efficiency based on lower heating value (LHV) of 47%.

power plant (350 gCO₂/kWh).⁵ Looking only at global CO₂ intensity masks national and regional developments: the United States (US) and the European Union (EU) reduced their CO₂ intensity of power generation by around 18% in the period 2004–14 and China by 23%. The absolute level of carbon intensity also varies among countries due to indigenous conditions. For example, the CO₂ intensity of power generation in Sweden was 11 gCO₂/kWh in 2014, reflecting its hydro and nuclear capacity, while in Germany it was 474 gCO₂/kWh, reflecting higher dependence on fossil fuels.

CCS currently plays virtually no role in power generation. Yet the signs are encouraging, with two large-scale coal-fired power plants with CCS now in operation: the 115 megawatt (MW) Boundary Dam power plant in Canada, which was retrofitted with CO₂ capture in 2014, and the retrofitted 640 MW unit at the Petra Nova power plant in Texas, United States, which started operation in January 2017. A third large-scale project is scheduled to start in the United States in the coming months – a new 582 MW lignite-fired integrated gasification combined-cycle (IGCC) plant equipped with pre-combustion capture technology. These three large-scale power plants with CCS will have a combined capacity of 1.3 GW, and the potential to capture around 5.2 million tonnes of CO₂ (MtCO₂) per year.

Decarbonisation pathways for the power sector

To better understand the efforts needed to enable deep decarbonisation of the power sector, it is helpful to look at current trends and policies in place and the expected impacts of announced policies and targets (including the Nationally Determined Contributions [NDCs], the climate pledges of the Paris Agreement). These provide the basis for the RTS, which serves, alongside the 2DS, as a benchmark to assess the feasibility and impacts of a radical change in technology deployment as projected in the B2DS.

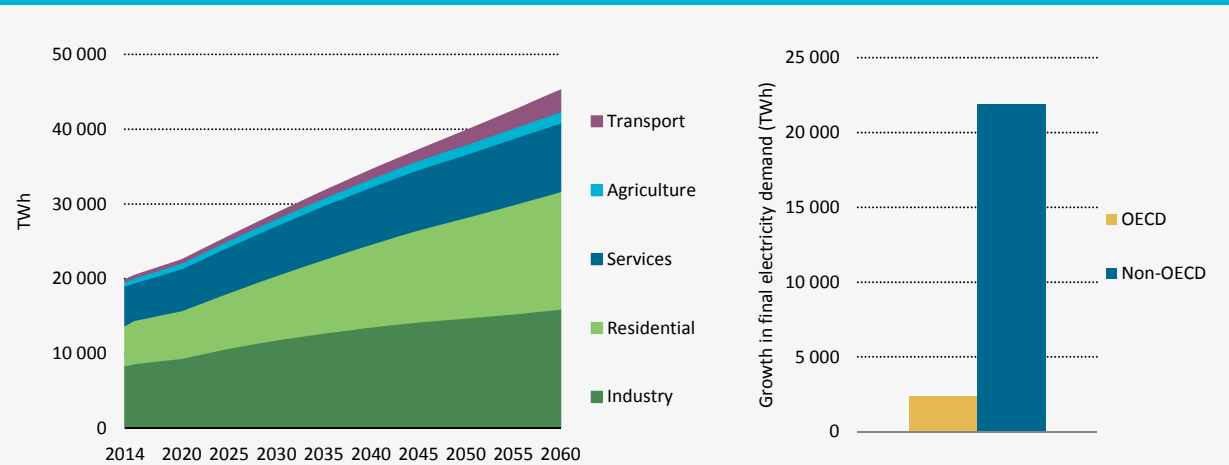
Future impact of current ambitions

Based on recent trends, existing measures and announced policies or targets, such as the NDCs, the RTS maps out how the energy sector could evolve in the period to 2060. In the RTS, global final electricity demand more than doubles, from 19 860 TWh in 2014 to 45 800 TWh (Figure 6.2). The buildings sector accounts for 55% of the increase, reflecting growth in income levels and per capita consumption in developing economies. Industry accounts for 32% of the increase and transport for 10%. In relative terms, electricity demand in the transport sector increases the most, by tenfold, but from a low level, since its use in transport today is largely limited to rail transport. The share of electricity in transport final energy demand rises from less than 1% in 2014 to 6% in 2060. Across all sectors, the share of electricity in global final energy demand increases from 18% in 2014 to 27% in 2060. Non-OECD countries are the main drivers and account for 90% of the global increase in final electricity demand by 2060 in the RTS. Electricity consumption⁶ increases from 3 030 kWh per capita in 2014 to 5 004 kWh per capita in 2060 under the RTS.

5. Gross efficiency LHV of 57%.

6. Electricity consumption includes final energy demand, electricity own-use in power plants and electricity consumed in other parts of the transformation sector.

Figure 6.2. Final electricity demand by sector and region in the RTS, 2014–60

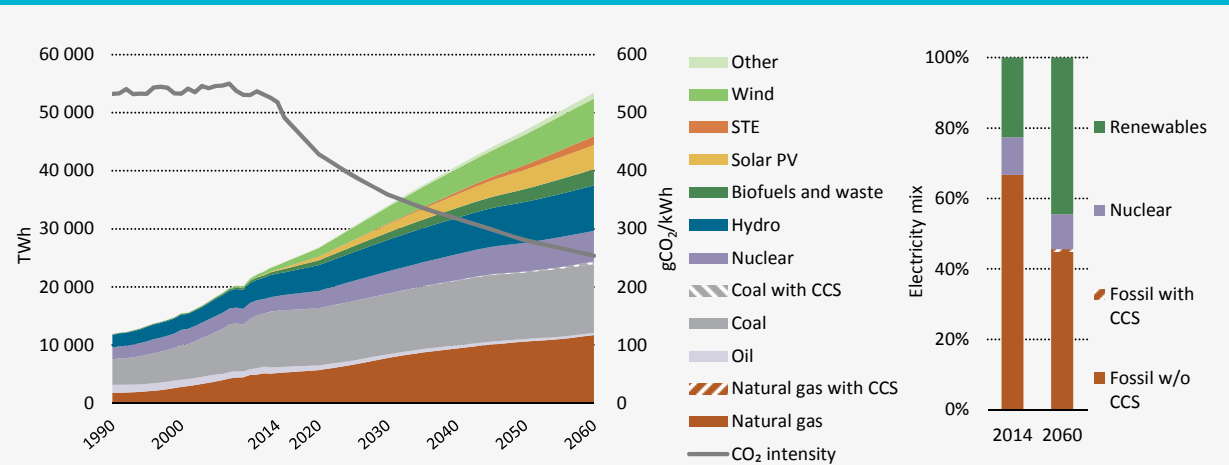


Source: Data for 2014 from IEA (2016a), *World Energy Statistics and Balances* (database), www.iea.org/statistics/.

Key point *Global final electricity demand more than doubles by 2060, with non-OECD countries accounting for 90% of the increase.*

In the global electricity generation mix, the share of renewables doubles by 2060 and is on par with fossil fuels, each providing around 45% (Figure 6.3). Nuclear remains at about today’s 10% share, but with capacity increasing from 418 GW in 2016 to 715 GW in 2060. The penetration of CCS technology reaches only about 60 GW in 2060, corresponding to less than 1% of global generation and capturing 355 MtCO₂ per year in 2060 (about 2% of power sector emissions).

Figure 6.3. Global electricity generation in the RTS



Note: STE = solar thermal electric.

Sources: Data for 1990–2014 from IEA (2016a), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics/; IEA (2016c), *CO₂ Emissions from Fuel Combustion* (database), www.iea.org/statistics/.

Key point *The share of renewables in global power generation nearly doubles to 45% by 2060 in the RTS, although its CO₂ intensity is only halved relative to today.*

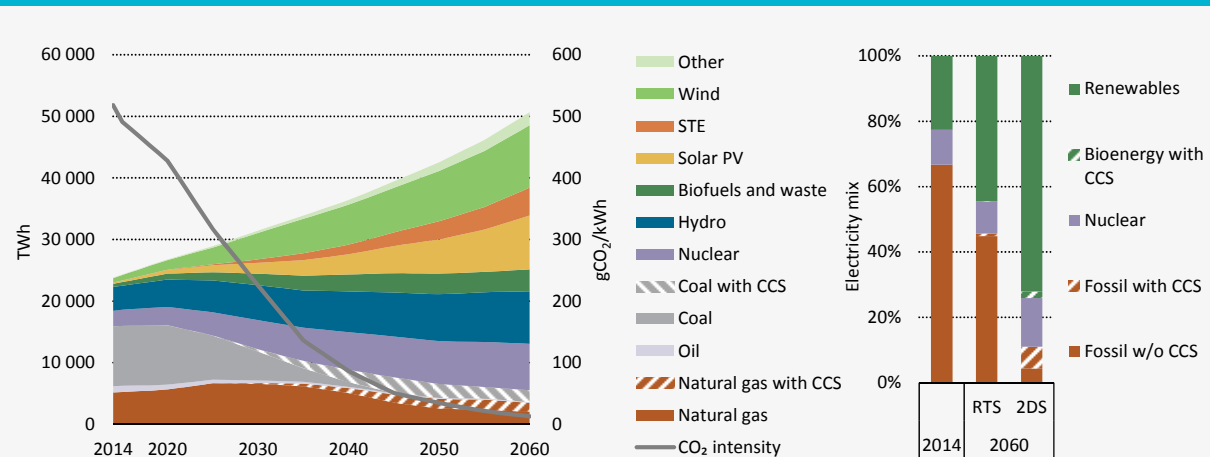
These developments help to sustain recent trends of CO₂ emissions tapering off in power generation, with emissions moderately increasing to around 15 GtCO₂ by 2060 in the RTS. Average global CO₂ intensity halves by 2060 to 254 gCO₂/kWh, relative to 519 gCO₂/kWh in 2014. By 2030, global CO₂ intensity falls to 360 gCO₂/kWh in the RTS, which is only slightly lower than the estimates of CO₂ intensity resulting from the pledges put forward in the Paris Agreement (IEA, 2015b).⁷

Pathway for the power sector in the 2DS

Previous editions of *ETP* have shown that the cost-effective low-carbon transition of the global energy sector requires drastic decarbonisation of the power sector by 2050. *ETP 2017* updates the 2DS and extends the modelling horizon to 2060, which confirms and strengthens the decarbonisation message.

In the 2DS, the global average CO₂ intensity of electricity generation falls from 519 gCO₂/kWh in 2014 to around 35 gCO₂/kWh in 2050 and approaches zero in 2060. Unabated (without CCS) coal-fired generation is almost completely phased out by 2045, a step change compared with the RTS, where it accounts for 26% in 2045. Due to its lower carbon intensity, gas-fired generation without CCS globally increases until 2025, maintaining its average share in the mix with 23% in 2025 compared with 22% in 2014. Afterwards, gas-fired generation is too carbon intensive for the transition, leading to a rapid decline after 2035 and a share of 4% in 2060 compared with 22% in the RTS. The share of unabated fossil fuel generation falls to 4% in the 2DS from 45% under the RTS in 2060, whereas the renewable share (excluding BECCS) increases to 72% in the 2DS from 44% in the RTS in 2060 (Figure 6.4).

Figure 6.4. Global electricity generation in the 2DS



Sources: Data for 2014 from IEA (2016a), *World Energy Statistics and Balances* (database), www.iea.org/statistics/; IEA (2016c), *CO₂ Emissions from Fuel Combustion* (database), www.iea.org/statistics/.

Key point *The share of low-carbon technologies in global power generation is about 96%, and average CO₂ intensity is approaching zero by 2060 in the 2DS.*

In the 2DS, fossil-fuelled power plants with CCS account for 635 GW of capacity in 2060, 7% of global electricity generation. In the coming years, CCS is mostly fitted to coal-fired power plants, notably in China. While initially CCS deployment is driven by coal-fired power plants, notably in China, the increasing CO₂ price in the 2DS favours after 2045 growth in

7. The estimate of CO₂ intensity of 379 gCO₂/kWh in 2030 is based on analysis of the NDC pledges.

gas-fired CCS due to their lower remaining emissions, whereas generation from coal power plants with CCS slightly declines by 2060. “Negative emissions” from BECCS are needed to offset some of the remaining emissions of fossil-fired power generation (with and without CCS). Around half of these remaining emissions are from gas-fired power plants without CCS, which are run to provide balancing services for the growing share of VRE, and about a third are from coal and gas power plants with CCS. These remaining CO₂ emissions are offset by BECCS plants, either with biomass co-firing at coal plants equipped with CCS or dedicated biomass-fired plants with CCS. BECCS in the power sector reaches with a global capacity of 142 GW a share of 2% in the global electricity mix and captures 940 MtCO₂ per year in 2060. Remaining sentence and one paragraph were missing. Please see following two comments. Around 60% of the increase in renewables-based generation between the RTS and 2DS in 2060 is from VRE, which increases the flexibility requirements of electricity systems for their integration. In the 2DS, this can be observed by the declining full-load hours for fossil plants with CCS (e.g. average full-load hours of coal-fired plants with CCS fall from 7 200 hours in the RTS to 6 200 hours in the 2DS in 2060), and by the increase in grid-connected generation for storage, which increases from 88 TWh in 2014 to 900 TWh in 2060. Flexible renewable generation technologies can also support the operation of the electricity system, reflected in the rise in deployment of hydro, biogas and STE plants with thermal energy storage or geothermal power plants in the 2DS.

Challenges for the power sector in moving beyond the 2DS

Given the high degree of decarbonisation achieved in the 2DS, the question arises whether the power sector can do more to move towards the “well below” 2°C target of the Paris Agreement. Two central targets that define this report’s B2DS are a further reduction in the cumulative CO₂ emissions of the energy sector and achievement of net-zero CO₂ emissions globally by 2060.

To better understand the possible contribution of the power sector to the B2DS objectives, it is helpful to look at the CO₂ emissions that remain in 2060 under the 2DS. About 1 070 MtCO₂ of those emissions are from fossil fuel-fired plants, of which around 80% are from unabated power plants and 20% from plants equipped with CCS. (Depending on the capture technology used and economic considerations, plants are designed to capture 85–90% of the CO₂ [Box 6.3]). These CO₂ emissions are almost completely offset by negative emissions (–940 MtCO₂) from BECCS power plants, leaving net emissions of 130 MtCO₂.

Cutting CO₂ emissions below the levels in the 2DS requires increased deployment of BECCS technologies so that the power sector can provide net-negative emissions to offset remaining emissions in other sectors.⁸ A critical factor for the use of BECCS is the availability of sustainable bioenergy in sufficient quantities to fuel these large-scale plants. Contributing the 940 MtCO₂ of negative emissions at BECCS power plants corresponds to a bioenergy input of 11 exajoules (EJ), which equates to 8% of the global primary bioenergy use in 2060 in the 2DS. Bioenergy is also needed in other energy sectors, notably in transport and industry, and is limited by the availability of land for energy crop production and land for food production. Thus, careful assessments are needed of how to best use this limited resource in the B2DS (see Chapter 7).

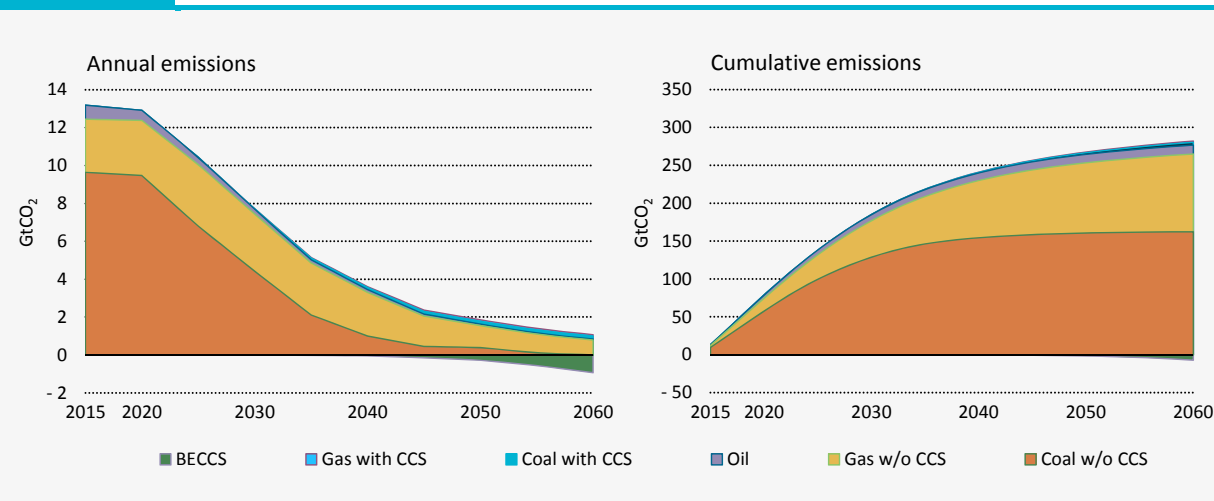
In addition to moving to net-zero emissions in the power sector is the question of how much the power sector can contribute to offsetting emissions in other sectors that are more challenging to decarbonise. In the 2DS, the power sector emits 275 GtCO₂ in the period to 2060, most of which are emitted in the coming two decades, about half by 2025 and 80% by 2035 (Figure 6.5). This indicates that reductions in cumulative emissions in the power sector have to happen in the coming two decades. Recognising the long lifetime of most fossil fuel-fired generation technologies, questions arise as to the viability of existing and planned generation facilities in a carbon-constrained world. Some may need to be retired earlier than their technical lifetime would indicate, raising concerns of stranded assets. Retrofit measures such as CCS or co-firing with biomass may alleviate the need for some early retirements.

8. BECCS technologies also are applied in the industry and fuel transformation sectors for emissions reductions.

Further reductions in cumulative emissions from the power sector can be achieved with BECCS power plants. In the 2DS, BECCS cuts the power sector's annual emissions to almost zero in 2060. However, on a cumulative basis to 2060, the negative CO₂ reductions attributable to BECCS in the 2DS are moderate at 7 GtCO₂, representing 2% of the cumulative emissions reductions in the power sector between the 2DS and the RTS. In the more ambitious B2DS, deployment of BECCS would need to start earlier and proceed at an accelerated rate to have an effective impact on cumulative emissions.

Figure

6.5. Annual and cumulative CO₂ emissions from the power sector in the 2DS, 2015–60



Note: Graph on the right shows cumulative emissions from 2015 over the projection period to 2060.

Key point

Half of the cumulative emissions from the power sector in the 2DS have been emitted by 2025 and 80% by 2035.

As discussed in the buildings, industry and transport chapters, electrification of end uses is an important pathway to reducing their CO₂ emissions, once the CO₂ intensity of electricity generation has been sufficiently reduced. Increased and more diverse use of electricity, if managed smartly through demand response, also can facilitate the integration of a growing share of VRE sources in electricity production. The flexibility of the electricity system requires attention in the 2DS and more so in the B2DS, with a larger share of VRE and its accelerated transition away from today's electricity mix. The following section takes a closer look at these issues and the technology needs of the B2DS in comparison with the 2DS.

Transition to a carbon-neutral power sector in the B2DS

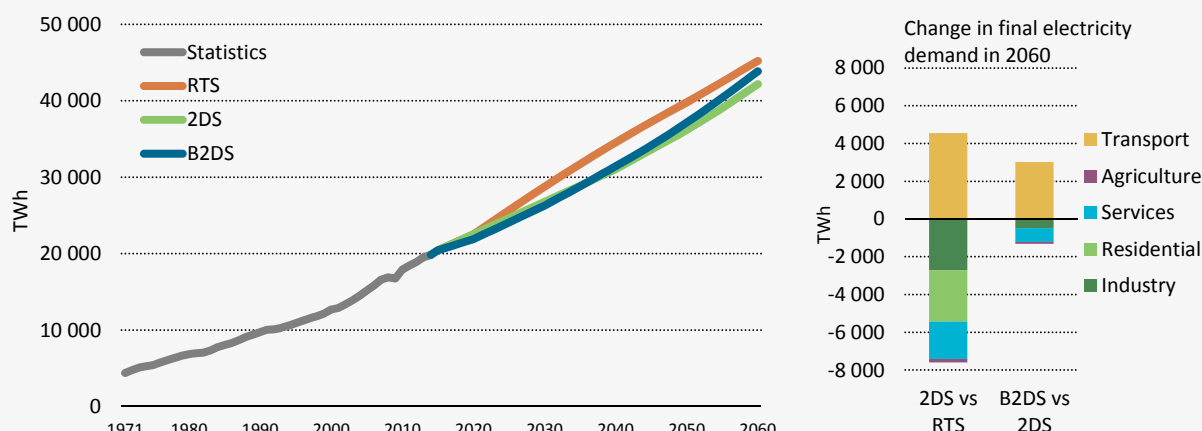
Global final electricity demand in the B2DS in 2060 is almost at the same level as in the RTS; however, this masks significant differences among the scenarios. In the 2DS, final electricity demand is 7% lower than in the RTS in 2060, thanks to efficiency improvements in the buildings and industry sectors, while increased electrification, especially of transport, lifts final electricity demand in the B2DS up to RTS levels (Figure 6.6). Efficiency improvements and electrification have to go hand in hand, with efficiency gains reducing or even offsetting rising electricity demand.

Overall, the average global share of electricity in final energy demand more than doubles in the B2DS, from 18% in 2014 to 41% in 2060, with the largest share (61%) being achieved in the buildings sector. In addition to greater use of electricity in the end-use sectors, electricity use also increases in the transformation sector in both the 2DS and B2DS, mainly

due to increased use of large-scale heat pumps for district heating systems and low-temperature heat delivery to the industrial sector. By 2060, these applications of electricity for heating services account for around 20% of the final heat demand in the B2DS.⁹

Electricity does not have to be drastically decarbonised to benefit from CO₂ reductions through the electrification of heating and transport services. Due to the often much higher efficiency of electric end-use technologies compared with their fossil counterparts, overall CO₂ reductions already occur where electricity continues to retain relatively high CO₂ intensity. For example, replacing a gasoline passenger light-duty vehicle (PLDV) with an EV yields overall CO₂ reductions, if the CO₂ intensity of electricity is lower than 550 gCO₂/kWh, a threshold above the emissions rate of gas-fired power plants.¹⁰ A ground source heat pump for space heating results in CO₂ reductions compared with a condensing gas boiler, if the CO₂ intensity falls below 710 gCO₂/kWh, a level almost achieved by high-efficiency coal power plants today.¹¹

Figure 6.6. Global final electricity demand by scenario



Source: Data for 2014 from IEA (2016a), *World Energy Statistics and Balances* (database), www.iea.org/statistics/.

Key point *Energy efficiency measures reduce global final electricity demand in the 2DS compared with the RTS in 2060, but electrification of transport offsets these gains in the B2DS.*

Strategies for generating electricity in the B2DS

Global electricity generation is fully decarbonised in the B2DS by 2050 (Figure 6.7). The share of renewables (excluding BECCS) reaches 74% in 2060 (compared with 72% in the 2DS), while coal-fired power generation without CCS is phased out by 2040.¹² The share of nuclear, at 15%, is similar to the level in the 2DS. The share of fossil-fuelled generation with CCS is, at 7% in 2060, the same as in the 2DS, but the share of gas-fired plants fitted with CCS in 2060 increases slightly from 3% in the 2DS to 4% in the B2DS. The higher remaining non-captured CO₂ emissions in the B2DS make coal-fired plants with CCS less attractive compared with gas-fired plants with CCS towards the end of the scenario horizon.

Under the B2DS, BECCS power plant capacity reaches around 300 GW in 2060 and offsets the remaining CO₂ emissions from fossil fuel-based plants with CCS. BECCS also provides substantial annual negative emissions (-2.2 GtCO₂) to help offset remaining CO₂ emissions in industry and transport. The share of BECCS in the global electricity mix in 2060 increases

9. Final heat demand refers here to heat produced for sale, but excludes any heat produced on site, e.g. within buildings or industrial premises, for own consumption.

10. Based on an efficiency of 0.37 kWh per vehicle kilometre (kWh/vkm) for a gasoline PLDV and 0.17 kWh/vkm for an EV.

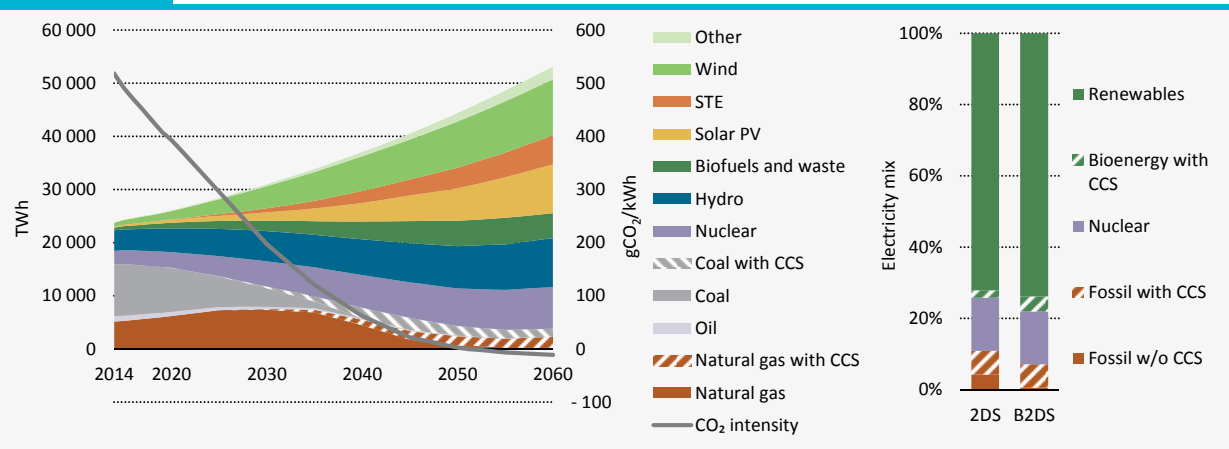
11. Based on an efficiency of 104% for a gas condensing boiler and 370% for an electric ground source heat pump.

12. An insignificant share of 0.5% remains in the global mix in 2060.

from 2% in the 2DS to 4% in the B2DS. As a result, the global average CO₂ intensity of power generation in the B2DS becomes negative after 2050 and is -10 gCO₂/kWh in 2060.

Figure

6.7. Global electricity generation in the B2DS (left) and generation mix in the 2DS and B2DS (right) in 2060



Sources: Data for 2014 from IEA (2016a), *World Energy Statistics and Balances* (database), www.iea.org/statistics/; IEA (2016c), *CO₂ Emissions from Fuel Combustion Statistics* (database), www.iea.org/statistics/.

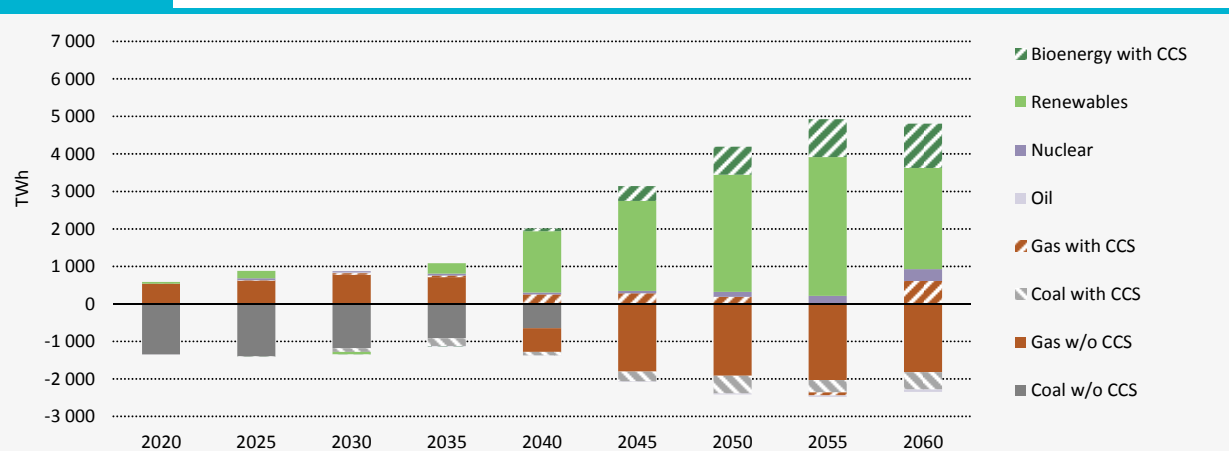
Key point

Global electricity generation is decarbonised by 2050 and is a source of negative CO₂ emissions, as BECCS has a 4% share of the fuel mix in the B2DS.

Electricity demand in the B2DS is initially lower than in the 2DS, but over time the more stringent carbon budget constraint leads to a decline in generation from unabated coal plants and a shift to natural gas without CCS up to 2030 (Figure 6.8). After 2030, rising demand in the B2DS is mainly met by increased generation from renewables, including BECCS after 2045, and to a lesser extent from natural gas with CCS, and nuclear. Generation from gas without CCS and coal with CCS is lower after 2045 in the carbon-constrained B2DS compared with the 2DS.

Figure

6.8. Changes in the global electricity generation mix in the B2DS relative to the 2DS



Key point

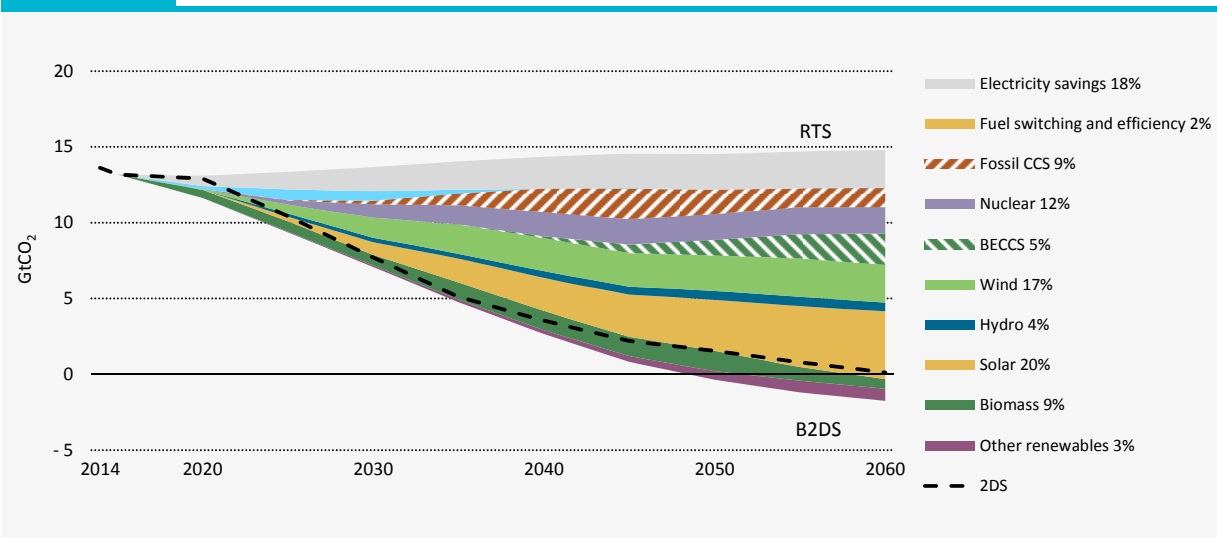
Power generation technologies change to meet the more ambitious decarbonisation targets in the B2DS relative to the 2DS.

In the B2DS, natural gas-fired power plants without CCS are a transitional technology that provides medium-load generation until reaching a peak in 2030. This is a higher level than in the 2DS due to a faster substitution of coal by less carbon-intensive generation options. But after 2030, gas-fired generation without CCS is too carbon intensive in the B2DS context, so the role of gas-fired capacity shifts from electricity generation to the provision of system services such as reserve capacity.

Moving from the RTS to the B2DS entails a drastic reduction in CO₂ emissions from the power sector. Annual emissions in 2060 are 15 GtCO₂ in the RTS versus -1.7 GtCO₂ in the B2DS, and cumulative emissions over the period 2015–60 are reduced by 436 GtCO₂ between the two scenarios, more than half (53%) being from renewables (excluding BECCS) (Figure 6.9). Changes in the end-use sectors, e.g. through efficiency measures and electrification from low-carbon sources, are responsible for around one-sixth of the cumulative reductions in the power sector. Nuclear provides 12% of the cumulative reductions and CCS-equipped fossil fuel plants 9%, although their contribution declines after 2045. Meanwhile, reductions from BECCS plants increase over time, providing 5% of the cumulative reductions between the RTS and the B2DS.

Figure

6.9. Key technologies for reducing CO₂ emissions from the power sector in the B2DS relative to the RTS



Key point

Renewables, excluding BECCS, account for 53% of the cumulative CO₂ reductions in the power sector needed to move from the RTS to the B2DS.

The power sector provides 42% of the overall CO₂ reductions needed to advance from the RTS to the 2DS, and 18% of the overall cumulative CO₂ reductions needed to transition from the 2DS to the B2DS. This reflects the high degree of decarbonisation in power generation achieved in the 2DS, which makes further reductions more costly than options in end-use sectors. Marginal abatement costs in the power sector increase to USD 565/tCO₂ by 2060 in the B2DS, compared with USD 240/tCO₂ in the 2DS (Box 6.1).

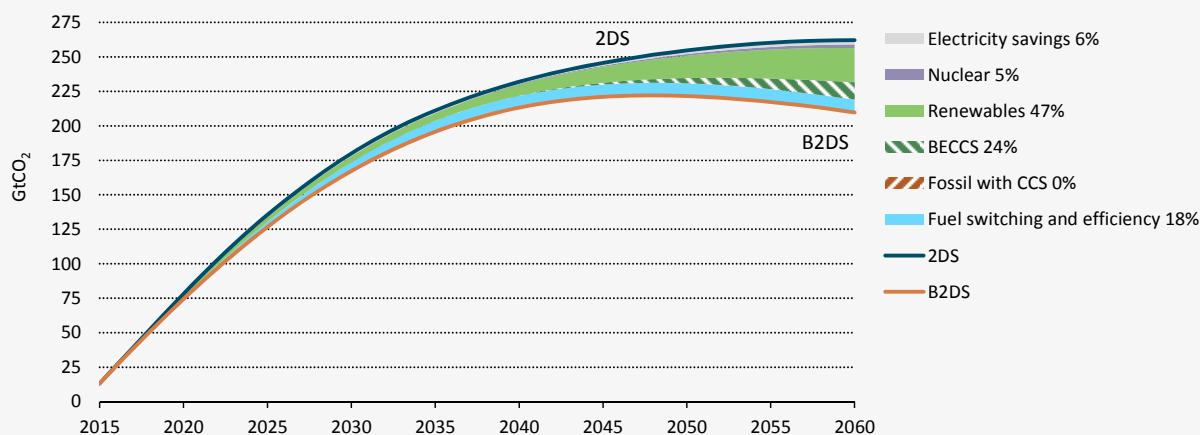
Comparing the evolution of the cumulative CO₂ emissions in the power sector in the 2DS and B2DS also illustrates the complexity of further reductions in cumulative emissions beyond the 2DS (Figure 6.10). Up to 2040, CO₂ reductions (relative to the 2DS) are largely achieved by lower utilisation of the remaining coal capacity and increased generation from renewables and some natural gas. By 2040, cumulative emissions are reduced in the B2DS by 19 GtCO₂ relative to the 2DS.

In the B2DS, natural gas-fired generation without CCS is almost fully phased out by 2060, and coal with CCS is reduced by 35% compared with its peak in the mid-2040s, while generation from BECCS, renewables and nuclear continues to increase. Overall, renewables

provide around half of the cumulative CO₂ reductions between the B2DS and the 2DS, followed by BECCS, which accounts for around a quarter of the emissions reductions. The uptake of BECCS also explains declining cumulative emissions in the B2DS by the end of the scenario horizon.

Figure

6.10. Evolution of cumulative CO₂ emissions from the power sector in the 2DS and B2DS, 2015–60



Notes: Graph shows cumulative emissions from 2015 over the projection period to 2060.

Key point

BECCS accounts for 45% of the cumulative CO₂ reductions of 58 GtCO₂ to transition from the 2DS to the more ambitious B2DS over the period to 2060.

The comparison shows that the potential for early reductions beyond that projected in the 2DS is limited, since it would involve lower utilisation of coal capacity or accelerating the early retirement of coal capacity. Under the 2DS, around 780 GW (45% of coal capacity in 2025) of coal capacity are already decommissioned in the period 2025–40 before the end of their technical lifetime. These early retirements would increase only moderately to 850 GW in the B2DS. Similarly, the economic potential for CCS retrofits is largely exhausted under the conditions and assumptions in the 2DS, with a total coal capacity of 230 GW being retrofitted with CCS by 2060. In the B2DS, this capacity actually declines to 170 GW, since due to their remaining CO₂ emissions and the more stringent carbon constraints, CCS retrofitting of coal plants becomes less attractive than their early retirement.

Significant parts of the cumulative reductions from the power sector in the B2DS have to come from BECCS after 2040, with capacity reaching around 300 GW by 2060 and requiring a build-out rate of up to 16 GW per year. No BECCS power plants currently operate at a commercial scale. In 2016, Japan's Ministry of Environment picked a consortium led by Toshiba Corporation and the Mizuho Information & Research Institute to construct and evaluate a demonstration facility capable of capturing more than 0.18 MtCO₂ per year from the 49 MW Mikawa thermal power plant from 2020 onwards (GCCSI, 2017). The chosen circulating fluidised bed (CFB) combustion technology in combination with post-combustion capture allows the use of various qualities of feedstock, including biomass, coal and wastes.

Biomass integrated gasification combined-cycle (BIGCC) with CCS could be another option, benefiting from a higher efficiency compared with post-combustion capture or oxy-fuelling and thus maximising the use of bioenergy input. BIGCC technology, however, is still at the pilot stage. In the scenario analysis, it has been assumed that BECCS power plants will be available by 2030. Besides the need to demonstrate the technology at a commercial scale, BECCS power plants also face the challenge of linking to CCS infrastructure and ensuring a stable and sufficiently large bioenergy supply chain. For BECCS capacity of 300 GW, an annual bioenergy supply of around 24 EJ would be needed, representing a sixth of total global primary bioenergy supply under the B2DS in 2060.

Box

6.1. Marginal abatement costs in the power sector

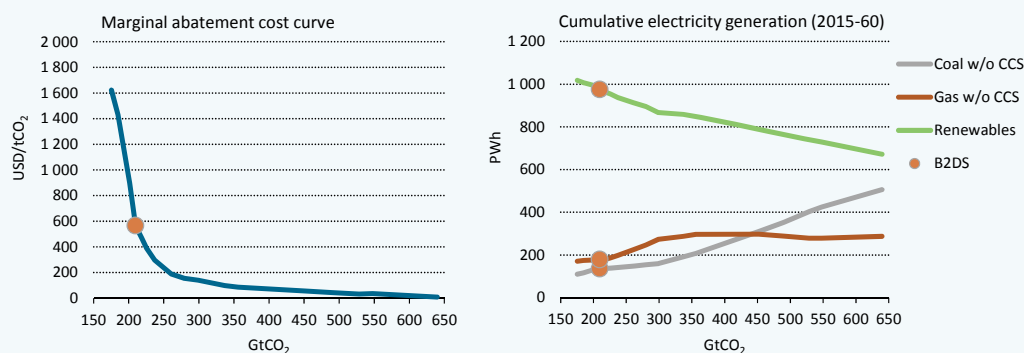
Marginal abatement costs represent the estimated cost of the abatement of the last tonne of CO₂ emissions. They are often used as a reference for the carbon price needed to trigger this abatement, by making the cost of emitting higher than the cost of avoidance. Since marginal abatement costs refer only to the marginal costs of CO₂ avoided, they can be used to compare the cost-effectiveness of mitigation measures across sectors. This is one of the advantages of this indicator and explains its wide usage.

Marginal abatement costs are a function of the reduction target to be achieved. Following a cost minimisation strategy, cheaper mitigation options are initially implemented, before more expensive measures are adopted. Thus, by step-wise increases in the reduction target and identification for each reduction step the marginal abatement cost curve (MACC) can be constructed.

MACCs typically reveal an exponential curve, with rapidly increasing marginal abatement costs with deeper reduction targets. This is shown in Figure 6.11 for the power sector, where the horizontal axis represents the cumulative CO₂ reduction target over the period 2015–60 and the vertical axis the marginal abatement costs in 2060. The technology assumptions (e.g. technological learning) and electricity demand have been kept as in the B2DS. Therefore the marginal abatement costs at the cumulative emissions levels of the 2DS and RTS do not match those actually observed in these two scenarios. Since the amount of bioenergy available has been limited to the quantities used in the B2DS, which constrains further deployment of BECCS, reducing the cumulative emissions of the power sector below the B2DS level mainly leads to an earlier and faster phase-out of coal- and gas-fired electricity generation without CCS. This constraint on bioenergy availability is also one factor in the increase in costs when reducing CO₂ emissions below B2DS levels.

For fossil-based generation with CCS, the shift from coal with CCS to gas with CCS, already observable in the B2DS, is further continued when reducing the CO₂ budget below the B2DS level. This also becomes apparent when looking at the cumulative electricity generation from coal over the period 2015–60. With a reduced carbon budget, the cumulative generation from coal continuously declines to a level of 135 petawatt hours (PWh) in the B2DS, which corresponds to just 14 years of coal-fired generation if kept at 2014 levels. This explains the need to retire unabated coal-fired power plants even earlier and the rapid increase in marginal abatement costs when moving to CO₂ budgets lower than the B2DS.

6.11. Figure: Marginal abatement costs in the power sector in 2060 and cumulative electricity generation as a function of cumulative CO₂ emissions, 2015–60



Notes: The MACC has been calculated based on the electricity demand and the technology costs in the B2DS; as these input data are different in the 2DS and RTS, one cannot determine the marginal abatement costs of the 2DS and RTS from this curve. Marginal abatement costs for the power sector in the 2DS are USD 240/tCO₂ in 2060. Cumulative emissions and generation refer to the period 2015–60

Key point: Marginal abatement costs rapidly increase when approaching the CO₂ budget of the B2DS or going below it.

Investment needs

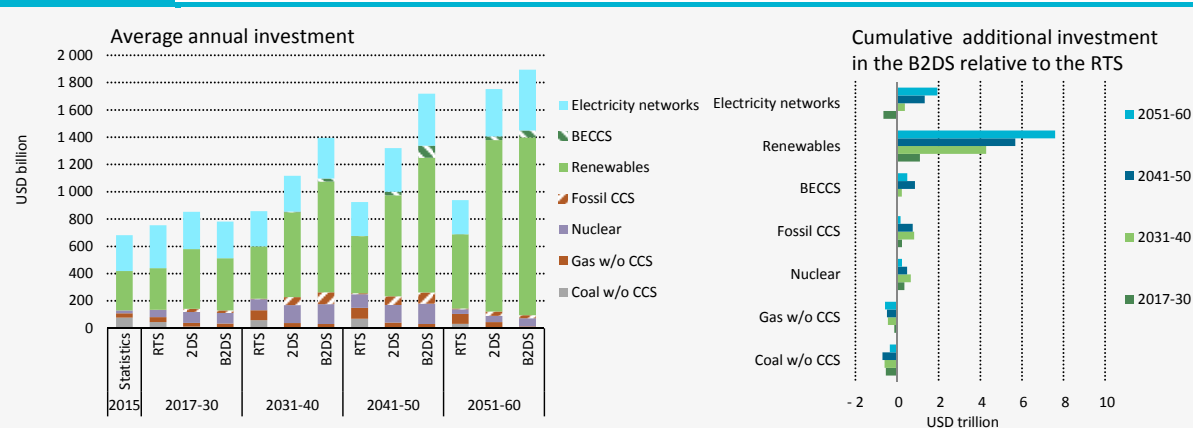
Achievement of the decarbonisation levels set out in the B2DS requires USD 61 trillion of investment in the power sector between 2017 and 2060, an increase of USD 6.4 trillion over that needed in the 2DS and USD 23 trillion more than in the RTS. This means that the additional investment needs of the B2DS relative to the RTS are almost 40% higher than those of the 2DS. Average annual investment in the B2DS is USD 1.4 trillion from 2017 to 2060, which is more than twice the investment level of USD 682 billion for power generation in 2015 (Figure 6.12).

Up to 2030, the additional cumulative investment in the B2DS compared with the 2DS is USD 865 billion lower than in the 2DS due to lower electricity demand. After that, higher investment levels are required, largely for renewables to further reduce CO₂ emissions, but also to meet rising electricity demand related to the greater electrification of end uses. Final electricity demand in 2060 in the B2DS is 9% higher than in the 2DS (Figure 6.6).

About 65% of the cumulative investment in the 2DS and the B2DS is needed in the power sectors of non-OECD countries. This is slightly higher than the current trend in which non-OECD countries accounted for almost 60% of the investment in the power sector in 2015. Together three countries – China, India and the United States – account for almost half of the global investment needs of the power sector in both scenarios.

Renewables energy investment dominates in all three scenarios. In the B2DS, renewables (excluding BECCS) and storage account for 59% of the cumulative power sector investment in the period 2017–60, with solar PV and STE responsible for more than one-quarter.¹³ Investment in transmission and distribution (T&D) networks accounts for 28%, followed by wind power with 19%, nuclear with 8% and CCS with 6%. Compared with the RTS, cumulative investment needs for low-carbon technologies, i.e. renewables, nuclear and CCS, are a combined USD 24 trillion higher in the B2DS, whereas investment in fossil-fired power plants without CCS is USD 3.8 trillion lower.

Figure 6.12. Investment needs in the power sector



Notes: gas includes investment in oil-fired generation. Renewables include investment in electricity storage of USD 1.2 trillion in the 2DS and USD 1.7 trillion in the B2DS.

Source: Data for 2015 from IEA (2016e), *World Energy Investment 2016*.

Key point

Cumulative investment of USD 61 trillion is needed for power generation in the B2DS, with annual investment in the last decade almost tripling compared with 2015.

13. Renewables and storage represent 46% of the cumulative investment in the RTS and 59% in the 2DS.

Key technologies for the transition

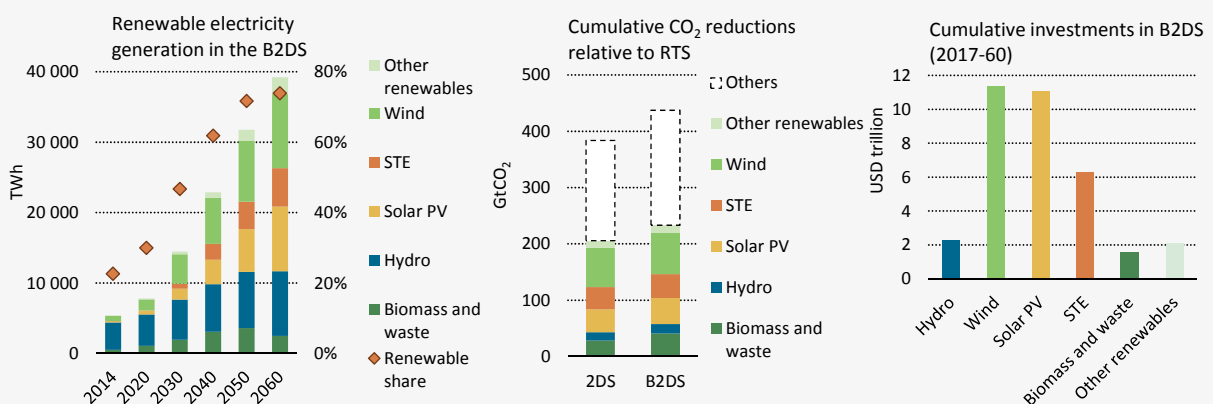
The key technologies for the power sector’s transition to the B2DS are discussed in this section. They are considered in terms of deployment needs, contribution to emissions reductions, investment needs and technology development status.

Renewables

Power generation technologies that use renewable energy sources are the backbone of the transition to a decarbonised electricity system. In the 2DS, the share of renewables in the global electricity mix increases from 23% in 2014 to 72% by 2060 (excluding BECCS). With its more ambitious reduction target, the renewables share increases to 74% in the B2DS (Figure 6.13). Of this, solar PV and hydro each account for about 9 000 TWh of electricity production in 2060, of a global total of 53 100 TWh. Wind power produces 10 500 TWh, which is more than the combined total of electricity produced in 2014 in the world’s two largest electricity-generating countries, China and the United States. Global installed solar PV capacity reaches 4 400 GW in 2050 and 6 700 GW in 2060 under the B2DS, while global wind capacity expands to 3 400 GW by 2050 and further to 4 200 GW by 2060. Increased electricity demand of 20% over the period 2050–60 is one driver for the capacity deployment, notably in the industry and transport sectors. Large parts of the increased demand for electricity fortunately occur in regions with relatively good solar potential, such as India, Africa, the Middle East and parts of the United States, which facilitates increased growth in solar PV capacity.

Figure

6.13. Indicators of the role of renewables in power generation in the B2DS



Source: Data for 2014 from IEA (2016a), *World Energy Statistics and Balances* (database), www.iea.org/statistics/.

Key point

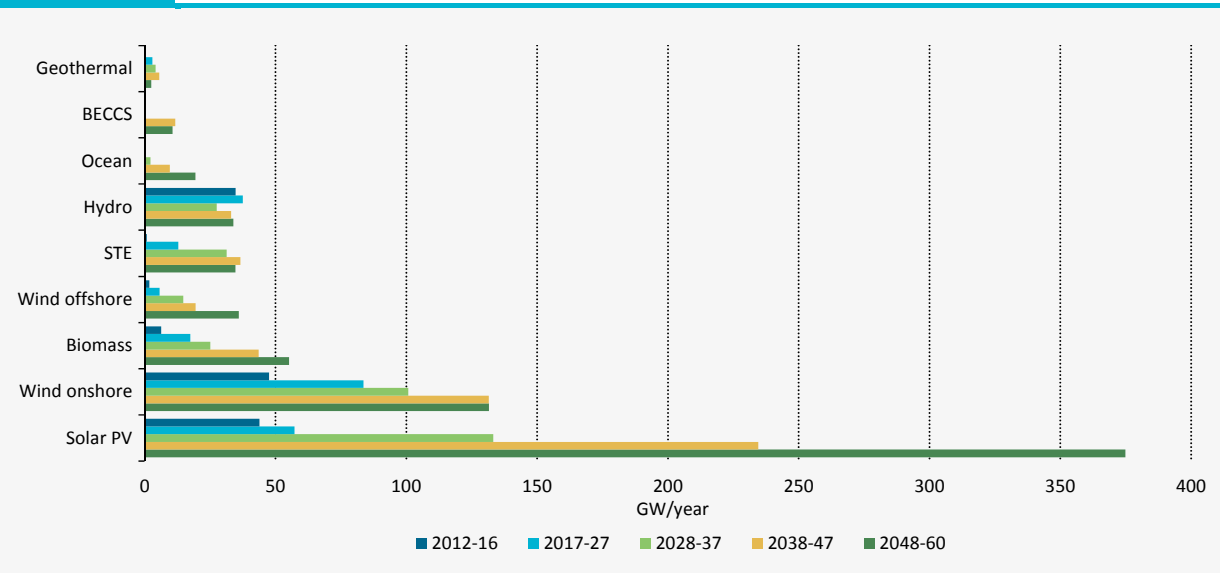
Renewables account for 53% of the cumulative CO₂ reductions of the power sector in the B2DS and require 79% of the cumulative investment needs for power generation.

Construction rates for renewables have to be accelerated to reach these levels of deployment in the B2DS. The largest capacity additions are needed in solar PV, where average capacity additions per year have to more than double from 57 GW per year over the period 2017–27 to 130 GW over the period 2028–37, and almost 235 GW per year in the decade 2038–47. Solar PV reaches a deployment level of 375 GW per year in the final years of the projection period (2048–60). The high deployment rates in the later years are also driven by the need to replace solar PV installations that are reaching the end of their lifetime. Accelerated deployment of other renewable energy technologies is also needed in the B2DS, although the annual build-out rates are lower, e.g. for onshore wind at a rate of

132 GW per year in the period 2048–60 (Figure 6.14). Due to learning effects, the massive deployment of solar PV leads to reductions in average specific investment costs for utility-scale PV of 67% by 2060 compared with 2015, and learning effects cut average specific investment costs by 18% for onshore wind power.

Figure

6.14. Deployment rates for renewables-based power technologies in the B2DS



Note: Hydropower does not include pumped storage.

Sources: Data for 2012–16 from IEA (2016d), *Medium-Term Renewable Energy Market Report*; Platts (2016), *World Electric Power Plants Database*.

Key point

The B2DS requires rapid acceleration in the deployment of renewables-based power technologies compared with current average annual additions.

The new capacity additions for renewables-based power technologies translate into cumulative investment needs of USD 34 trillion, accounting for 78% of the total investment needs in power generation in the B2DS (59% of the entire power sector including electricity networks). The largest investments are in wind and solar PV, each with investment of USD 11 trillion over the 2017–60 period. Average annual investment in renewables is USD 1 045 billion, which is 3.5 times the investment level (USD 288 billion) in 2015, and compares with average annual investment in renewables of USD 734 billion in 2DS and USD 405 billion in the RTS. 70% of the cumulative investment in renewables-based power technologies in the B2DS occurs in non-OECD countries.

As a result of this rapid deployment, renewables provide more than half of the cumulative CO₂ reductions needed in the power sector between 2015 and 2060 to move from the RTS to the 2DS (54%) or to the B2DS (53%). In the context of the overall energy system, renewables in electricity generation provide 23% of the cumulative reduction of 1 020 GtCO₂ needed for the transition from the RTS to the B2DS between 2015 and 2060.

Accelerated deployment of renewables results in emissions reductions in the power sector. It also involves finding approaches to incorporate the variability of sources such as PV and wind in a manner to ensure effective operation and reliability of electric power systems. In the B2DS, the global average annual share of VRE increases from 4% in 2014 to 18% in 2030 and doubles to 37% in 2060 (with variations from 14–47% across the regions considered in the model analysis). Electricity systems need to be flexible enough to balance the variability of renewables-based generation, for example when the wind is insufficient to operate turbines, or when solar PV produces more electricity than being demanded locally

and needs to be curtailed (or transferred to another demand centre or stored). Various strategies exist to increase the flexibility of electricity systems, and depending on local and regional circumstances may include adjusting the output of other generation on the system, employing storage technologies, tapping demand-side response measures to manage load and creating larger balancing areas through interconnected system (IEA, 2014).

Natural gas-fired power plants have operational flexibility that allows rapid upward and downward adjustment to their generation, which adds to flexibility of the electricity system on the generation side. In the 2DS in 2060, natural gas without CCS accounts for 10% of global installed generation capacity but only 4% of electricity generation. Running at low full-load hours (around 1 100 hours on average in the 2DS and 200 hours in the B2DS), these gas plants balance the VRE generation and also provide reserve capacity. This is a significant change to their operation before 2040 in the 2DS and B2DS, where gas-fired power plants without CCS run at full load of around 3 000 hours and contribute to emissions reductions by replacing coal-fired generation. After 2040, electricity from gas plants without CCS is too carbon intensive in the context of the 2DS and B2DS for generating electricity, but can still provide system services for the integration of VRE.

Electricity storage is an important option. In the 2DS and B2DS, global storage capacity starts to rise rapidly when the share of VRE exceeds 25% in the period 2035–40. In the 2DS, global storage capacity increases from 153 GW in 2014, when it is mainly used for load following, spinning reserve or for arbitrage between peak and off-peak prices, to 400 GW in 2060, when storage is largely used for balancing services to better align VRE generation with demand. In the B2DS, storage capacity needs to rise further to 450 GW.

Demand-side response measures also provide power system flexibility in the low-carbon scenarios. In the 2DS, demand response in the transport, industry and buildings sectors (e.g. EVs, compressed air storage in industry, heat pumps in buildings) as well as the transformation sector (e.g. large-scale heat pumps or electrolyzers for hydrogen production) shifts electricity loads on the order of 320 GW in 2060, while in the B2DS this demand response increases to 410 GW. At times of surplus electricity production, demand response options with low specific additional investment costs are attractive for shifting demand to hours with surplus supply (e.g. electric resistance boilers in district heating systems), while capital-intensive technologies can provide downward regulation at times of solar and wind scarcity (e.g. electrolyzers or heat pumps). Even with these flexibility measures, curtailment of 2% of global VRE generation is unavoidable in the B2DS in 2060.

It should be highlighted that VRE technologies can be designed and integrated in a system-friendly way. A mix of solar and wind deployment in a suitable region can result in a more stable generation profile than using the individual technology by itself, increasing the combined value for the electricity system. For example in Germany, wind conditions are better during winter than summer months, while solar insolation reaches its peak in the summer months.

Considering specific technologies, wind turbines can be designed to have a favourable production profile and to have good system integration properties, which increase their economic value (Hirth and Müller, 2016). Examples include turbines characterised by higher hub heights and a larger rotor area per specific power output, which enables higher electricity generation in times of low wind speeds, thus increasing the average capacity factor.

PV systems can be designed to better match supply and demand. Instead of facing solar panels to the equator to maximise annual output, they can be oriented in such a way to maximise output during certain times of the day. For example, west-facing panels could provide electricity in the last few hours of daylight in countries with afternoon or early evening peaks. This would require appropriate time-of-delivery (TOD) price signals for the owners of the PV system. Tracking systems, either single-axis to follow the sun or dual-axis to also adjust the tilt angle, could also benefit from TOD prices. Another option, becoming more attractive with falling module costs, could be to design fixed-tilted PV systems with panels at different orientations, thus delivering a more regular output throughout the day (IEA, 2015a).

In addition, flexible renewable technologies, such as hydropower dams, biomass and STE power plants, can support the integration of VRE. STE plants, if equipped with thermal storage, can complement electricity generation from solar PV in sunny regions by shifting

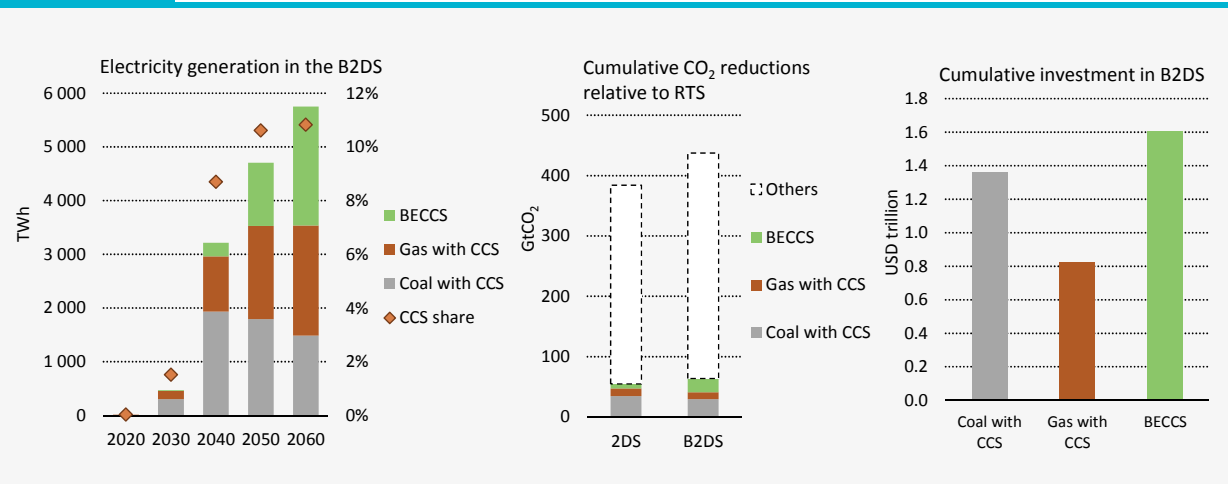
electricity generation to after sunset, as evening hours often coincide with demand peaks. In the B2DS, globally around 24 000 gigawatt hours (GWh) of thermal storage are included in STE plants in 2060, which allows the shifting of the operation of the STE capacity of 1 275 GW by around six to seven hours.¹⁴ Biogas-fired power technologies, such as gas engines, gas turbines or combined-cycle gas turbines, can also provide flexibility and system services. In the B2DS, around 580 GW of biogas-fired capacity, running at average full-load hours of 1 400 hours, support the operation of the electricity system in 2060.

CCS

CCS has made important advances in recent years; two large-scale power generation CCS-equipped projects are operational, one in the United States and one in Canada, with a third under construction in the United States. Nonetheless, CCS currently plays only a minor role in electricity generation, accounting for less than 0.01% of power generation in 2016. Moreover, CCS capacity in the pipeline does not meet the levels required to achieve the 2DS and B2DS targets in the near term, emphasising the need for greater policy efforts and RD&D.

A more detailed description of the various capture routes for CCS and CO₂ storage is provided in Chapter 8. This section focuses on CCS in power generation and in particular on biomass technologies that may be equipped with CCS (BECCS).

Figure 6.15. Indicators of the role of CCS in power generation in the B2DS



Key point *CCS provides 20% of the cumulative CO₂ reductions in the B2DS (relative to the RTS), with BECCS accounting for more than 40% of the cumulative reductions from CCS and for half of CCS investment.*

CCS in power generation is deployed rapidly in the 2DS from 2030 onward, reaching 780 GW of installed capacity in 2060, of which 140 GW are BECCS technologies. Deployment in the B2DS is even higher, reaching 950 GW in 2060, of which 300 GW are BECCS. Power generation with CCS represents 9% of total generation in 2060 in the 2DS and 11% in the B2DS. Fossil fuel-based CCS accounts for the vast majority of the CO₂ captured in the 2DS in power generation, at first mostly from coal-fired power, but in later years also increasingly from gas (Figure 6.15). However, with CO₂ capture rates of 85–90% for fossil-fired CCS power plants, not all CO₂ emissions are captured, which means that 5.4 GtCO₂ of residual emissions are still emitted from fossil-based power plants equipped

14. Solar field, thermal storage and turbines are modelled separately, so that the configuration of the STE capacity in different model regions is determined endogenously.

with CCS in the 2DS on a cumulative basis to 2060. To reduce residual emissions from CCS and move towards net-negative emissions in the power sector in the B2DS, different pathways can be taken, including increasing CO₂ capture rates (Box 6.3), switching from coal-fired to gas-fired power plants with CCS (which have lower residual emissions), and increasing the share of BECCS power plants. In the period to 2060, BECCS in the power sector provides 6% (15 GtCO₂) of the cumulative reductions across all sectors required to move from the 2DS to the more ambitious B2DS.

In order to help achieve negative emissions, CCS may be combined with various biomass power generation technologies, which are briefly characterised in this section.

Biomass co-firing with coal

Under this process, biomass is added to the combustion of coal either directly or indirectly. Direct co-firing is a commercial technology where biomass is blended, milled and burned with coal, or it is ground in a biomass mill or modified coal mill and then blended with pulverised coal. The blended substance is either fed to the burners directly or through a dedicated biomass burner, or injected directly into the boiler. The maximum share of biomass is relatively limited in direct co-firing for existing boilers, typically around 10%, due to prohibitively high maintenance costs and operating expenditure at higher shares. For newly built plants, these costs can be reduced through appropriate design and planning.

Indirect co-firing involves the dedicated conversion of biomass in a fluidised bed gasifier that produces a combustible gas with low calorific value, which can be injected into the boiler of an existing coal power plant.

Whether using direct or indirect biomass co-firing, the higher the ratio of biomass to coal, the lower the CO₂ emissions emitted. The possible ratios depend on the characteristics of the biomass and the power plant design. Achieving elevated co-firing ratios has proved difficult for several reasons, including the fact that biomass has lower energy density and a different inorganic composition to hard coal, it is vulnerable to biodegradation, and it is hydrophilic in nature. Power plant modifications are often required to accommodate biomass, which necessitates investment and higher costs. Investment costs for biomass co-firing are inherently site-specific and it is difficult to obtain reliable cost data. They are estimated to range between USD 700 per kilowatt (kW) to USD 1 000/kW for direct co-firing and USD 3 300/kW to USD 4 400/kW for indirect co-firing (IEA/NEA, 2015). To overcome these challenges and significantly increase the biomass co-firing share, certain plants are using thermal pretreatment technologies that increase the homogeneity, brittleness and/or energy density of biomass.

Dedicated biomass firing

It is possible to operate power plants exclusively using biomass. This typically takes place in purpose-built biomass plants, in small modified pulverised coal boilers or in medium-sized co-generation plants previously fired with coal or lignite, often using CFB combustion technology. The size of dedicated biomass plants is limited by the availability of biomass and the transport costs associated with the feedstock. Costs of coal plant conversion to biomass firing vary substantially. They are estimated to be around USD 600/kW for plant conversion using wood pellets and about USD 1 700/kW using wood chips (DEA, 2016). Recent examples of coal-fired power plant conversions to biomass are the Atikokan Generating Station in Canada, which switched from coal to the use of wood pellets. Further examples of fuel switching to biomass include the Lynemouth project in the United Kingdom and the Gardanne project in France, which will use CFB technology. CFB has the advantage of being flexible with regard to the biomass feedstock. CFB plants are usually smaller than utility boilers and typically located in close proximity to urban areas or industrial facilities in order to supply heat.

The same capture technologies that are available to coal-fired power combustion plants are also suitable for biomass co-firing and dedicated biomass firing, i.e. post-combustion capture or oxy-fuel combustion. Co-firing biomass is assumed to not have significant impact on post-combustion capture.

Biomethane for power generation

Biomethane obtained from fermentation and upgraded by CO₂ separation (and storage) or gasification-based biosynthetic natural gas can be used as fuel in gas-fired power technologies. One of the benefits is that there are virtually no co-firing ratio limitations; however, the availability of biogas may ultimately restrict its role in power generation. Additional costs for CCS due to the use of biomass are limited as conventional post-combustion capture technology can be applied.

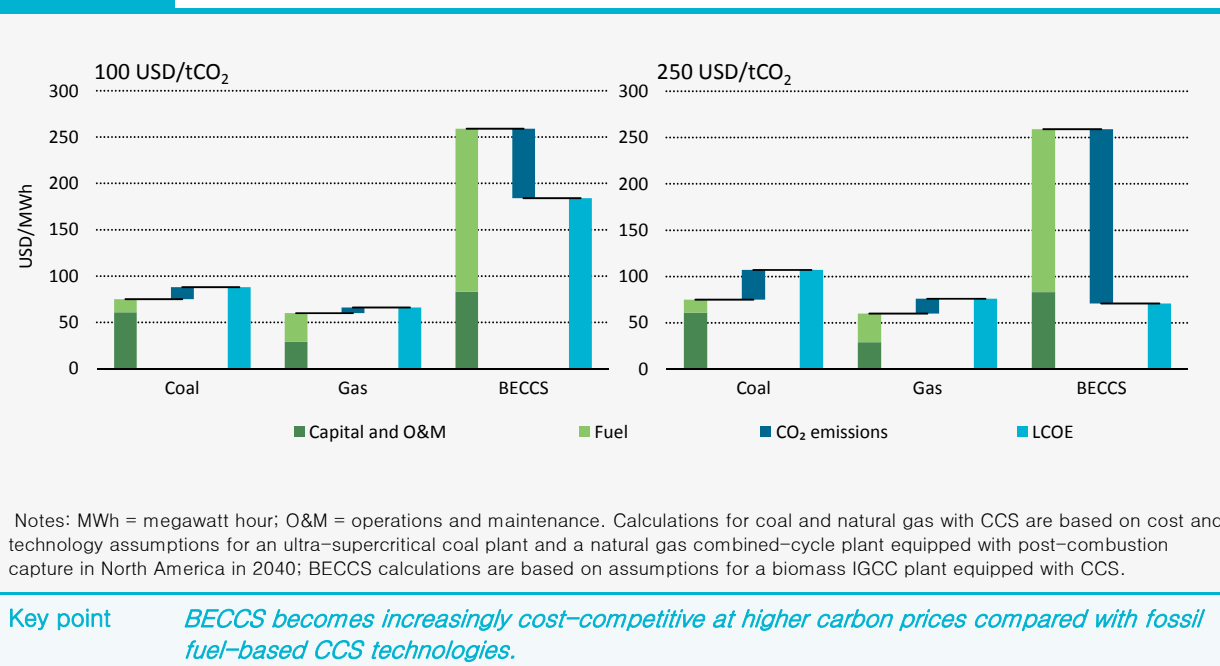
Biomass gasification

Gasifying biomass allows for a large variety of biomass feedstocks to be used. Efficiencies of dedicated biomass in IGCC plants are estimated to be in the 35–44% range for plant sizes up to about 250 megawatts electric. There are several demonstration projects for biomass integrated gasification with CCS, but no commercial project is in operation yet. Pre-combustion capture technology is currently considered the most promising option for biomass gasification, offering the potential to benefit from experiences gained from IGCC power plants with pre-combustion capture.

On a levelised cost of electricity (LCOE) basis, BECCS is generally more costly at low and moderate carbon prices than fossil fuel-based CCS due to higher investment costs, lower efficiencies and the higher cost of biomass compared with coal- or gas-fired plants with CCS. With stronger climate ambition and higher carbon prices, BECCS becomes increasingly economically interesting because of the monetisation of negative emissions (Figure 6.16).

Figure

6.16. Impact of carbon prices on the levelised cost of CCS

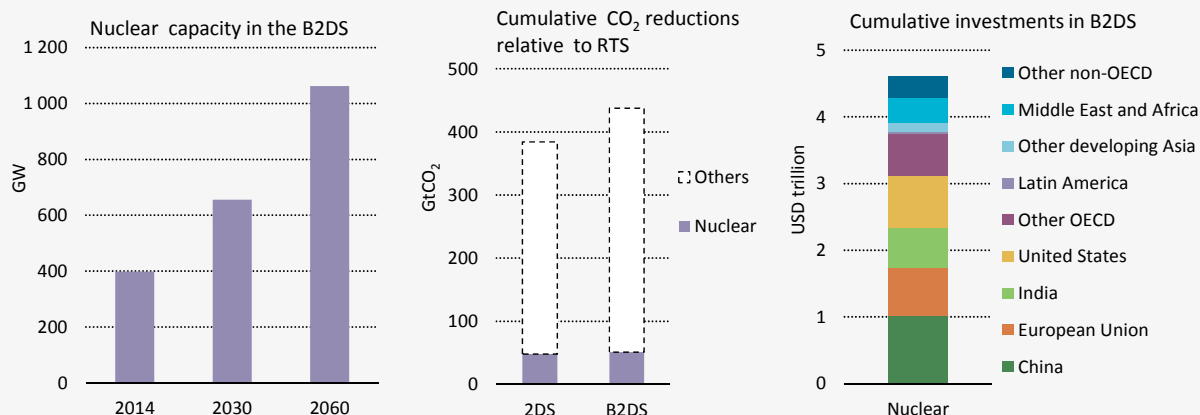


Nuclear power

Today, nuclear power is providing low-carbon electricity at scale, with an 11% share of the global electricity generation mix and installed capacity of 408 GW in 2015, second only to hydropower in terms of generation. However, nuclear power faces various challenges: not only public concerns about safe operation and questions of long-term disposal of spent nuclear fuel, but also economic challenges, since it is a very capital-intensive technology. Despite these challenges, nuclear roughly maintains its current level with a share of 10% of the generation mix in 2060 in the RTS.

Nuclear power benefits from the stringent carbon constraint in the B2DS, with its generation share increasing to 15% by 2060 and installed capacity compared with today more than doubling to 1 062 GW by 2060. Of this, 64% is installed in non-OECD countries, with China alone accounting for 28% of global capacity (Figure 6.17). With only 65 GW of the capacity existing in 2016 still operating in 2060, achieving this long-term deployment level will require construction rates for new nuclear capacity of 23 GW per year on average between 2017 and 2060. This is more than twice the capacity of 10 GW that was added in 2015 and 2016, which represented the largest annual nuclear capacity additions over the last 25 years. In some years in the period 2035–40, construction rates may increase to 33 GW per year, comparable to the historic peak of 34 GW connected to the grid in 1984.

Figure 6.17. Indicators of the role of nuclear in power generation in the B2DS



Source: Data for 2014 from IAEA (2017), *Power Reactor Information System*.

Key point *Global nuclear capacity more than doubles in the B2DS and provides around 12% of the cumulative CO₂ reductions to move from the RTS to the B2DS.*

In addition to being a recognised low-carbon electricity source, nuclear energy is also a low-carbon source of heat and can play a relevant role in decarbonising other parts of the energy system where heat is being consumed, e.g. district heating, seawater desalination, industrial production processes and fuel synthesis. These applications have not been considered in these *ETP* scenarios since they are very site-specific, such as district heating, or experience so far is limited to a few small-scale projects, as in the case of seawater desalination.¹⁵

According to the International Atomic Energy Agency (IAEA), the provision of nuclear-generated heat has the benefit of experience of more than 750 reactor operation years from 74 reactors, mainly for district heating and desalination application (Khamis, 2014). Industrial process heat applications with nuclear-produced steam have also been developed, such as for a paper mill in Norway, a cardboard factory in Switzerland, heavy water production in Canada and a salt refinery in Germany.

The use of nuclear energy for co-generation of heat is not a new development, and the technology has been in use for several decades. One of the first applications was the Ågesta reactor in the suburbs of Stockholm, which provided district heating (up to 70 MW of heat) between 1964 and 1974. Switzerland also has an operating district heating system associated with the Beznau nuclear power plant. This has operated for more than 25 years and provides heat to 15 000 local residents, with an annual saving of 46 MtCO₂. District

15. In the current *ETP* model, desalination is not modelled separately and is part of energy demand in the services sector.

heating feasibility studies have been conducted to assess the potential for connecting existing or new nuclear power plants to existing district heating systems in large cities such as Paris, Lyon and Helsinki. Economic analysis has shown that in spite of the cost of building a new heat transport system over long distances (80–100 kilometres [km]), nuclear district heating systems could be competitive with existing solutions and provide substantial benefits through reduced CO₂ and air pollution emissions (Jasserand and Devezeaux de Lavergne, 2015).

Seawater desalination facilities using nuclear plants are in use in Japan, the United States, India and Kazakhstan. New projects are under discussion in the Middle East. Today, the combined seawater desalination capacity in the Persian Gulf exceeds 22 Mt of water per year, about half the global desalination capacity, and is almost completely based on burning oil and gas. Several technical advantages are available from co-locating a power plant and a desalination plant, such as reduced overall water intake, reduced thermal releases or better dilution of brine. Currently, Saudi Arabia is carrying out a feasibility study with Korea on the development of the SMART small modular reactor with desalination capacities. Egypt is planning to build a nuclear power plant with Russian assistance that could be coupled to a desalination plant. Jordan is planning a nuclear power plant that could serve a desalination plant at a different location.

In the longer term, nuclear energy could also be used for producing hydrogen. Today, hydrogen is mainly produced using steam methane reforming from natural gas, which releases CO₂ emissions. Hydrogen can be produced from nuclear power through electrolysis, with the efficiency of the electrolysis improving the higher the temperature, or through thermochemical water splitting. To provide the heat for these processes at the necessary temperature level (800–1 000°C), high-temperature gas-cooled reactors (HTRs) are needed. The technology has been developed at a pilot scale, with reactors being operated in the past in the United Kingdom, the United States and Germany, but their development has suffered from various problems and setbacks. China is currently constructing a modular reactor, HTR-PM (High-Temperature Reactor-Pebble-bed Modules), as an industrial prototype. The two HTR-PM reactors, with a combined electric capacity of 210 MW, are expected to start commercial operation by the end of 2017, although initially for electricity generation only. In Japan, a very high temperature test reactor has operated with an outlet temperature of 950°C since 1998, with plans to connect it to a hydrogen production unit in the coming years. In Korea, the steel producer POSCO is aiming to introduce hydrogen by 2021 as a reducing agent in the steel production process, with the hydrogen coming from nuclear power.

Electricity system infrastructure in the B2DS: Supporting the transformation to a low-carbon power sector

With over 50 million km installed worldwide (about the distance to Mars), the electricity network is one of the most complex infrastructures in existence. Traditionally it has been managed in a unidirectional manner, with electricity generated in large-scale production plants and supplied to consumers with little participation from the demand side.

Electricity networks have become more technically advanced over the years, and data flows have doubled every two years. The costs of remote sensing devices and computing have both reduced on average by half every 30 months over the past 20 years. Applying the same learning rate to the efficiency of a 1996 PLDV would have resulted in a range of 200 000 miles by 2016. The transition to a decarbonised energy system requires advances to develop “smart grids”, both new and existing, to effectively incorporate equipment and techniques to make it possible to monitor and control demand rapidly and at large scale, and options to make demand flexible and to match supply dynamically.

In addition to reducing carbon emissions from generation, the electricity system networks have an importation role in the transition towards the objectives behind the B2DS. Certain sectors have begun to see significant transformation in this sense: digitalization is gradually

changing traditional utility business models; ICT companies are making inroads in energy markets; and increased asset utilisation and operational optimisation are reducing costs for large energy companies, ranging from oil and gas to electricity network owners and operators. However, achieving the B2DS would require a much higher turnover of electricity infrastructure than seen at present (in some cases tripling current replacement rates) and a deep technological shift towards digitalisation, flexibility from demand-side response measures and distributed energy resources.

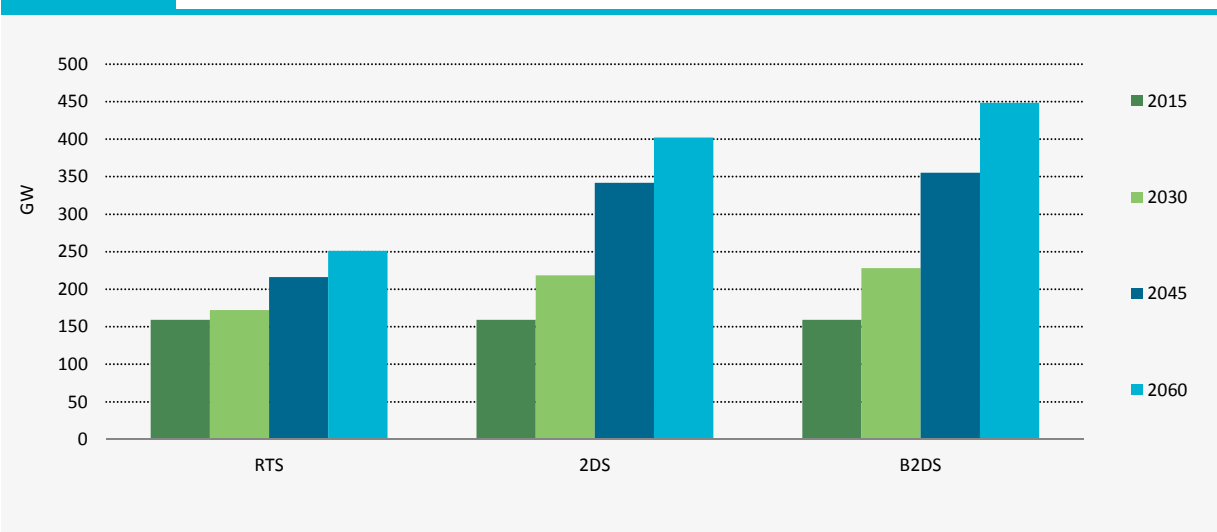
Electricity system infrastructure consistent with achieving the B2DS rests on three key pillars. Their technological challenges and opportunities are discussed in the following sections:

- **Storage:** Accelerate deployment of storage, including behind the meter, which would significantly alter the outlook for battery technology deployment and manufacturing.
- **High-voltage transmission infrastructure:** Transform high-voltage electricity networks to support inclusion of greater distributed generation and interconnections.
- **An active demand side:** Much greater participation of the demand side is needed, which requires advanced metering infrastructure, load disaggregation from EVs and other options.

Storage

Accelerated deployment of storage is a key enabler of electricity infrastructure in support of the transition to a low-carbon power system envisaged in the B2DS. Strong growth in storage technologies has recently been driven by cost and performance improvements in battery technology, better understanding of business models, and regulatory changes in individual jurisdictions. This growth, however, builds from a small base of slightly more than 150 GW of pumped hydro storage (a technology expected to continue to grow at historic growth rates) and just over 1 GW of all other storage technologies combined. The trend in storage capacity growth is on track as against the 2DS due to positive market and policy effects, but an additional 45 GW of capacity is needed by 2050 in the B2DS, which is 180 GW more than in the RTS.

Figure 6.18. Deployment of storage technologies in the scenarios



Key point *The lion's share of future storage will use technologies other than pumped hydro.*

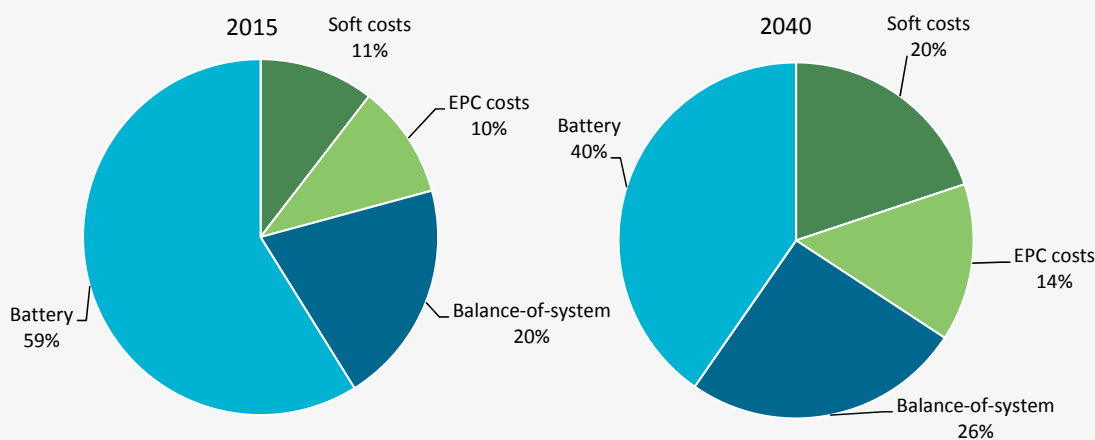
In the B2DS, batteries are the key storage technology due to cost reductions and the ability to rapidly ramp up manufacturing capacity. While pumped hydro accounted for 96% of storage in 2016, practically all of the new storage capacity across all scenarios will be from technologies other than pumped hydro, led by battery storage (Figure 6.18). The challenge

for the higher storage needs of the B2DS is one of accelerating battery storage deployment and cost cutting, while pushing advanced battery technologies towards rapid commercialisation. Further policy action is needed to tackle challenges to deployment, including continued regulatory reform and developing balanced approaches to deployment of behind-the-meter storage options.

More precisely for batteries, a cost target of USD 70/kWh would need to be reached by 2050. This is just below the estimated base cost for current battery technologies – a key challenge for both the technology itself and its manufacturing throughput. To reach this level at the speed required, two questions remain: what is the likely technological pathway that could deliver this target; and are there any potential issues preventing scaling up at the necessary deployment rates?

The current generation of batteries relies largely on lithium-ion, with nearly 90% of utility-scale stationary energy storage capacity in 2016 based on lithium-ion chemistries. This has led to concerns over the supply of lithium and other metals used in battery components (Box 6.2). Other technologies, such as sodium sulphur and flow batteries, are being tested at demonstration scale. Depending on the market, balance-of-system (BOS) and soft costs for these projects have been shown to be a significant stumbling block. As with solar PV, much of the cost reduction in coming years will come from optimising these components. Midway through the outlook period, by 2040, the share of costs attributable to battery components versus all other soft and BOS costs is expected to drop to about 30% from 60% today (Figure 6.19).

Figure 6.19. Cost components in battery storage in the scenarios



Key point

Battery costs are expected to drop much faster than installation costs.

The technological pathway towards the sub-USD 70/kWh level also requires improvements to the technology itself. In particular, disruptive systems will be necessary to reach high penetration in the transport sector (e.g. lithium-sulphur or solid-state batteries), which could have spillovers relevant to utility-scale battery storage. Novel cathode materials and a focus on device optimisation are two technological frontiers that would need to be breached over the next ten years. While the current generation of batteries has not been deployed long enough to properly assess durability, the need to address this issue will continue, particularly in scenarios with high shares of renewables where rapid storage cycling is more likely.

Box

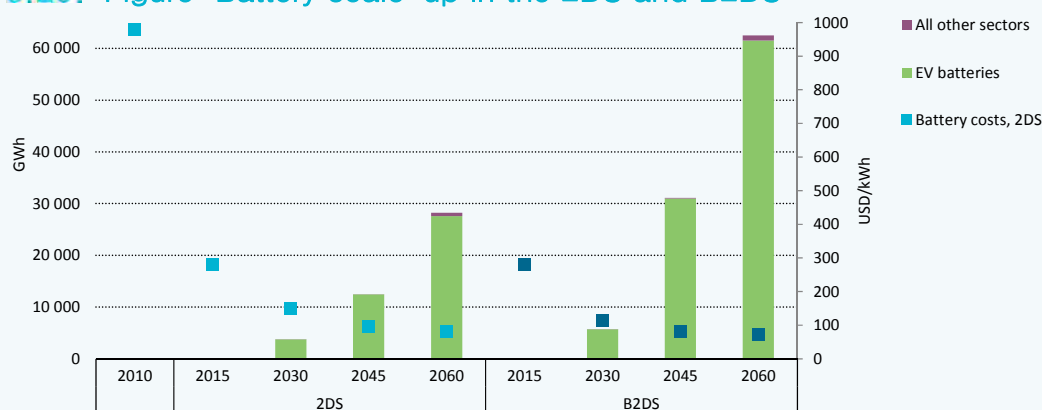
6.2. Is materials availability a barrier for scaling up battery storage in the B2DS?

The potential for growth in battery storage under the B2DS depends on the availability of low-cost lithium-ion battery storage, which in turn hinges on the ability to ramp up production across the battery supply chain. Currently predominant lithium-ion battery chemistries consist of three main components: a graphite anode, an electrolyte of lithium salts and a cathode where a range of combinations of chemical elements can be paired with lithium. Batteries in mobile phones commonly have cobalt and lithium cathodes, while designs for EVs tend to feature combinations of cobalt, aluminium, manganese, and nickel with lithium. The two most common types of EV battery today are the NMC (nickel-manganese-cobalt) and NMA (nickel-manganese-aluminium), with a range of higher energy density and more stable NMC chemistries in the pipeline set to dominate future battery markets.

It is initially important to understand that the materials themselves are a small proportion of the active mass of a battery, and the metals in the cathode are a small proportion of the active mass – all in all, active metals total around a tenth of total battery costs. Lithium itself is the charge carrier in lithium-ion batteries, and is known as a critical metal – meaning its availability is critical to the battery chemistry. The global lithium resource is ample, with nearly three-quarters of known reserves hosted by three countries, Bolivia, Chile and Argentina, largely concentrated in vast salt flats. Even under the B2DS, the global demand for lithium for EVs and stationary batteries would be of the order of 3% of known reserves. While long-term availability of lithium is not a central challenge in the 2DS, short-term supply crunches are possible. Lithium prices are highly variable, and have risen threefold in the past five years. However, depending on the battery design, the cost of lithium is between 1% and 3% of the total installed cost of the battery. Global markets and resource bases for nickel and manganese are also orders of magnitude larger than the likely demand from battery EVs.

Of all these active metals, concern is rising that production of cobalt in particular might experience supply crunches as battery production ramps up – cobalt prices have nearly doubled since 2010. Two-thirds of global cobalt supply is in the Democratic Republic of Congo. With a sustained increase in prices, global cobalt supply could increase from Canada, Southeast Asia and Australia.

6.20. Figure: Battery scale-up in the 2DS and B2DS



Key point: Batteries experience a huge scale-up in the B2DS, with EV battery markets leading other sectors in size.

Any long-term analysis of battery markets needs to be accompanied by strong caveats.

The share of battery chemistries has shifted substantially in the past four years and, in the long-term horizon of the B2DS, is likely to be vastly different from today. In particular, industry players recognise that higher-density NMC batteries are likely to be closer to production than expected. Other battery designs in the innovation pipeline (e.g. lithium-sulphur or lithium-air) are denser, and require less or different raw materials.

In addition, plans will be required for the reuse or safe disposal of end-of-life batteries. Currently the market for recycling battery components, particularly lithium, is not well developed, but can be economical. With the order-of-magnitude difference in size between EV batteries and utility-scale batteries (Figure 6.20), unexplored opportunities may also exist for repurposing EV batteries for use in providing ancillary services to electricity networks. In the B2DS, the sheer volume of batteries that will need to be recycled will likely spur innovation in these areas.

High-voltage transmission infrastructure

A large-scale expansion of high-voltage transmission infrastructure is another key enabler of power system transformation in the B2DS. The power sector worldwide spent around USD 700 billion in 2015 to maintain, upgrade or expand power system assets, from generation to end-use consumers (IEA, 2016e). Electricity networks accounted for nearly 40% of this investment. The global electricity grid is a complex and vast system encompassing 50 million km of networks. In the B2DS, an additional 38 million km is required. Importantly, the way in which the investment is directed needs to change, with much more emphasis on flexibility and interconnections. Investment in transmission needs to be increased to keep pace with policy developments, both in absolute terms (a doubling of investment per unit of energy delivered), and as a share of power sector investment.

Transmission – and interconnections in particular – is playing an increasingly pivotal role in the energy transition, as countries look to meet CO₂ emissions and renewable penetration targets while maintaining energy security. To date, the approach towards interconnecting grids has largely been national, driven only to a limited degree by regional policy initiatives. Notably, the European Commission has stepped up related efforts by including spending targets in their plans, amounting to 140 billion euros by 2020. Around 45% of the 2015 Projects of Common Interest, which receive priority support, are classified as either high-voltage direct current (HVDC) transmission or interconnection projects.

In the 20th century, the ramp-up rate for HVDC transmission grids was significant, although volumes were low and reached just 55 GW by 2000. In the decade that followed, capacity increased at an average rate of 6%, but 2010 saw a significant leap (up 27% from the previous year), as the first ultra-high voltage (UHV) direct current project in China and the first offshore wind connection in Europe both came on line. In 2015, the cumulative capacity of HVDC grids and interconnection was around 250 GW. Based on the known pipeline of projects, 2018 is expected to show another step up, rising 35% against developments expected in 2017.

Currently, the capacity of high-voltage transmission links and interconnectors worldwide amounts to about 250 GW, equivalent to the combined total generation capacity of France and Italy. HVDC and interconnection capacity is expected to expand by a third before 2020. In the B2DS, this capacity would need to increase substantially. A prime driver for developing HVDC grids and interconnectors is the ability to shift VRE-based power production to areas of demand when conditions would otherwise lead to curtailment. This is an important part of the build-out for VRE sources, which are expected to rise ninefold by 2060 relative to 2015 levels. It is estimated that HVDC transmission and interconnector volumes could need to reach 2.4 terawatts by 2060 in order to achieve the B2DS.

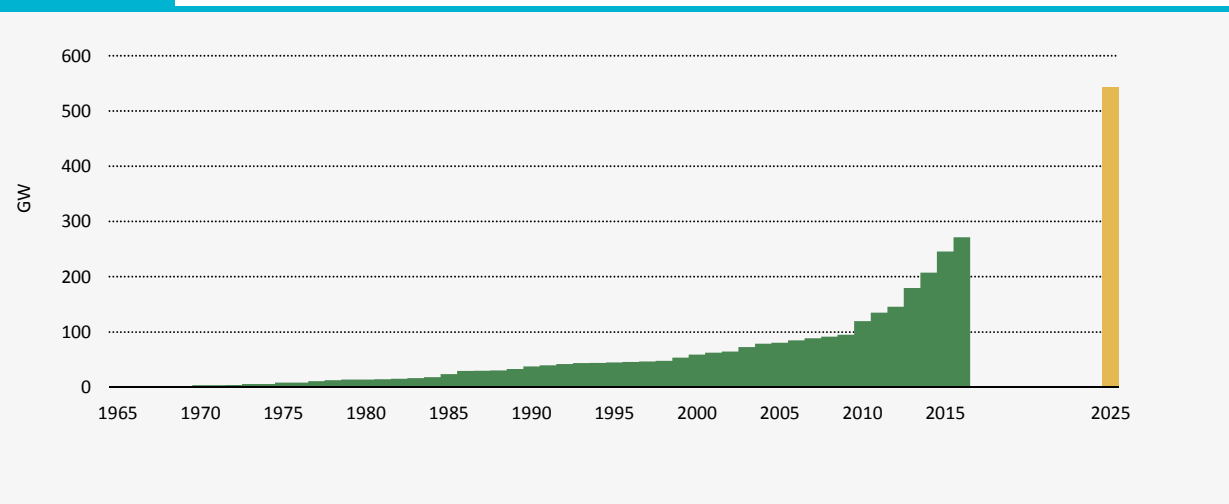
Figure 6.21. Early investment needs in electricity networks in the B2DS



Key point *Investment in T&D needs to accelerate early in the transition to the B2DS.*

Reaching these volumes of interconnection also represents a fundamental shift in power transmission technology. Alternating current (AC) has been the preferred global platform for electrical transmission to homes and businesses for the past 100 years. However, high-voltage AC (HVAC) transmission has limitations, starting with transmission capacity and distance constraints, as well as the impossibility of directly connecting two AC power networks of different frequencies. With the rapid growth of VRE; the growth in access to electricity; the electrification of new services in transport, industry and buildings; and the need to build a smarter grid, new technologies for transmitting power over long distances and between power systems are expected to grow far beyond their current levels of deployment.

Figure 6.22. Early deployment of interconnection capacity in the B2DS



Key point *Annual investment in transmission capacity dedicated to interconnections triples by 2025.*

Over a certain distance, the so-called "break-even distance" (approximately 600–800 km for current technologies), HVDC becomes the lowest-cost option. In addition, there are no

technical limits to the potential length of a HVDC cable. In a long AC cable transmission, the reactive power flow due to the large cable capacitance limits the maximum possible transmission distance. With HVDC lines, there is no such limitation.

When AC systems are to be connected, they must be synchronised. This means that they should operate at the same voltage and frequency, which can be difficult to achieve. Since HVDC is asynchronous, it can adapt to any rated voltage and frequency it receives. Therefore HVDC is used to connect large AC systems in many parts of the world. Despite positive examples, such as the NordBalt link connecting the Baltic and Nordic regions, which began trial operation in 2016, experience with projects linking asynchronous grids is greatly lacking. Examples include links between the asynchronous grids of Brazil, Uruguay and Argentina. Plans are also in place to increase the power exchange capacity between east and west Japan to 2 500 MW. In the B2DS, the demand for synchronisation would increase substantially, as the number of rotating machines and the system inertia in grids decreases as a result of higher shares of VRE.

A range of transmission technologies can be employed to increase the capacity needs of the B2DS, including flexible alternating current transmission systems in HVAC lines, and in particular flexible HVDC. An important component of flexible HVDC is a voltage–source converter – a way of converting direct current to AC with much greater freedom and flexibility.

To date, flexible HVDC systems remain costly, particularly at voltages of 500 kilovolts (kV) or higher. In the medium term, as more flexible links are deployed, voltages and capacities are expected to increase. To develop the interconnected systems envisaged in the B2DS, multi-terminal voltage source converter (VSC) systems are required; they are currently in an early phase of deployment. High-profile examples include the first multi-terminal 800 kV project, located in India, and the first five-terminal VSC–HVDC link, which is in Zhoushan, China. However, the manufacturing chains for these technologies are fragmented and not well developed, lead times are long, and as a result there is a need to develop standardised approaches to technology design and manufacturing. *ETP* analysis estimates that investment in flexible HVDC systems will increase by 350% in the B2DS.

Significantly for the B2DS, increasing voltage allows remote resources to become economical. The current push to increase voltages and transmission distances is delivering entire systems that transmit power at 800 kV and 1 000 kV, which significantly reduces losses over long distances. Examples of key resources that are particularly far from loads around the world include distant hydropower in the Patagonia region of Chile and in Brazil, wind and hydropower in western China, and solar power in the Rajasthan desert in India. The B2DS includes an additional USD 180 billion for the connection of distant resources, relative to the 2DS.

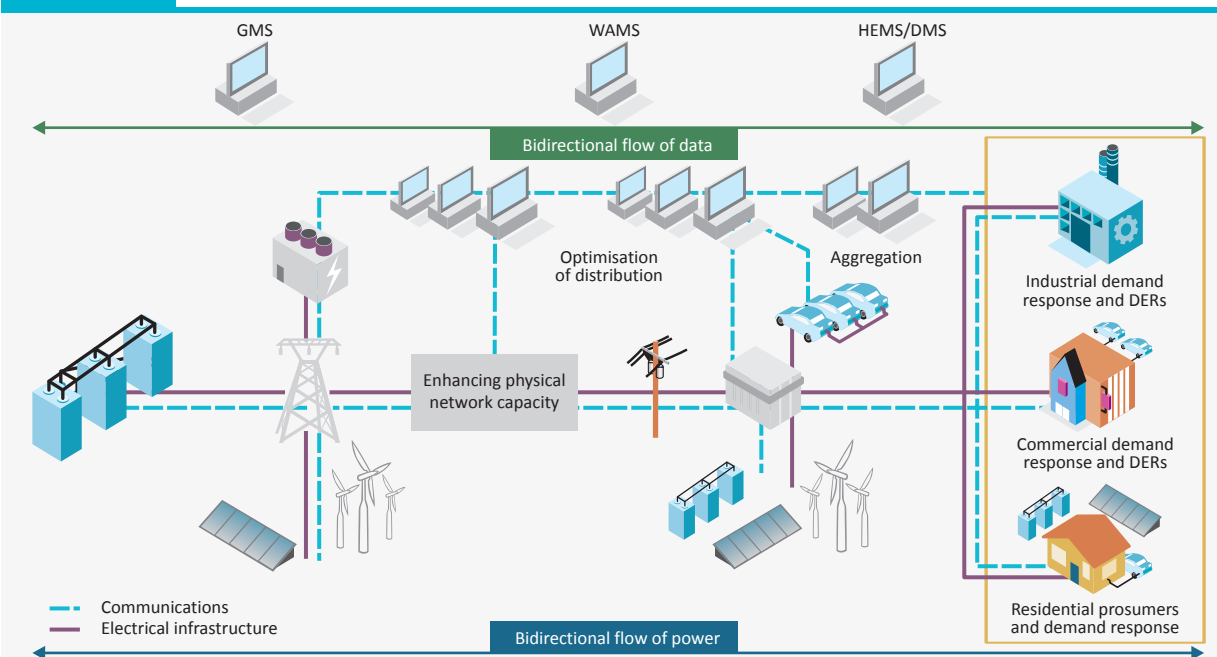
The levels of deployment projected in the B2DS also require a step change in the technology employed. UHV technologies above 800 kV are seeing increased deployment and technically could connect vast amounts of extremely remote resources. The 1 100 kV Xinjiang–Anhui line in China, planned for 2017, is to deliver 12 GW of power over 3 300 km, which would achieve historic highs for capacity, distance and voltage. Currently, UHV projects can be seen as large-scale demonstrations, but the economic rationale is not always obvious in other regions.

An active demand side

A further pillar of electricity infrastructure in the B2DS is a highly active demand side. Involving the demand side through the suite of digital technologies under the smart-grid umbrella can reduce the cost of managing electricity infrastructure and increase the hosting capacity necessary for the 2DS. Activating the demand side requires some form of interoperable electricity infrastructure (Figure 6.23) that enables business models and solutions to contribute to the flexibility of the system, allowing it to cope with variable (e.g. wind and solar) or inflexible (e.g. nuclear, VRE) supply and increase the overall efficiency of electricity markets. These solutions include aggregation of demand response and virtual power plants. In particular, smart charging of the large numbers of deployed EVs, and shifting electricity and heat loads in the residential and commercial sector, allow consumers to more directly participate in their energy use and enable vast amounts of flexibility in the B2DS.

Figure

6.23. Key technologies to enable active demand-side participation in the B2DS



Notes: HEMS = home energy management system; GMS = grid management system; WAMS = wide area management system; DERs = distributed energy resources.

Key point

Enabling the high penetration of demand-side response requires co-ordination across a range of sectors and infrastructure.

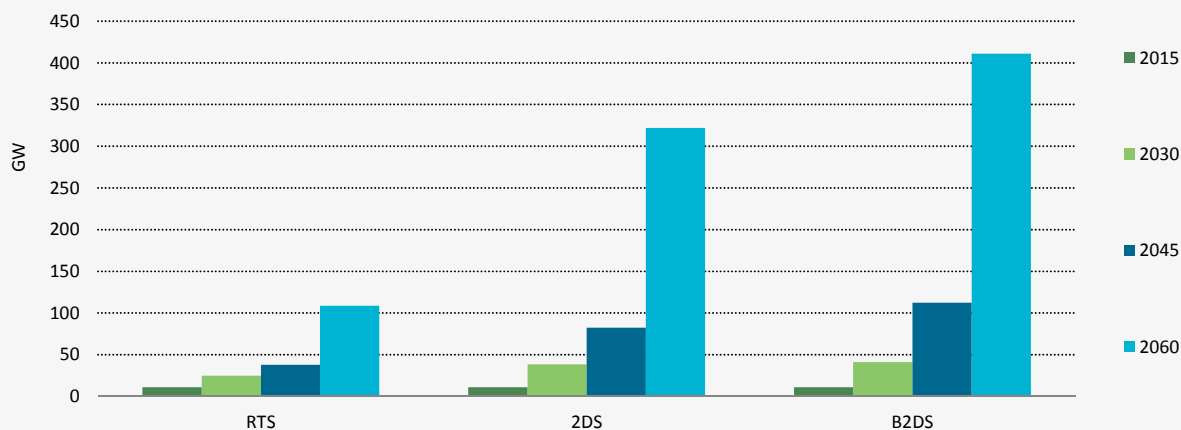
The physical layer consists of an advanced metering infrastructure that requires bidirectional information flow between end-user meters and appliances, that exchanges information with the distribution network, and that provides a medium for allowing either control signals back from the network operator or price signals that consumers can react to. Such infrastructure is understood to be at the “grid-edge” (i.e. hosted by a grid and supplier, but actively interacting with those from the demand side), and can help improve electricity grids by providing grid services, by using the data to carry out predictive maintenance and detect failures early on, and by allowing for much better planning of grids. The physical infrastructure that supports such services has reached a relatively high penetration in many regions, with some markets undergoing a second round of deployment or upgrading to improve functionalities. This physical layer, coupled with ICT solutions, allows for the creation of digital networks at the home (HEMS), local grid (WAMS) or larger area (GMS) levels.

However, infrastructure is only part of what is needed to enable large volumes of demand response; business models that facilitate the necessary flexibility from active demand response have yet to be adopted at significant scale. In the B2DS, investment in physical infrastructure allows the hosting of 200 GW of additional demand response measures compared with the RTS, across all end-use sectors. More significantly, the scale-up needs to occur faster as high shares of flexibility need to be in place by 2035 to facilitate the deployment of solar PV systems during the last two decades of the outlook period.

A number of uncertainties remain in relation to ramping up demand response to the level needed in the B2DS. Particularly in the residential sector, strategies for demand response that rely on reading the properties of loads from the overall demand profile (load signatures) and early deployment in field trials have shown adoption rates that are far lower than that necessary even in a 2DS world. For example, nearly 45% of all electric heating in the B2DS

would require some form of load control, which would represent a tripling of the amount of response available from the most optimistic field trials yet in Japan and Sweden.

Figure 6.24. Deployment of demand response in the scenarios



Key point

Once the necessary infrastructure is in place, demand response solutions increase rapidly towards the end of the outlook period.

Early retirements

The results of the 2DS and B2DS illustrate that under ambitious climate targets, fossil fuel-based electricity generation without CCS becomes largely unsustainable by 2060. This affects decisions regarding future investment as well as existing and under-construction power plants. Based on their technical lifetimes, some 730 GW of existing and under-construction coal-fired power plants could still operate in 2060 and emit around 3.4 GtCO₂ per year, an emissions level that is incompatible with either the 2DS or the B2DS pathway.¹⁶ Early retirements of fossil fuel power capacity, in particular for coal power plants, before the end of their technical lifetime, are therefore unavoidable in these scenarios. These early retirements lead to economic losses for the plant owners through foregone future electricity sales or, more severely, by not being able to recuperate the investment made in the plants. Stranded assets are those that fit into the latter category, but this analysis does not attempt to quantify them.

In the B2DS, around 1 715 GW of coal- and gas-fired capacity are retired before the end of their technical lifetime over the period 2015–60. In the 2DS, the prematurely retired capacity is 1 520 GW (Figure 6.25). In both scenarios, coal capacity, being almost completely built before 2020, accounts for the lion's share of the early retirements, with 1 330 GW in the B2DS and 1 285 GW in the 2DS. The reason for the very similar retirements in coal capacity is that in both scenarios, coal-fired generation without CCS is almost completely phased out by 2045.

Retrofitting coal plants with CO₂ capture equipment and developing suitable storage options could be an avenue to continued use of coal plants in the 2DS and B2DS. The cost-effectiveness, however, depends on various technical and economic factors, such as remaining lifetime, efficiency of the original plant and distance to storage sites, so that only a proportion of the coal power capacity is retrofitted with CCS in the scenarios. For example, an assessment of China's existing coal power fleet identified a technical retrofit potential of 310 GW, of which 100 GW could be retrofitted at additional electricity generation costs of less than USD 50/kWh (IEA, 2016f). In the 2DS, global CCS retrofits

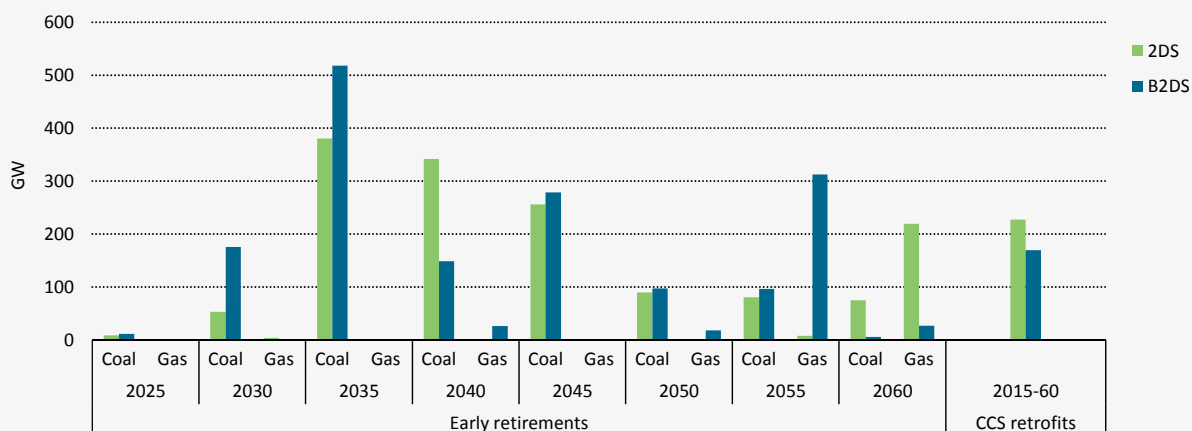
16. Assuming these plants would operate with similar full-load hours as today.

total around 230 GW, and in the B2DS, they total around 170 GW. In both scenarios, coal-fired power plants with CCS become too carbon intensive at a certain point, since 10–15% of their emissions are not captured. In the more drastic B2DS, this point is reached earlier, explaining the lower number of retrofits compared to the 2DS.

Co-firing with biomass or negative emissions from dedicated BECCS plants could be an option to offset these remaining emissions, but hinges on the availability and price of bioenergy. Developing coal-fired plants with CCS with higher capture rates is discussed in Box 6.3.

Figure

6.25. Early retirements and CCS retrofits of coal- and gas-fired capacity in the 2DS and B2DS



Note: Numbers of early retirements represent capacity being retired within a five-year period, with the given year being the middle year of that period, e.g. 2035 represents the period 2033–37.

Key point

While total early retirements of coal capacity are around 1 285 GW in the 2DS and 1 330 GW in the B2DS, they occur earlier in the B2DS.

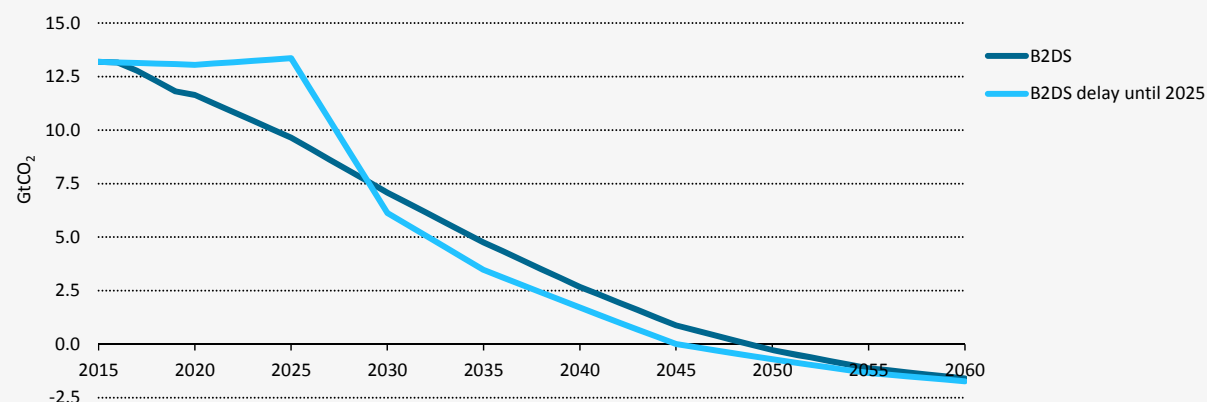
In the transition to a low-carbon electricity system, stranded assets are not restricted to generation and may apply in other parts of the electricity system, such as efficiency and demand response measures, and storage facilities. Electricity system infrastructure has long planning horizons and long technical lifetimes, which makes turnover slow. Therefore, investment in long-lived assets such as T&D systems must anticipate the evolution of demand, which inherently risks under- or oversizing the system assets. Undersizing can lead to bottlenecks in a T&D system and possibly less-than-optimal operation of generation plants, whereas oversizing can mean underutilisation of the T&D assets. While underuse may not necessarily prevail over the life of the assets, it can result in economic losses in some years by not using the plants and infrastructure optimally. Delays in the construction of transmission lines can also lead to a temporary underutilisation of generation assets, a situation that has been observed in Germany for grid connection of offshore wind farms and in China for onshore wind plants. Integrated planning approaches and co-ordination need to take a holistic approach to the entire electricity system, from generation, T&D and storage to the electricity consumers, to build efficient electricity systems and to help reduce the risks of creating stranded assets.

Impacts of delayed action

To illustrate the impact of delayed action in the power sector on achievement of the B2DS, a variant of the scenario has been analysed that delays the necessary measures. It assumes that the power sector follows the RTS path up to 2025 before undertaking the measures needed in the B2DS. Furthermore, it assumes the same cumulative CO₂ budget over the period 2015–60 and the same emissions level in 2060 as in the B2DS.¹⁷ The delay leads to higher CO₂ emissions in the initial years compared with the B2DS, which then need to be offset in later years (Figure 6.26). It also assumes that the available amount of bioenergy for the power sector is limited to the amount used in the B2DS. This avoids a situation where higher initial emissions can be offset by ramping up BECCS in later years.

Figure

6.26. CO₂ emissions from the power sector in the B2DS and its delayed variant



Key point

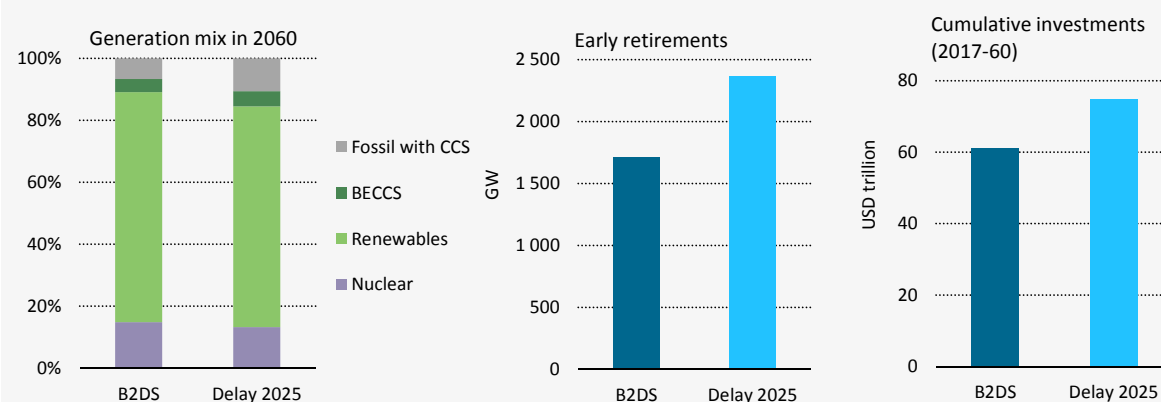
Increased emissions in early years in the delayed variant are offset by lower emissions in the period after 2030 to stay within the B2DS carbon budget.

In the delayed variant, generation from fossil fuel-based plants with CCS is reduced by one-third in 2060 relative to the B2DS and is mainly replaced by renewables-based generation. Avoiding the non-captured CO₂ emissions from mainly coal-fired plants equipped with CCS is needed in the variant to stay within the cumulative emissions budget of the B2DS. As a result, retrofitting of coal-fired plants with CCS becomes less attractive, so that only 30 GW are retrofitted in this variant compared with 170 GW in the B2DS. Early retirements of coal and gas capacity increase by around 630 GW to 2 350 GW in the variant. The premature retirement of fossil power plants in the delay variant results in foregone electricity generation of 150 000 TWh between 2014 and 2060, which represents 9% of the total cumulative electricity generation. This is more than double that in the B2DS, with foregone generation of 70 000 TWh. The foregone generation in the delay variant creates lost revenues, which are estimated (on an undiscounted basis) at around USD 8.3 trillion between 2014 and 2060 (USD 3.7 trillion in the B2DS). In addition, the need for deeper emissions cuts compared with the B2DS, to offset the initially higher emissions from the delay, leads to an increase in the investment costs in the power sector of USD 14 trillion, or 22% of the investment in the B2DS (Figure 6.27).

17. Decisions for new capacity additions, which have been taken before 2025, based on the RTS results, are still executed, even if the start date of these new capacity additions occurs after 2025 due to the construction period.

Figure

6.27. Generation mix, early retirements and cumulative investment in the B2DS and the delayed variant



Key point

Delaying action until 2025 increases early retirements by 630 GW and investment needs increase by more than 20%.

The delayed variant illustrates the substantial consequences that a delay in efforts can have in the transition to the low-carbon energy system foreseen in the B2DS. Retrofitting coal-fired power plants with CCS, often considered as a remedy against early retirements and stranded assets, is not a suitable option here due to the carbon budget constraint, for which the non-captured CO₂ emissions from coal-fired plants with CCS become problematic. This is partly due to capture rates of 85–90% for coal-fired CCS technologies assumed in the scenarios, which could be affected by improvements in capture rates, possibly increasing the potential for further CCS retrofits in the delayed variant as well as in the B2DS (Box 6.3).

Box

6.3. Role of the capture rate in CCS for coal-fired plants

Global electricity generation from coal-fired power plants equipped with CCS declines in the B2DS after 2045 and is almost halved by 2060 (Figure 6.28). Part of the decline reflects that some of the capacity retrofitted with CCS is at the end of its technical lifetime and that generation from the remaining coal capacity with CCS declines, resulting in a drop in global average full-load hours of 5 600 hours in 2060 compared with 7 200 hours in 2045.

The cause of the declining generation from coal-fired plants equipped with CCS and the lack of new investment is their production of non-captured CO₂. With a capture rate of 85% and an efficiency of 41%, a hard coal power plant with post-combustion CO₂ capture still emits 125 gCO₂/kWh in 2060. For oxy-fuelled CO₂ capture, a higher capture rate of 90% has been assumed; however, at the same efficiency, remaining emissions are 83 gCO₂/kWh in 2060, at a time when the global average CO₂ intensity of the power sector has become negative at -11 gCO₂/kWh.

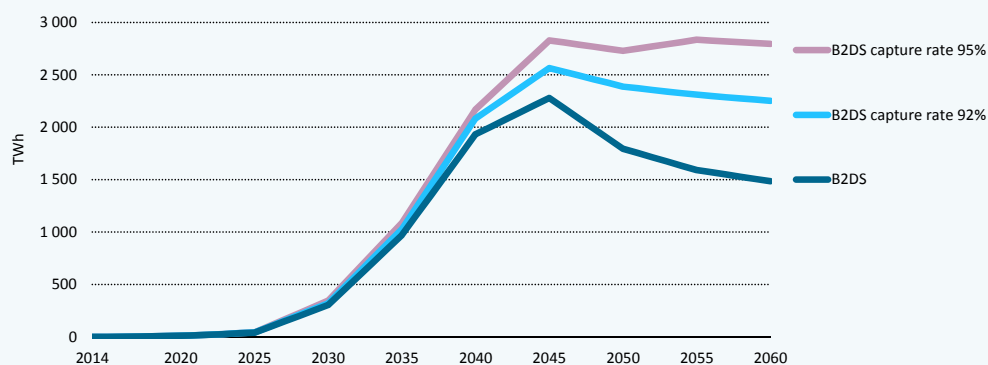
Increasing the capture rate can be a way to reduce the remaining emissions and thus increase the attractiveness of coal-fired power plants with CCS after 2045 in the B2DS. From a technical perspective, higher capture rates are possible. Capture rates at post-combustion plants can be raised by increasing the CO₂ absorption capacity. This can be done by using a leaner absorber solvent, i.e. the regenerated solvent entering the absorber

has a lower CO₂ concentration, which requires more energy for regeneration, higher solvent recirculation between the absorber and desorber columns, and higher or more absorbent columns. At oxy-fuelled power plants, the theoretical capture rate of 100% could be achieved. Technically, the capture rate can be increased by removing CO₂ through an additional scrubbing step from vent streams leaving the plant. For pre-combustion capture plants, i.e. IGCC coal power plants, a 100% capture rate cannot be realised due to equilibrium conditions in the physical absorption process. The capture rate can be raised by increasing the conversion rate of carbon monoxide to CO₂ in the shift reaction after gasification and by increasing the CO₂ absorption capacity of the CO₂ capture unit in the same way as for the post-combustion system (IEAGHG, 2006).

To illustrate the impact of a higher capture rate on the generation side from coal-fired power plants with CCS, two variants of the B2DS with higher capture rates have been analysed: one with a capture rate of 92% and one of 95% for three coal-based capture technologies (post-combustion, oxy-fuelling, pre-combustion). The B2DS assumes a capture rate of 85% for post-combustion as well as pre-combustion technologies and of 90% for oxy-fuel capture. A higher capture rate will increase the energy demand of the power plant and reduce its efficiency. The actual efficiency decline depends on the process design, but studies indicate that the decline could be of the order of 1–2 percentage points (Göttlicher, 1999; NETL, 2015). In this analysis, a 2-percentage-point drop in efficiency has been assumed for all three capture technologies. Investment costs are also likely to increase, e.g. the need for higher absorbers in the case of post-combustion, but have been kept unchanged compared with the B2DS, so that the variants explore the technical potential under rather optimistic cost assumptions.

For post-combustion capture plants, the 92% variant leads to a CO₂ intensity of 65 gCO₂/kWh in 2060 and 41 gCO₂/kWh in the 95% variant (117 gCO₂/kWh at 85% capture rate in the B2DS). In the 92% variant, global coal-fired generation with CCS can almost maintain its 2045 generation level, with only a moderate decline by 2060, and is around 50% higher in 2060 compared with the B2DS. In the 95% variant, generation from coal with CCS even increases and almost doubles compared with the B2DS in 2060. This sensitivity analysis indicates that the capture rate of coal-fired CCS power plants becomes an important design parameter under very stringent climate targets, as in the B2DS

6.28. Figure: Global electricity generation from coal plants with CCS in the B2DS at various capture rates



Key point: Higher capture rates for coal-fired power plants with CCS reduce their uncaptured CO₂ emissions and allow extended operations under the B2DS conditions.

Another critical assumption is the availability of bioenergy for the power sector. Greater availability of bioenergy in the variant to the B2DS allows for greater deployment of BECCS to offset the initially higher emissions caused by the delay in action. In the delayed variant, these higher emissions amount to 23 GtCO₂. If these were to be fully offset through BECCS over a 20-year period, i.e. 1.15 GtCO₂ negative emissions from BECCS power plants per year, this results in an additional annual bioenergy demand of around 14 EJ, an additional 10% of the total primary bioenergy demand in the B2DS in 2060. But making room for these additional quantities requires greater effort in other sectors to use less biomass or provide more biomass for the energy sector, not necessarily an easy undertaking given constraints on land availability and the need for food production.

The analysis of the variants illustrates that delaying action to after 2025 significantly increases the cost and effort of reaching deep decarbonisation in the power sector. Early action is key to reaching the B2DS pathway. With regard to technology development, exploring cost-effective capture technologies for coal-fired power plants with higher capture rates could increase their attractiveness in a world with serious carbon constraints and high carbon prices. Also, the decline in coal-fired CCS generation in the B2DS in the decade 2050–60 indicates the need for higher capture rates and support for RD&D.

Policy actions for fast-tracking integrated electricity systems towards zero emissions

Recommended policy actions for the near term

The power sector plays a critical role in the transition to a low-carbon energy future. As this chapter shows, the power sector has the potential for deep carbon emission cuts and is capable of providing negative emissions with the use of BECCS. This requires continued and reinforced policies to spur low-carbon technologies into electricity markets, such as renewable energy sources, fossil fuel plants equipped with CCS, and nuclear power. In addition, zero-carbon electricity can support the decarbonisation of end-use sectors such as heating and transport. Smart solutions for electric end uses may in turn support the operation of the electricity system, e.g. integration of VRE sources.

To advance along the 2DS pathway, deployment of low-carbon generation technologies must be significantly accelerated over the next four decades compared with historic rates. Given that most of these technologies are capital intensive, supportive and predictable policy and regulatory conditions will be essential to attract private investment. A strong carbon price should be the cornerstone of low-carbon policies, but experience so far shows that the introduction and strengthening of carbon prices will take time and not generate the deployment rates needed for the transition towards a 2°C pathway. Therefore, especially in the transition phase, additional support schemes are needed to reduce the investment risks for low-carbon technologies and accelerate their deployment. Examples of long-term support schemes that can be technology-specific and adjusted to reflect technology and market maturity include power purchase agreements and feed-in premiums (IEA, 2016g).

Emerging and developing economies need to be a focal point for investment in low-carbon technologies, as 80% of the cumulative CO₂ reductions from the RTS to the 2DS in the power sector occur in non-OECD economies. While certain non-OECD countries, such as China, are already leaders in the development and deployment of low-carbon technologies, many developing countries lack domestic financial resources or suffer from unattractive market conditions to draw foreign investment. The need to provide financial resources for climate mitigation and adaptation was stressed in the Paris Agreement; developed countries are urged to scale up their contribution to achieving the goal of providing USD 100 billion per year to developing countries by 2020. In the context of technology innovation and economic development, support initiatives should address local priorities, needs and conditions, e.g. adapting technologies to local conditions, strengthening capacity, and addressing basic needs by providing access to electricity and clean energy technologies.

Most of the low-carbon power technologies deployed in the 2DS have been demonstrated at scale and are commercially available. Their further development and innovation depend

on the maturity of the individual technologies and may vary from demonstration at large scale, as in the case of wave power, to improving performance and reducing costs, as in the case of offshore wind. Even established technologies need adjustment for new conditions. For example, natural gas-fired power generation is generally designed to maximise full-load efficiency, but in low-carbon electricity systems may be valuable running in partial-load mode to provide system flexibility services. For nuclear power, should countries include it in their power generation mix, then the potential for it to provide services additional to base-load operation should be carefully evaluated, e.g. heat for district systems, industrial processing and water desalination. Given the long lifetime of nuclear plants, this should not be limited to new plants, but should also be explored at existing plants.

To release the full potential to decarbonise the power sector, in addition to RD&D for individual technology areas, policies and programmes must take an integrated view of the power sector and its connections with other parts of the energy system. Innovation is needed in the overall design and operation of the electricity system, taking into account the interdependencies of electricity, heat and mobility. Electrification of mobility and heating services is a case in point, where system approaches can cut emissions, in the first instance by replacing conventional vehicle technologies and liquid fossil fuels with EVs fuelled by low-carbon electricity, and in the second by utilising environmental or waste heat streams with electric heat pumps for heating purposes in buildings and industry. Integrating demand response approaches and technologies into electricity systems can also benefit the integration of VRE sources in the power supply. With increasing generation from VRE sources plus increased electrification, opportunities for increasing the flexibility and reliability of electricity systems should be assessed to take advantage of local conditions and to develop roadmaps for their effective implementation.

Early retirement of coal-fired power capacity is unavoidable to achieve the carbon-constrained scenario pathways. To minimise early retirements and related economic losses, retrofitting plants with CCS can be a viable option for emissions reductions at existing or under-construction coal- and gas-fired power plants. This is included in the 2DS, but the earlier decarbonisation needs of the B2DS require a more rapid phase-out of unabated coal-fired generation. Certain drivers have to be put in place in order for retrofits to play a role. These include continued efforts by government and industry in technology innovation and cost reductions for both CCS in general and retrofits in particular. Regulations and permits for new fossil-fired power plants must promote CCS readiness to take account of the possibility for retrofits. Particular attention should be directed to the location of the power plant in relation to possibilities for the co-location of CO₂ storage and utilisation.

Complementary to developing technology solutions, such as CCS retrofits, governments can provide investors and stakeholders with better information on the climate vulnerability and policy exposure of their investments. Through regulation, the construction of new coal-fired capacity can be banned or emissions standards established. In early 2017, China's National Energy Administration announced that it would cancel plans to build more than 100 coal-fired power plants with combined capacity of 120 GW. This decision may not only be driven by air pollution concerns and climate change pledges, but also may reflect the current surplus of coal-fired capacity.

For gas-fired power plants, biomethane can be an alternative to natural gas to allow continued generation and to provide system services. Such an option, however, needs to be part of an overall transition strategy that also includes linkages to the buildings and the transport sectors. Using biomethane could allow the continued operation of gas-fired power plants and other parts of the gas infrastructure and technologies in other sectors to reduce the potential for stranded assets in gas supply and consumption. The substitution potential depends on local conditions such as the gas infrastructure, sources for biomethane production or in the case of bio-gasification, the economics of biomethane production compared with the direct use of bioenergy. Regulatory questions, such as gas grid codes, quality standards and cross-border trade, need to be addressed. Feed-in tariffs for biogas into the gas grid, such as in the United Kingdom and France, could help in the initial phase of developing a biomethane supply infrastructure.

Policy implications for the B2DS

Moving from the 2DS to the B2DS requires earlier, faster and deeper decarbonisation of the power sector. While the low-carbon technologies are largely very similar, their deployment is needed in the near term and at an accelerated rate in the B2DS. This calls for more technology RD&D and deployment support. Early retirements of fossil fuel-fired power capacity without CCS, mainly coal, occur around five to ten years earlier in the B2DS, which incurs economic losses. With the transition to a 2°C pathway already requiring deployment of many low-carbon technologies at an unprecedented rate, their deployment has to be even further accelerated in the B2DS. This step change in the B2DS is also reflected in the investment needs of the power sector, with the additional investment in the B2DS (relative to the RTS) being one-third higher than that in the 2DS.

With increasing mitigation ambitions beyond a 2°C target, “negative” emission technologies are likely to be increasingly needed to offset emissions in other sectors that are more difficult or costly to mitigate. In this context, BECCS in power generation (besides its application in biofuel production and industry) is needed in the B2DS at a global scale of 420 GW in 2060, with large-scale deployment starting by 2030. None of these plants have yet to be built, so demonstrating the technology at a commercial scale, including the biomass supply chain and CO₂ storage, is needed to gain practical experience and further develop the technology.

Technology RD&D should also explore solutions to increase the co-firing share of bioenergy in coal-fired power plants with CCS, beyond today’s typical share of 10–15%. Direct or indirect co-firing of bioenergy in fossil fuel-fired plants with CCS could be an important step in a transition to BECCS plants, by gradually developing the required bioenergy supply chain and increasing the possibility of coal-fired plants with CCS under B2DS conditions by offsetting their non-captured CO₂ emissions. To reduce the remaining emissions from fossil fuel-fired generation with CCS, engineering design studies should also explore the technical and economic consequences of capture rates higher than today’s level of 85–90%.

Given the challenges of sourcing bioenergy supply and linking a BECCS plant to CO₂ transport and storage infrastructure, planning and deployment support from governments is needed, at least in the initial deployment phase. Support measures should seek to mitigate the multiple risks regarding bioenergy availability and price, and the reliability of technology. Carbon prices and related policy measures influence the opportunities for BECCS. For example, the EU Emissions Trading System provides exemptions for fossil fuel plants equipped with CCS, but not for BECCS. BECCS technologies should be included as a mitigation option in greenhouse gas accounting for regulatory purposes and in emissions trading schemes.

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Chapter 7



Delivering sustainable bioenergy

Bioenergy can play an important role across the energy sector, in electricity production, in providing heat for buildings and for industry, and in transport, improving energy diversity and security.

Well-established bioenergy technologies can make an immediate impact in reducing energy-related emissions. A significant contribution from sustainable bioenergy is needed as part of the transition to a low-carbon energy future as embodied in the *Energy Technology Perspectives (ETP) 2°C Scenario (2DS)* and the *Beyond 2°C Scenario (B2DS)*. A number of technologies still at earlier stages of maturity will need to be developed, demonstrated and deployed to facilitate an expanded role for bioenergy. However, bioenergy can play this role in a low-carbon future only when its use leads to unambiguous carbon savings without other serious negative impacts that affect its sustainability.

Key findings

- **Bioenergy already plays an important role in today's energy system**, providing about 11% of final energy consumption, although half of this comprises “traditional use” of biomass. Modern bioenergy provides some 7% of heat requirements, 2% of electricity generation and 3% of transport energy needs.
- While there has been some growth in bioenergy supply and demand in recent years, **current rates of market development are well below the rates of deployment envisaged within low-carbon scenarios** including the International Energy Agency (IEA) 2DS and B2DS – particularly in the transport, industry and buildings sectors.
- **Factors holding back deployment include the higher relative costs of bioenergy solutions when energy prices are low and more importantly a lack of policy certainty**, which stems in part from continuing concerns about the sustainability of some bioenergy options. A strong sustainability governance framework will be essential if bioenergy is to grow significantly.
- **A number of short-term no regret deployment opportunities are available**, based on proven technologies that can lead to unambiguous carbon savings, improve energy diversity and security and provide a range of environmental and social benefits.
- **An expanded role for bioenergy is a key element of all three ETP energy outlook scenarios** – the Reference Technology Scenario (RTS), 2DS and B2DS.

- **In the RTS, the inefficient traditional use of biomass is reduced as clean energy access improves, and the use of biomass in modern ways to supply heat to buildings, and especially to industry, grows.** Bioenergy for transport grows by a factor of four by 2060 (mainly through the extended use of conventional biofuels rather than advanced technologies) and bioelectricity also grows significantly, providing over 5% of generation in 2060.
- **In the 2DS, bioenergy plays an enhanced contribution, with its use concentrated in sectors for which alternative decarbonisation opportunities are limited.** In particular, its contribution to the transport sector rises significantly (more than 2.5 times that in RTS), complementing other measures in the sector including the enhanced role of electrification. Bioenergy plays an important role in decarbonising long-haul transport, including the aviation sector, and this requires the development and deployment of new low-carbon technologies adapted to supply these market needs.
- **In the B2DS, bioenergy continues to play an important role, with certain changes in the priority sectors for bioenergy.** In particular there is an expanded role for carbon capture and storage (CCS) as a way of creating “negative emissions” linked to electricity generation, the industrial sector and in the production of biofuels.
- **Delivering the necessary contribution of bioenergy in the 2DS and the B2DS will depend on the development and deployment of a number of new technologies, notably for transport fuels.** The cost of energy produced by these new routes is currently high compared with those from fossil fuel alternatives and more conventional bio-based fuels. Policy intervention will be needed to provide the conditions necessary for demonstration and commercialisation of these key technologies.
- **The supply of sustainable bioenergy required to make these contributions will need to grow – from today’s 63 exajoules (EJ) to around 145 EJ in the 2DS and B2DS.** While this is within the range of many global estimates of available sustainable resource, mobilising this resource will be a major challenge.
- **Optimising carbon benefits from the potentially constrained biomass supply will require very efficient production and use of bioenergy,** and favour integrated systems that co-produce useful energy streams from biomass alongside a number of useful materials and chemicals.
- **Although certain issues remain unresolved, much has been learned in the last ten years** about the factors that influence biomass sustainability and how to manage them. The range of estimates of sustainable bioenergy potential have narrowed and estimates within the 100 EJ to 300 EJ range may be considered reasonable.
- **The prospects of delivering higher levels of bioenergy will be influenced by a number of factors,** notably by the balance between increases in agricultural productivity and efficiency (especially the reduction of food waste) and food needs. The chances of achieving a higher supply of sustainable feedstock can be enhanced by efforts to bring derelict and abandoned land back into use, providing significant resources for sustainable local food and energy use, co-production of food and energy, and by using land dedicated to energy production as efficiently as possible, using high yielding species.
- **Delivering the required feedstock will require mobilising the full range of potential resources and will be challenging.** However experience suggests that given clear market opportunities appropriate supply chains can be created and appropriate regulatory frameworks can also be developed.

Opportunities for policy action

- **Increasing the supply of biomass for bioenergy will critically depend on establishing confidence in an internationally accepted sustainability governance regime.** This needs to ensure that bioenergy leads unequivocally to significant carbon savings and avoids other problems affecting sustainability, while encouraging sustainable bioenergy use and promoting best practice and innovation.
- **A policy environment that favours capital-intensive technologies is a prerequisite for the expanded role of bioenergy in all three scenarios.** This needs to consist of a stable and predictable policy environment, clear targets to provide confidence that a market will be developed, support policies, and an appropriate and clear regulatory regime.
- **Investment from industry to expand capacity, develop and commercialise new technology, and drive down costs is essential,** particularly in the 2DS and B2DS. This will happen only with supportive enabling policy environments that may include ambitious national targets, quotas for advanced bioenergy systems and financial de-risking measures.
- **Efforts to commercialise the technologies need to be backed up by research, development and demonstration (RD&D) focused on the technologies and sectors where bioenergy can play the most important role in decarbonisation.** This needs to be led by industry and supported by governments. Some important RD&D challenges are not currently being given sufficient attention; therefore some reordering of priorities will be needed.
- **The role of bioenergy in the B2DS relies on its deployment with carbon capture and storage (BECCS) or use (BECCU).** A strong and unprecedented policy support would be required to facilitate this deployment.

Overview

This chapter aims to highlight the importance of bioenergy in the transition to a clean energy future. It examines the expanded role for bioenergy in the context of three scenarios that look to 2060 with varying levels of ambition to achieve climate change goals.¹

- **In RTS,** the contribution of bioenergy to end-uses grows by a factor of 45%, despite a decline in traditional use of biomass.
- **In 2DS** that draws a trajectory to keep emissions to the levels compatible with limiting the rise in global mean temperature to 2°C by 2100, bioenergy plays an enhanced contribution, with its use concentrated in sectors for which alternative decarbonisation opportunities are limited, e.g. transport.
- **In B2DS,** bioenergy continues to play an important role in order to aim for the “well below 2°C” target of the Paris Agreement. In particular, there is an expanded role for bioenergy with CCS to generate “negative emissions”.

Energy from biomass (bioenergy) is the oldest source of energy known to mankind, and is still the largest source of renewable energy globally, accounting for around 11% of world total primary energy supply.

1. For additional information on the three scenarios, see Chapter 1, “Global outlook.”

Much biomass is used inefficiently to provide energy for cooking and heating for poorer households in emerging and developing economies. While playing an important role in providing such energy, such “traditional uses” of biomass are also the cause of very significant health issues due to their contribution to poor indoor and outdoor air quality (IEA, 2016a). Sourcing sufficient biomass also puts pressure on local forestry resources. There are therefore a number of global efforts to improve access to clean sources of energy for cooking and heating by providing more efficient sources either using other fuels or by using biomass more efficiently (SE4ALL 2017).

However, bioenergy can also play an important role as a modern and efficient source of energy, and such uses have been growing in recent years. Bioenergy is a unique source of renewable energy as it can be provided as solid, gaseous or liquid fuels. It can be used to generate electricity and to provide transport fuels, and as a source of heat (including high-temperature heat for industrial purposes). Bioenergy can be stored at times of low demand and provide dispatchable energy when needed.

An expanded role for modern bioenergy is an important element in low-carbon energy scenarios, as a widely available renewable energy source that, in the right circumstances, can play an important role in reducing carbon emissions in heating, electricity and transport applications that are difficult to decarbonise in other ways, as discussed below. Delivering such an enhanced role is challenging, and a number of technical, economic and market barriers will have to be overcome if its contribution is to be optimised.²

However, bioenergy can play this important role in reducing carbon emissions from the energy sector only if its use leads to unequivocal and significant carbon savings, and does not lead to other unmanaged impacts on the environment or create social or economic problems. Well-designed sustainability policies and regulation are a prerequisite for a substantially expanded role for bioenergy. These need to discourage and prevent bad practice, but also encourage and incentivise good practice and innovation to deliver sustainable supply, given the need for a significant expansion in the use of sustainable bioenergy.

What is bioenergy

A wide range of biomass feedstocks can be used as sources of bioenergy. These include: wet organic wastes, such as sewage sludge, animal wastes and organic liquid effluents, and the organic fraction of municipal solid waste (MSW); residues from agriculture and forestry; crops grown for energy, including food crops such as corn, wheat, sugar and vegetable oils; and non-food crops such as perennial lignocellulosic plants (e.g. grasses such as miscanthus and trees such as short-rotation willow) or oil-bearing crops such as jatropha or camelina.

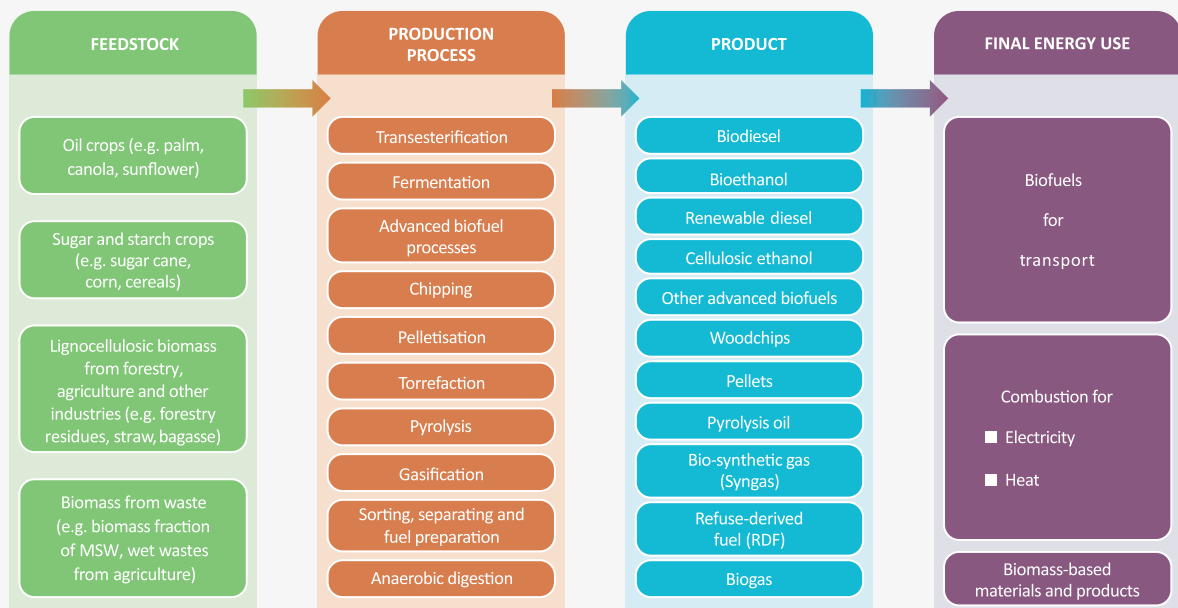
Many ways are available to turn these feedstocks into a product that can be used for electricity, heat or transport. Figure 7.1 illustrates a number of the main pathways available for these applications (IEA, 2017).

Each of these bioenergy pathways may consist of several steps, including biomass production, collection or harvesting, preparation to improve the physical characteristics of the fuel, pretreatment to change the chemical properties, and finally conversion of the biomass to useful energy. The number of these steps may differ depending on the type, location and source of biomass, and the technology utilised to provide the relevant final use.

2. An updated version of the IEA Bioenergy Roadmap, which will look in more detail at the opportunities and barriers to the development of bioenergy, will be published shortly after *Energy Technology Perspectives ETP 2017*.

Figure

7.1. Potential configurations of bioenergy pathways: From biomass to final energy use



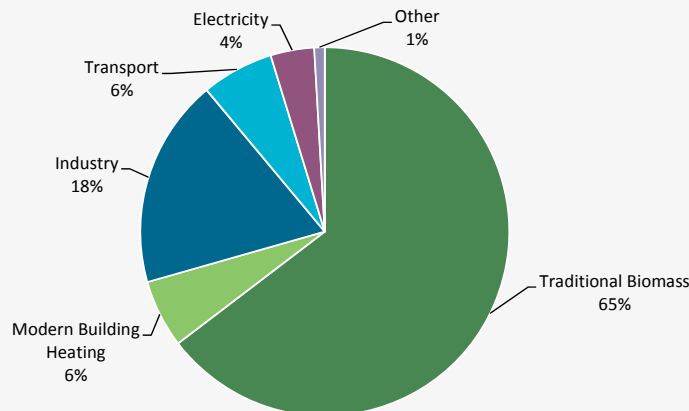
Key point *There are many potential bioenergy pathways from feedstock to useful energy.*

Recent trends

Bioenergy accounted for nearly 11% (46 EJ) of world final energy demand in 2015 (Figure 7.2), with primary energy demand for biomass at some 63 EJ (IEA, 2016a). While bioenergy makes a significant contribution to each of the main sectors – heat for buildings and industry, electricity and transport – the picture is dominated by the use of biomass for cooking and heating in developing and emerging countries – so-called traditional use of biomass. More modern production of heat – particularly for industry – is the next-largest sector. Electricity production and transport fuel use are currently less significant.

Figure

7.2. Bioenergy in final energy consumption by end use



Source: IEA (2016b), *World Energy Statistics and Balances* (database), www.iea.org/statistics/.

Key point *Bioenergy is today dominated by the traditional use of biomass and by uses for heat in industry and buildings.*

Bioenergy for heat

Over half of current global energy demand is used to provide heat – for cooking, space and water heating in buildings, and industrial processes. Bioenergy makes a contribution to heating in the buildings sector, notably via the traditional use of biomass for cooking and heating in developing economies, as well as more modern use of biomass for heating residential, commercial and industrial premises, and to supply industrial heat

While it is difficult to quantify precisely given the informal nature of its supply and use, it is estimated that in 2015 some 30 EJ (or around 7%) of total final energy demand was provided by the traditional use of fuels, including wood, charcoal, agricultural residues and animal dung, which provide for water heating, cooking and heating in colder climates. Some 2.7 billion people still rely on traditional use of biomass as their principal source of energy. Given growing populations in the developing world, traditional use of biomass has been growing. This is despite many efforts to promote more sustainable production and use of these fuels, including work co-ordinated under the United Nation's Sustainable Energy for All (SE4ALL) initiative and linked to the target to ensure universal access to clean energy by 2030.

Modern use of bioenergy for heat has been growing slowly (at some 2% per year) and provided some 11 EJ in 2015. In addition there was a significant contribution to the 0.8 EJ of renewable heat provided as commercial heat, for example in district heating systems or produced and sold from biomass-fired co-generation systems (IEA, 2016c).³ Two-thirds of this energy was used in industry and agriculture, principally in the pulp and paper industry, the food industry (especially in sugar and vegetable oil extraction), and the timber sector.

Bioenergy is also playing an increasing role in heating in the buildings sector. While in general there is not a strong policy emphasis on renewable heat, most European Union (EU) countries have included heat in their action plans to achieve their mandatory renewable energy targets, and biomass heating dominates their efforts. In particular, the use of biomass feedstocks as a fuel for district heating systems has been growing, notably in countries with a colder climate and ready supplies of biomass. Overall it is expected that modern biomass use for heat will continue to grow slowly (at around 2% per year) reaching some 15 EJ by 2021, with use in industry and agriculture reaching just under 10 EJ and building use around 5 EJ (IEA, 2016b).

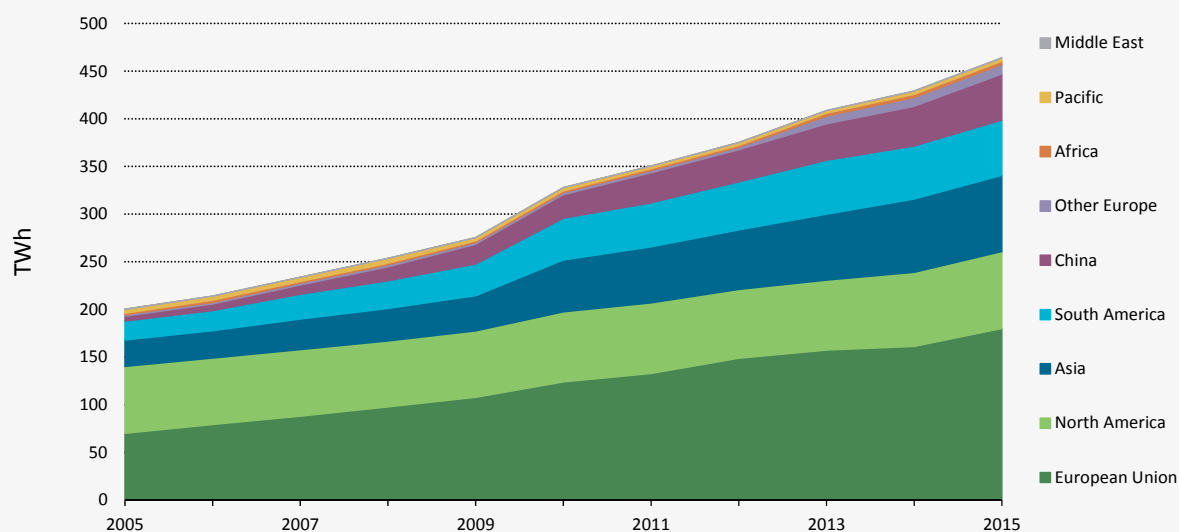
Bioelectricity

Global production of electricity from biomass has more than doubled since 2005 (Figure 7.3) (IEA, 2016b). Bioelectricity now provides some 2% of global electricity generation. Markedly different patterns of biomass sources and technologies can be seen in different countries, depending on the availability of resources and on the details of the supportive policies. For example, in Germany, generation is principally from the anaerobic digestion of energy crops and agricultural wastes. In the United Kingdom (UK), by contrast, generation is dominated by a number of large-scale generation projects where imported wood pellets are used for power generation, including in some converted coal-fired plants. In Sweden, bioenergy provides electricity alongside heat for both industry and district heating, and electricity via co-generation systems. In Brazil, the growth has come from increased generation from agricultural wastes, and in particular of the use of bagasse to fuel co-generation systems in sugar production.

Detailed analysis of the policy and markets in the most significant countries indicates that by 2021, global generation from biomass will continue to grow at around 6% per year, to reach some 670 terawatt hours (TWh) per year (IEA, 2016b).

3. Note: *Co-generation* refers to the combined production of heat and power.

Figure 7.3. Bioenergy power generation by region



Source: IEA (2016c), *Medium-Term Renewable Energy Report 2016*.

Key point *Bioelectricity generation has more than doubled since 2005, with notable growth in Europe and the People's Republic of China (hereafter, "China")*

Transport

Biofuel production has increased by a factor of 3.5 since 2005. In 2015, biofuels' contribution to final energy consumption in the transport sector equated to around 3.2 EJ – equivalent to 3% of all transport fuel demand and 4% of world road transport fuel demand (IEA, 2016c). This production is made up of ethanol (75%) and biodiesel (25%), with a growing share of hydrotreated vegetable oil (HVO)⁴ in recent years (around 4% of total biofuels production).

Biofuels saw strong growth between 2005 and 2010, driven in particular by growing ethanol production in the United States and Brazil, and biodiesel in the European Union. Growth subsequently slowed due to a number of factors, including, in Europe, policy uncertainty stimulated by concerns about the sustainability of certain biofuels, and in particular, about the real level of carbon savings taking land-use changes into account. Growth has now resumed but at lower rates, and is mostly concentrated in Southeast Asia.

Global ethanol production is dominated by the United States and Brazil, who between them account for 85% of global ethanol production. The geographic pattern of production of biodiesel is more diverse than that of ethanol, although the United States and Brazil are still major suppliers. Others include Germany, Argentina, Indonesia and other EU countries.

Concerns about the sustainability of conventional biofuels, including bioethanol and biodiesel produced from food-based feedstocks such as sugar, maize and palm oil, are stimulating the development and production of a range of new and advanced liquid biofuels⁵ from lignocellulosic feedstocks. Such feedstocks, including farm and forest

4. While initially developed to convert vegetable oils to fuels, HVO processes now use a wide variety of lipid containing feedstocks including used cooking oils, animal fats and vegetable oils, and by-products from paper- and pulp-making processes such as tall oil.

5. There are different definitions of what constitutes an advanced biofuel. The IEA uses the following: "Advanced biofuels are sustainable fuels produced from non-food crop feedstocks which are capable of delivering significant life-cycle greenhouse gas (GHG) emissions savings compared to fossil fuel alternatives and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts." (IEA, 2016b). Whether HVO is classified as an advanced biofuel or not depends on the feedstock used in its production.

residues, high-yielding grasses, and short-rotation coppice wood, expand the range of sustainable resources from which biofuels may be produced and also offer enhanced carbon savings. Certain liquid biofuels are also “drop-in fuels”, which can be direct substitutes for specific fossil fuels, for example in aviation.

These new and advanced technologies are at different stages of maturity. A number of plants are now operating at a commercial scale, but output still accounts for a small fraction of total biofuel production.

In the medium term, production of both ethanol and biodiesel are expected to continue to grow alongside increases in newer fuels, including HVO (IEA, 2016c).

Short-term perspective

Bioenergy has been growing over the last ten years, notably in the electricity sector, driven by favourable policies and financial support, particularly in Europe. Lower rates of growth have been experienced in the heating sector and recently in the transport sector due to a lack of policy attention in the case of heat, and policy uncertainty in the case of biofuels. IEA medium-term forecasts, based on detailed assessments of trends and policies in each of the major markets, indicate that these relatively low growth rates are likely to persist to 2021 and beyond, despite being well below rates of growth needed to meet the long-term targets associated with the 2DS and B2DS.

In order to accelerate progress, more intensive effort will be required – both to stimulate faster deployment of technologies that have already been developed and that can be rolled out in a broader range of countries and regions, and to bring forward next-generation technology.

Bioenergy in decarbonisation scenarios

Future impact of current ambitions: Bioenergy in the RTS

In the RTS, the contribution of bioenergy to end-uses grows by a factor of 45%, despite a decline in traditional use of biomass, as explained below. (Figure 7.4). This growth is stimulated by the continuation of favourable policies already in place. Analysis of the evolution of final energy consumption of bioenergy for each end use shows that the net primary biomass supply needed to meet these demands (taking account of conversion losses) rises by 50% from the current level of 63 EJ, to 99 EJ by 2060.

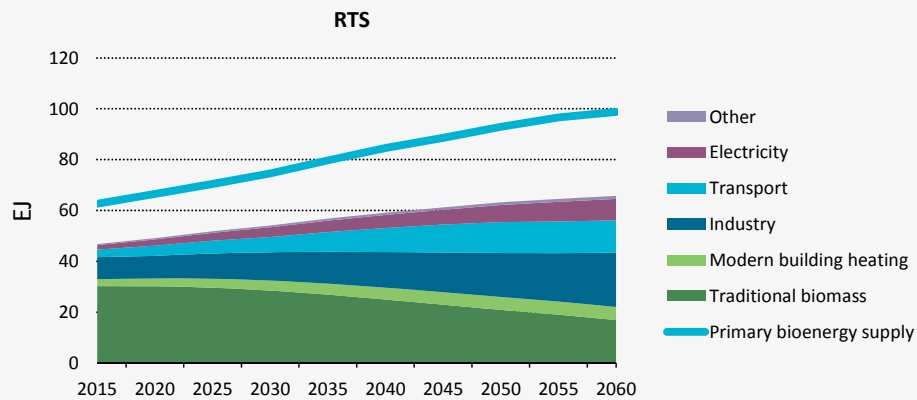
In the buildings sector under the RTS, traditional use of biomass decreases from 30 EJ to 17 EJ by 2060 in light of programmes aimed at improving access to clean energy and better economic circumstances in a number of countries. By 2060, traditional use of biomass is expected to be concentrated in sub-Saharan Africa and Asia. Biomass for more efficient heating in buildings grows by around 90% from 2015 levels, concentrated in Africa, North America, China, Western Europe and Eurasia, and India.

Bioenergy supply to industry and the agricultural sector can provide carbon savings in both low-temperature applications (e.g. for steam raising or drying) and in high-temperature applications (e.g. as a fuel in the cement industry). In response to policies encouraging carbon reduction its use grows sharply in the RTS, from 9 EJ to 23 EJ, with growth concentrated in the pulp and paper sector and for the provision of process heat and steam in other bio-related industries, such as the timber and agro-industrial sectors. For high-temperature applications, growth is concentrated in the cement industry.

Electricity generation from biomass and wastes in the RTS increases by a factor of 4.7 between 2015 and 2060, increasing from 2% to over 5% of total generation.

In the RTS, transport use of biofuels grows by a factor of four, mainly based on expansion of current conventional biofuel technologies and a limited deployment of advanced biofuels, reaching 12 EJ in 2060.

Figure 7.4. Contribution of bioenergy to final energy consumption – RTS



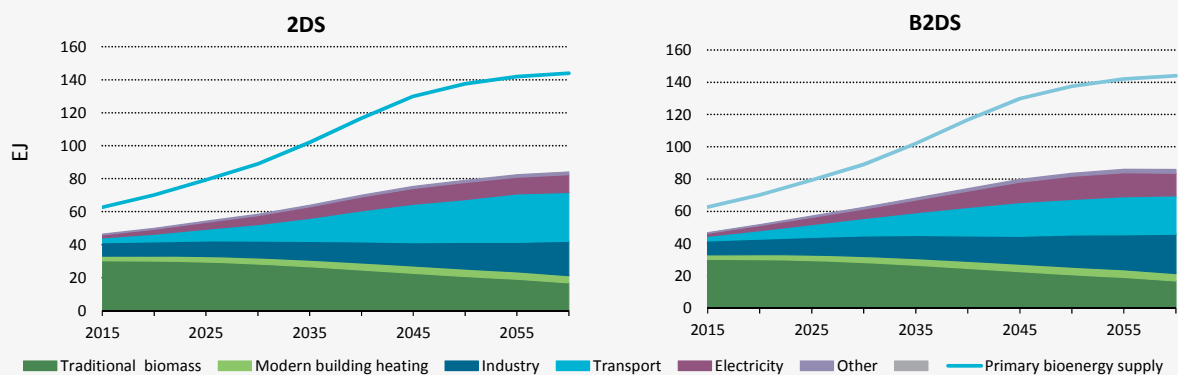
Key point *All bioenergy sectors grow strongly in the RTS (except traditional biomass), and primary biomass supply rises by over 50%.*

Bioenergy in the clean energy transformation: 2DS and B2DS

In modelling the role of bioenergy in the 2DS and B2DS, given potential constraints on the overall availability of sustainable biomass feedstocks, total available biomass supply was capped at around 145EJ. Bioenergy use is focused where bioenergy can fulfil a specific role in decarbonising sectors for which other options are scarce. The deployment patterns in the 2DS and B2DS are shown in Figure 7.5.

In particular, 2DS bioenergy plays an enhanced role in the transport sector. To meet all sectoral demands, the overall level of primary biomass supply rises to 145 EJ in 2060.

Figure 7.5. Contribution of bioenergy to final energy consumption – in 2DS and B2DS



Key point *Bioenergy for transport grows strongly in the 2DS, and total biomass supply exceeds 140 EJ. In the B2DS, there is a shift in bioenergy use patterns to facilitate the use of BECCS.*

In the B2DS, bioenergy continues to play an important role but with the emphasis shifting somewhat. This is in response to other changes in energy use and the fuel mix brought about by higher levels of energy efficiency and the greater contribution of other technologies. One key change is the greater extent to which bioenergy production is

coupled with BECCS or BECCU. The overall level of sustainable biomass input needed in the B2DS is similar to that in the 2DS (peaking at 145 EJ).

In the 2DS and B2DS, the role of bioenergy in the buildings sector does not change radically compared with the RTS. Traditional biomass use follows the same pattern as in the RTS, reducing by around 40% between 2015 and 2060, reflecting the difficulties of reducing such uses. Growth in modern biomass heating is constrained by the greater emphasis on reducing building heat demand, and is slightly lower in the 2DS and B2DS than in the RTS (4.5 EJ and 4.6 EJ compared with 5.2 EJ).

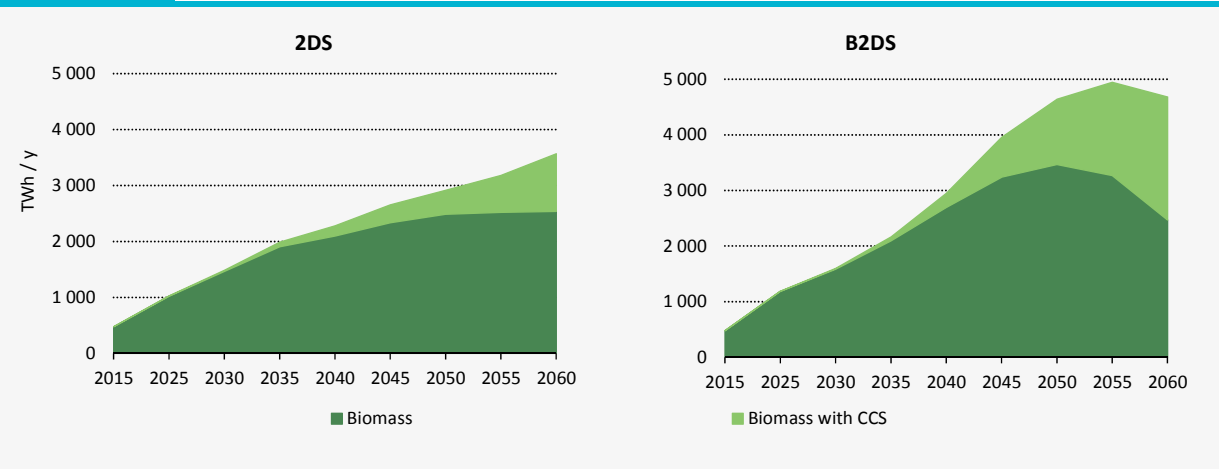
In the 2DS, the absolute contribution of bioenergy to the industrial sector drops slightly compared with the RTS, although its share in total energy use rises from 8% to 13% as measures to reduce overall energy demand in the industrial sector take effect. The overall level of bioenergy used in this sector still increases by a factor of nearly 2.5 by 2060 compared with 2015 levels. The industrial sector is projected to be the greatest user of bioenergy after the transport sector. Some deployment of BECCS is also seen in the industrial sector. In the B2DS, bioenergy makes a 30% higher contribution to demand in the industrial and agricultural sectors compared with the 2DS, with strong growth in non-energy-intensive sectors and the cement industry. This scenario also sees growth in the use of biomass as chemical feedstock.

Biomass use for the generation of electricity can play an enhanced role in low-carbon scenarios in circumstances where its generation costs are low (for example where feedstock costs are low or where the heat can be efficiently used), where it complements high levels of variable renewable generation from wind and solar by providing flexible dispatchable power, and where it can help reduce emissions through being used in conjunction with CCS or carbon capture and use (CCU). In the 2DS, the absolute contribution of bioenergy to electricity production increases more strongly than in the RTS. The share of bioelectricity in total generation rises to nearly 7% by 2060. Towards the end of the modelled period, BECCS begins to play an important role (Figure 7.6).

In the B2DS, bioelectricity generation rises to nearly 5 000 TWh, 10% of total electricity generation. This scenario sees a strong shift to increased use of electricity generation coupled to BECCS (Figure 7.6).

Figure

7.6. Bioelectricity – gross generation in the 2DS and B2DS



Key point

Bioelectricity production grows six-fold in the 2DS, with BECCS playing a key role by 2060. The B2DS sees strong growth in BECCS, with a switch from non-CCS generation after 2050.

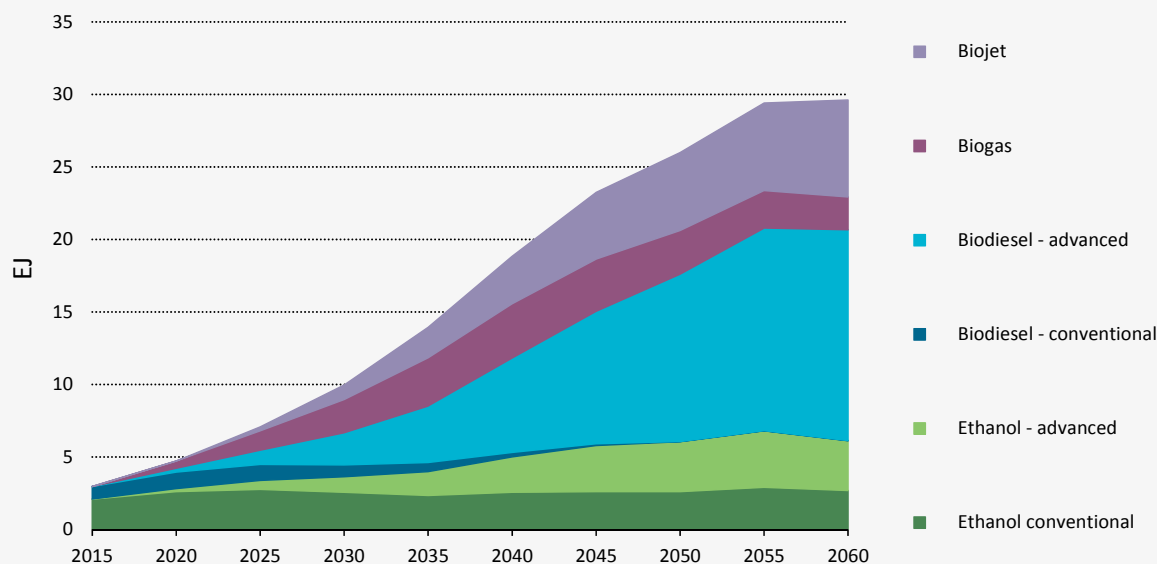
The 2DS sees a major expansion of the role of bioenergy in the transport sector, reaching nearly 30 EJ in 2060 (2.5 times that in the RTS and nearly 10 times today's level). It plays a key role in the decarbonisation of long-haul transport modes, complementing measures

aimed at constraining the sector's energy needs and the enhanced role of electrification and other measures in urban and other shorter-haul transport applications. The pattern of biofuel production also changes markedly to meet these specific end uses (Figure 7.7).

Preference is given to more sustainable fuels that have better overall GHG performance and fewer other potential impacts, and to a range of advanced bio-based fuels that can be applied in those sectors where demand for liquid fuels will be concentrated. These include advanced ethanol, jet fuel (biojet), and advanced biodiesel used in applications for which conventional biofuels such as bioethanol or fatty acid methyl ester (FAME) biodiesel are unsuitable. Conventional ethanol production will have a continuing role where production costs are low and the GHG balance is favourable, which is likely to favour sugar cane-based fuels. The role of biogas is likely to expand, especially in sectors where fossil compressed natural gas (CNG) has been adopted, but conventional vegetable oil-based biodiesel will be phased out in favour of better-performing fuels.

The absolute contribution of biofuels to transport is lower in the B2DS than in the 2DS in 2060 (24 EJ compared with 30 EJ), due to the overall reduction in transport energy demand between the two scenarios (a 19% reduction) and a higher value placed on negative emissions. Biofuels' share of overall transport energy demand actually rises to 32.1% in the B2DS (from 30.9% in the 2DS), with biogas playing stronger roles in the mix.

Figure 7.7. Role of transport biofuels – final energy demand in the 2DS



Key point

The 2DS sees a dramatic rise in biofuel production, concentrated on advanced biofuels for long-haul applications.

Technologies and strategies for decarbonisation

Biomass feedstocks have a number of advantages over fossil fuels. In particular, they can produce lower life-cycle carbon dioxide (CO₂) emissions per unit of useful energy delivered, if sourced and used sustainably (see sustainability section for further discussion). In addition, they generally contain less sulphur than crude oil or coal. The sources are widely distributed and relatively accessible.

However, the characteristics of these biomass feedstocks as delivered by collection and harvesting systems differ markedly from those of fossil fuels such as oil, coal and gas, posing certain technical and economic challenges. In particular:

- The bulk density and calorific value are lower, which means that transporting untreated feedstocks can be more difficult and costly. This can limit the area within which it is possible to source biomass and thus the economic scale of operation.
- Untreated biomass often contains high levels of moisture, which reduces the net calorific value and affects handling and storage properties. Dry biomass also absorbs water, and undercover storage is often necessary to keep the fuels dry and avoid degradation.
- Certain biomass resources are generated seasonally, e.g. during a specific harvesting period, so storage is needed to provide energy all year round.
- Systems for storing and handling and for feeding raw biomass into combustion or conversion systems have to be larger and therefore more expensive than the fossil fuel equivalents.
- The chemical composition of biomass feedstocks differs markedly from solid fossil fuels, especially due to higher oxygen content. This means that their use in systems designed for fossil fuels poses problems so that they have to be used in adapted systems, or else converted to fuels that are chemically similar to fossil fuels.

These properties mean that systems for using biomass have to be specifically designed to match the feedstock properties, and that processing of biomass before conversion to energy is often necessary to optimise the efficiency and economics of the bioenergy pathway. So when considering the technologies, three stages need to be taken into account:

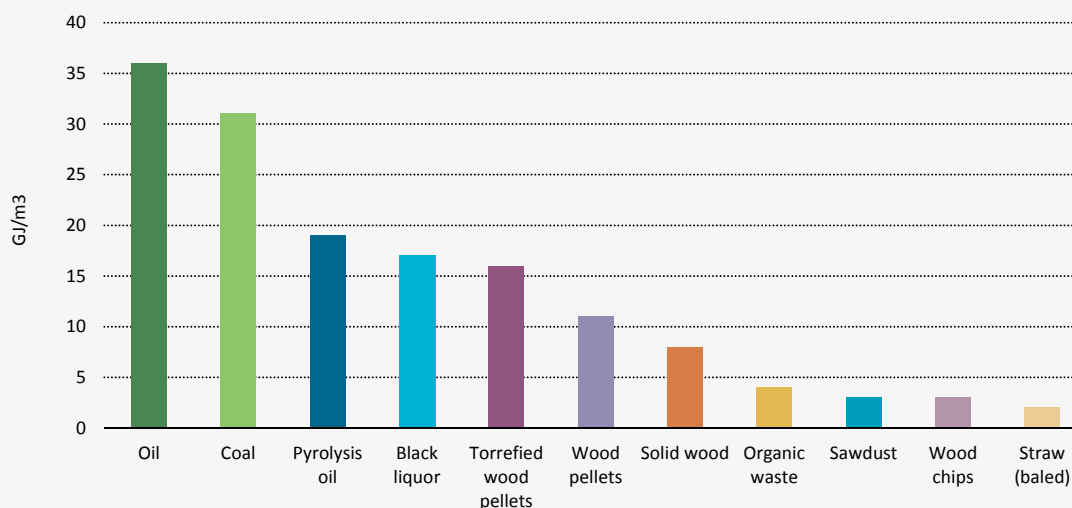
- fuel preparation: used to change the physical nature of the feedstocks to make the fuels more homogeneous and easier to handle and transport, and to improve the energy density
- pretreatment: used to change the chemical nature of the feedstocks and to produce intermediate products that are more amenable to conversion to usable end products
- conversion: to heat or electricity and fuels, or to other useful energy products.

Each of these stages is explored in further detail below.

Table 7.1 summarises the status of each of the main technologies that are either commercially available or that remain under development, classifying them according to whether they are already widely deployed, at an early stage of deployment, being demonstrated at a scale close to that of commercial plants, or at the pilot plant or research and development (R&D) stage.

Fuel preparation

Common forms of fuel preparation include drying, size reduction, pelletisation and briquetting, and torrefaction. One aim of these processes is to improve the energy density of the fuels to facilitate handling and transport. Pretreatment can progressively improve the energy density of biomass fuels, but it will never reach the same levels as coal or oil without further conversion (Figure 7.8).

Figure 7.8. Effect of biomass preparation on energy density

Notes : GJ/m³ = gigajoules per cubic metre.

Key point *Preparation technologies can significantly increase biomass energy density, but never achieve fossil fuel levels.*

Technologies for drying and size reduction are fully commercialised, and plants can be designed that are capable of treating many different forms of raw material – from simple chipping and drying systems for woodchips to much more complex systems that aim to separate the components of MSW to recover materials alongside an energy product. Pelletisation is also now a fully commercial option, used particularly for long-haul transport of fuels for large-scale use, for example in major power generation plants. Pellets are also extensively used in smaller-scale heating applications where their higher density facilitates delivery, handling and storage. Pellet production capacity has grown rapidly in recent years to meet growing market demand (IEA, 2016b). Despite continuing efforts to develop, demonstrate and commercialise the technology, the market for torrefaction⁶ technologies has developed more slowly than anticipated five years ago (IEA Bioenergy, 2016b). However, some progress has been made and torrefaction technology is now proven at a pilot scale, with a number of demonstration and (semi-) commercial facilities having been built.

6. In torrefaction, biomass is heated up in the absence of oxygen to between 200°C and 300°C and turned into char. The torrefied wood is typically pelletised and has a higher bulk density and 25% to 30% higher energy density than conventional wood pellets.

Table 7.1. Technology development status of main bioenergy options

Technology	Basic and applied R&D	Demonstration	Early commercialisation	Widely deployed
Fuel preparation				
Drying				Widely deployed
Size reduction				Widely deployed
Pelletisation				Widely deployed
Torrefaction		Demonstration		
Fuel pretreatment				
Anaerobic digestion				Widely deployed
Pyrolysis		Demonstration		
Gasification				
<i>Small scale</i>			Early commercialisation	
<i>Large scale</i>		Demonstration		
Conversion				
Heat				Widely deployed
Electricity				
<i>Large-scale generation/ co-generation</i>				Widely deployed
<i>Co-firing</i>				Widely deployed
<i>BIGCC</i>	Basic and applied R&D			
<i>ORC</i>			Early commercialisation	
<i>Gasification/engines</i>			Early commercialisation	
<i>Biofuel cells</i>	Basic and applied R&D			
Biogas upgrading			Early commercialisation	
Biofuels				
<i>Ethanol from sugar crops</i>				Widely deployed
<i>Biodiesel from oil crops</i>				Widely deployed
<i>Cellulosic ethanol</i>		Demonstration		
<i>Other biological routes</i>	Basic and applied R&D	Demonstration		
<i>VO</i>			Early commercialisation	
<i>Upgraded pyrolysis oil</i>	Basic and applied R&D			
<i>Upgraded synthesis gas</i>		Demonstration		
<i>Hydrothermal liquefaction</i>	Basic and applied R&D			
<i>Waste gases and power to fuels</i>		Demonstration		

Notes: BIGCC = biomass integrated gasification combined cycle; ORC = organic Rankine cycle.

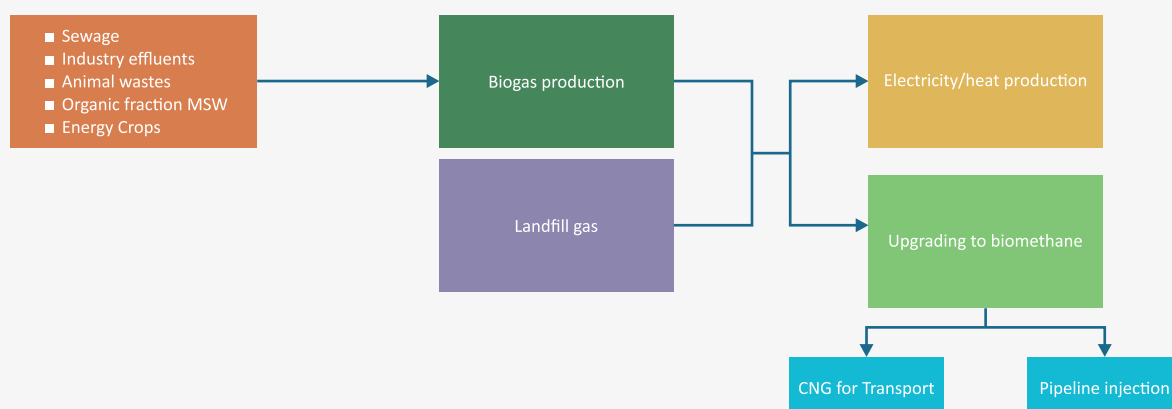
Fuel pretreatment

Three main pretreatment technologies can be used to upgrade feedstocks chemically to produce intermediate products more amenable to conversion to usable end products:

- Anaerobic digestion to biogas and biomethane. The production of biogas depends on the biological degradation of a wide range of biomass materials in the absence of air (anaerobic conditions) to produce a mixture of methane and CO₂. The gas can be used for heating and for electricity production, or upgraded by separating the CO₂ and impurities to produce a pipeline-quality methane (biomethane), which can be injected into gas distribution systems or used to replace CNG in transport (Figure 7.9).
- Thermochemical liquefaction processes, such as pyrolysis, where biomass is heated to temperatures between 400°C and 600°C in the absence of oxygen. The process produces solid charcoal, liquid pyrolysis oil (also referred to as bio-oil) and a product gas. The bio-oil can be used directly to produce heat or power, or upgraded, for example by hydrogenation, to produce a diesel-type fuel.
- Gasification, in which biomass is heated with a restricted supply of air, producing a synthesis gas mixture consisting of carbon monoxide (CO) and hydrogen (H₂), plus other components that, depending on the operating conditions, can include CO₂ and methane. The resulting gas can be used in a number of ways: as a fuel gas for industrial furnaces and kilns or to generate heat and power via a gas engine or gas turbine, or it can be further processed to methane or to produce more complex hydrocarbon fuels and chemicals, as well as a role in ammonia and methanol synthesis.

Anaerobic digestion is now a fully commercial technology, with a range of well-established designs available, and can be tailored to treat particular feedstocks and mixtures. These include large-scale digesters installed at municipal water treatment facilities or operating at a regional scale, taking a range of wastes from industrial and agricultural sources. There are also much smaller-scale designs suited for installation at a village or household scale in emerging economies and developing countries – such systems can contribute to efforts to improve energy access.

Figure 7.9. Anaerobic digestion options



Key point *Anaerobic digestion can provide methane for a range of applications.*

Pyrolysis technologies have been under development for many years, but have yet to be significantly deployed at scale. Challenging technical issues include the quality of the pyrolysis oil (such as relatively high oxygen content) and its long-term stability, as well as the economics of its production and use. Several commercial-scale projects have been

built, but the success rate has so far not been high. However, a new impetus has been seen recently. In 2015, for example, Biomass Technology Group opened a pyrolysis plant in the Netherlands to produce 15 megawatts (MW) of fuel oil from woody biomass, and Fortum opened a 50 000-tonne-per-year plant in Finland producing 30 MW of oil per year. Significant activity is also linked to the upgrading of pyrolysis oil to fuel at a pilot scale, which can substitute for diesel or jet fuel.

The potential for biomass gasification to convert heterogeneous, low-density feedstocks into a clean, energy-rich gas for production of heat, power and transport fuels has long been recognised. However, the technology has not yet fully matured and, until recently, costs and technical reliability have discouraged widespread adoption. Some hundreds of small-scale gasifiers are now in operation, producing heat and power for farms, small factories and local communities. In addition, several industrial-scale systems have been established – the largest exceeding 100 MW thermal input – producing synthesis gas for heat and power and to produce substitute natural gas or other fuels. Despite these large-scale demonstration projects, examples of successful large-scale operation are rare, with persistent problems associated with tar formation, which affects downstream processing of the gas.

Conversion

The biomass sources, after preparation and pretreatment where this is technically or economically desirable, can now be converted into useful energy – in the form of heat, electricity or fuels (or in combination).

Biomass for heat

As discussed earlier in this chapter, most bioenergy continues to be used as the principal source of heat for cooking and space heating in many less-developed countries, using an open fire or a simple stove for burning wood, agricultural residues, animal dung or charcoal – commonly referred to as traditional biomass use.

The traditionally used open fires or simple stoves have very low conversion efficiency – often in the range of 10% to 20%. Poor combustion can cause severe problems of smoke pollution, especially when these systems are used indoors, giving rise to significant health problems. This poor performance means that collecting sufficient fuel is a time- and effort-consuming exercise, and fuel demand often exceeds the available sustainable supply. In addition to the replacement of biomass heat with fossil fuel solutions, such as liquefied petroleum gas, many improved stove designs are now being widely adopted, with better efficiency and cleaner combustion. They improve indoor air quality and reduce fuel use, thus improving health and taking pressure off the biomass resources.

However, despite many international initiatives, some 2.7 billion people continue to rely on traditional biomass, and even in 2050 it is anticipated that many people, mainly in Asia and Africa, will still be using these fuels. Further efforts to promote the use of efficient cooking and heating devices are therefore imperative.

Modern and efficient biomass combustion plants for the production of heat use very mature technology, with systems available that can cope with a wide variety of biomass fuels at very different scales, ranging from the hundreds of megawatts thermal down to small-scale systems for use in individual households. Modern biomass heating technologies include efficient systems for the combustion of wood logs, chips, and pellets; MSW incineration; and use of biogas. Combustion in well-designed plants is highly efficient, and in larger-scale plants emissions can be carefully controlled to meet stringent air quality standards. Bioenergy heat can also be distributed through a heat network to supply industry, commercial operations and households. The larger scale of operation allows economies of scale to be realised, and it is easier to ensure that good emissions standards are achieved at these larger scales. Such systems can also operate in co-generation mode to produce heat and power.

In industrial applications, bioenergy is often used for steam and heat production in the biomass handling industries, notably in the pulp and paper sector where black liquor, wood offcuts, and other wastes and residues are used. In the sugar cane mill industry, bagasse and increasingly also cane trash is used for the co-generation of steam. Biomass residues

are also used in other related sectors – notably in the timber sector (where wood is used for kiln drying, for example) and in the food sector where, for example, effluents and residues are used in anaerobic digestion systems and the resulting biogas used for heat and power applications.

One of the chief applications of biomass and wastes for high-temperature process heat is in cement production, where biomass (and more especially waste material) is extensively used as a supplementary co-firing fuel. The low-cost waste fuels can be directly introduced into the highly rigorous alkaline conditions that are found in the kilns. Furthermore, certain limekilns in the pulp and paper industry are fired with fuel gas from gasification or clean wood powder.

To date, other high-temperature applications remain rare – except for a small amount of charcoal used in iron and steel production in Brazil. The key technical issue to be resolved is to design biomass and waste fuel preparation and feeding systems that are compatible with the process and do not impact on product quality or by-product quality, since the residues of combustion are usually incorporated into the final materials produced.

Factors affecting the cost of heat produced from biomass are principally the nature of the fuel to be used and the capital cost of the equipment. While the scale of the plant affects the specific capital cost of the system, unlike power generation the efficiency at which fuels can be converted to useful heat energy is not highly sensitive to scale, since high efficiencies can be achieved in well-designed and well-operated systems from residential scale to large industrial applications.

Biomass heat systems are significantly more expensive in capital terms than coal, oil or gas boilers at a similar scale. The volumes of fuel that need to be handled are higher, the combustion zones and boiler systems need to be larger, and emissions control systems need to be carefully designed and operated. This means that, for a given fuel cost, the utilisation rate of the system is the most critical factor in determining the cost of producing heat. Systems used for individual residential or commercial space heating applications tend to have low utilisation rates (depending on climate), whereas larger-scale plants for heating and especially for co-generation – for industrial purposes or for district heating – can achieve higher full-load hours. This improves the competitive position of biomass compared with fossil fuel alternatives.

The extent to which biomass heating is financially competitive with oil and gas alternatives in buildings also depends critically on the difference in price between fossil fuels and the bioenergy fuels used. At today's fossil fuel prices, biomass heating is likely to be strictly competitive only where high utilisation rates can be achieved, where significant support is available through grants for capital costs or revenue support, or where fossil fuel prices are elevated through carbon or energy taxes. The technology for biomass heating systems is well established and the scope for significant technological development to significantly reduce costs is low. However, scope exists for cost reductions through development of standardised packaged systems.

For applications of biomass in high-temperature industrial processes, the critical issue is the cost of the biomass feedstock compared with existing fuels – often low-cost coal. This favours wastes and other low-cost feedstocks (including certain chemical and other fossil-based wastes). Nevertheless, competition in the absence of a significant carbon price is challenging.

Biomass for electricity generation

A number of routes exist to produce electricity from biomass. The most established is to generate power from biomass using combustion and steam turbines. The efficiency of power generation depends on the scale of the plant; at the largest scale of biomass use (over 100 MW), efficiency approaches those of conventional coal plants with a comparable capacity (circa 35%), while efficiency falls off sharply at lower scales – to around 25% at the 10 MW scale and only 8% to 12% at 1 MW (Koppejan and van Loo, 2012). In many applications, the scale of operation is limited either by feedstock availability or by the opportunities available to match heat loads to allow efficient co-generation.

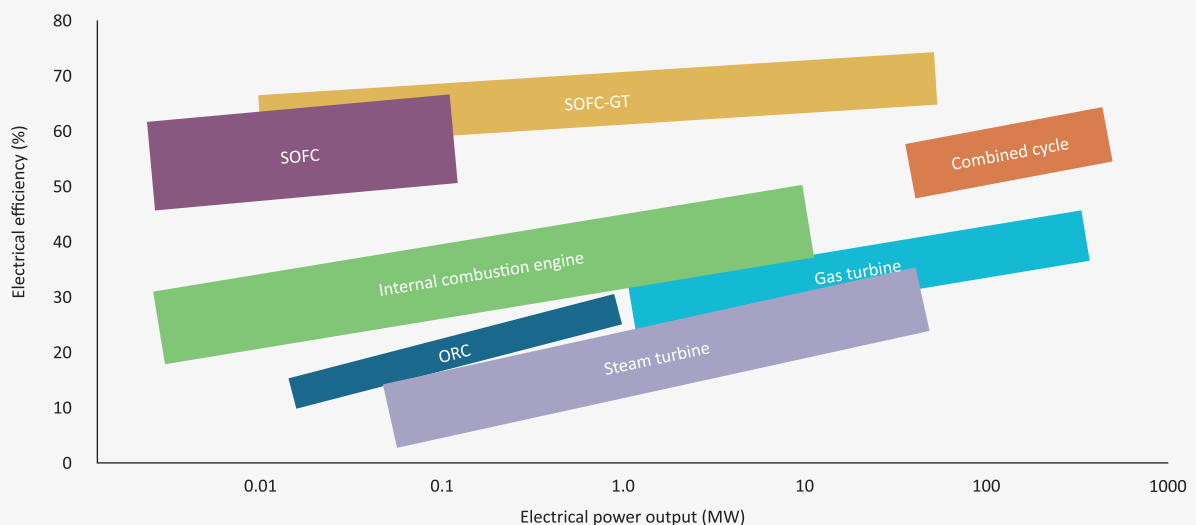
Co-firing of biomass with coal (or conversion of coal-fired power plants to operate entirely on biomass) in existing large power station boilers has proved to be one of the most cost-effective large-scale options. This approach makes use of the existing infrastructure of the coal plant and thus requires only relatively minor investment in biomass pretreatment and feed-in systems; it also profits from the comparatively higher conversion efficiencies of these large-scale coal plants.

In principle, at a larger scale biomass-fuelled gasification-based systems can be coupled with combined gas and steam turbines to form a BIGCC. This should provide efficiency advantages compared with combustion. However, little recent progress has been made in demonstrating and deploying such technologies at a large scale.

Producing both heat and power is a key technique employed to improve the overall conversion efficiency of biomass use, improving both resource utilisation and the overall economics while providing carbon savings. When a good match exists between heat production and demand, such co-generation plants have typical overall (thermal plus electricity) efficiencies in the range of 80% to 90% (IEA Bioenergy, 2015a). However, it is not always easy to ensure good spatial and temporal matching of electricity and heat demand.

The relatively low electrical efficiency of electricity generation from biomass systems is the driver prompting development of more efficient systems that can operate at smaller scales. These include gasifier systems linked to engines, ORC systems, and fuel cell systems, which can offer higher efficiencies than steam cycles at smaller scales of operation (Figure 7.10).

Figure 7.10. Generation efficiency and scale



Notes: SOFC = solid oxide fuel cell; SOFC-GT = solid oxide fuel cell gas turbine.

Key point *Steam turbine efficiency falls sharply at lower scales of operation, prompting the development of new technologies for small-scale use.*

Adapted diesel- and gas-fired engines and turbines are widely deployed using liquid biofuels and biogases from digestion or thermal gasification. Smaller-scale gasification systems are deployed in certain countries (notably in India and other Asian markets) and also more recently in Europe. Further work is needed to ensure that reliable performance and acceptable emissions levels can be achieved, and to reduce costs.

In an ORC system, heat from the combustion of biomass is transferred to an organic fluid (rather than to water as in a steam system), which is vaporised at a temperature of around 300°C. The vaporised fluid drives a turbine and is then condensed (with heat recovery) in a closed cycle. This allows for more efficient electricity generation than is possible for steam cycles at this scale and for simpler plant design since, for example, no superheating is required. Europe now has more than 120 plants in operation, with sizes between 0.2 megawatt electric (MW_e) and 2.5 MW_e used to provide electricity and heat for industrial processes and for district heating schemes (Bini et al., 2017).

Another route offering the potential for higher conversion efficiencies is the use of solid oxide fuel cells (SOFCs) fuelled by biogas or biosynthetic gas. For example, the aim of the Bio-Hypp project, funded under the EU Horizon 2020 programme, is to develop a 30 kilowatt (kW) fuel cell that uses biomethane and that can provide a cell conversion efficiency of up to 60% electrical efficiency at that scale and 70% at larger scales. The system uses an SOFC linked to a micro-turbine and should be capable of operating on a wide range of gas quality, while also being able to operate flexibly with a high turndown ratio (Bio-Hypp, 2017).

The cost of electricity produced from biomass energy varies widely depending on a number of factors relating to capital cost, plant efficiency, fuel cost, fuel availability, the cost of finance, and whether the plant produces solely electricity or operates in co-generation mode. Generation costs also vary significantly from region to region, depending on the quality of the installation (efficiency and reliability) and particularly on the environmental standards that have to be met. Indicative reference capital costs for a number of systems are shown in Table 7.2 alongside generation costs (shown as levelised cost of energy [LCOE]) (IEA, 2016c).

Table

7.2. Reference global investment costs and LCOE ranges for bioenergy power technologies

Bioenergy technology type	Investment cost (USD/kW)	LCOE (USD/MWh)	Comment on investment costs
Biogas	1 000–8 500	50–190	Average biogas investment cost in Europe USD 3 500 to USD 5 500; lower-end investment costs refer to Asian countries, e.g. China, India and Thailand.
Coal-to-biomass conversion	350–1 800	Not available	Costs are highly specific to each project.
Dedicated biomass electricity	800–4 500	80–200	The lowest investment costs are generally found in India for plants fuelled by agricultural residues.
Energy from waste	2 600–8 000	40–220	Higher-end costs in Europe and Japan; lower-end costs in China and Thailand.
Gasification	2 000–8 000	50–250	Covers technologies using a range of feedstocks such as MSW, black liquor, and agricultural and forestry residues.
Landfill gas	1 800–2 300	40–90	The investment cost range is more uniform over different regions than observed for other bioenergy technologies.
Low-level co-firing	260–600	40–120	Refers to <10% biomass share by energy combusted in coal power plants.

Notes: USD = United States dollar; MWh = megawatt hour.

A strong relationship exists between the source of fuels and the possible scale of generation. Wastes and process residues are generally available only in limited quantities (related to production volumes) at a particular site. The potential for collection in large quantities is constrained by delivery costs. These factors typically limit operation to 20 MW to 30 MW as a maximum. A trade-off therefore exists between increasing the scale of

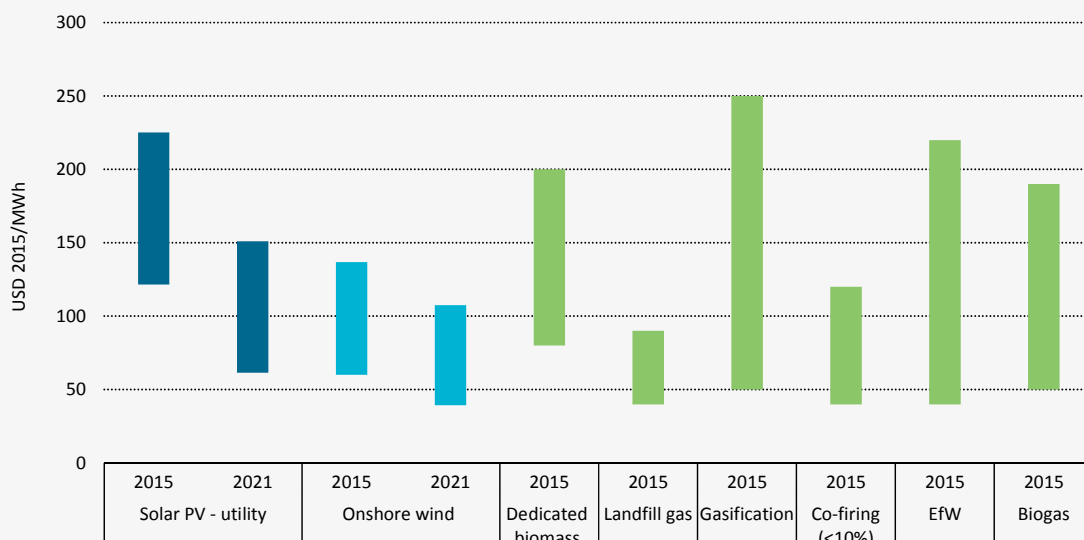
operation, with lower capital costs and higher efficiencies, and the difficulties of procuring low-cost feedstocks at a large scale.

The most widely deployed bioenergy generation technologies are mature and therefore offer limited scope for further cost reductions. There is some potential to reduce costs through standardisation of system design and by incremental improvements to generation efficiency, but it is unlikely that dramatic cost reductions (such as those being experienced in the wind and solar photovoltaic [PV] sectors) will be seen. New developments aimed at improving the efficiency of smaller-scale generation should lead to more significant cost reductions, but these are likely to bring the cost of such systems closer to, rather than below, those of larger-scale projects.

By contrast, the cost of some other renewable technologies, notably of wind and solar PV generation, has been falling rapidly, and this trend is expected to continue. This means that the cost of bioenergy generation will not only tend to be high compared with fossil fuel options, but also face increasing competition from other renewable energy generation options on an LCOE basis when the wind and solar resource is favourable (Figure 7.11).

Figure

7.11. Comparison of LCOE of bioenergy and other renewable energy generation options



Key point

Bioelectricity faces growing competition from wind and solar PV technologies, whose costs are expected to continue to fall.

Factors that will favour reduced costs are the use of low-cost feedstocks (such as process residues available at the generation site or waste fuels), smaller-scale projects where there is excellent utilisation of the heat produced, and larger-scale projects where high generation efficiencies and utilisation rates can be achieved.

In addition, bioelectricity projects may be favoured on account of other benefits they offer – for example, the environmental benefits associated with improved waste management, or the social benefits associated with rural development. In these cases it is important that such benefits are monetised (for example through taxes or regulatory measures that push up the cost of, or ban, alternative waste disposal measures).

A further benefit of many bioelectricity systems is that they can produce dispatchable power and respond flexibly to the needs of grid systems – unlike certain variable sources such as solar PV and wind systems. This positive characteristic can be rewarded by allowing

electricity from biomass sources to benefit from the flexibility service it provides (see section on “Bioenergy technology priorities for deep decarbonisation – electricity” for further discussion).

Biogas upgrading

Anaerobic digestion produces biogas in the form of a mixture of methane and CO₂, alongside a number of minor components that can include water, hydrogen sulphide, siloxanes, ammonia and other contaminants, depending on its source. To upgrade the gas to a biomethane that can be used for transport needs or injected into gas pipelines, its quality needs to be improved by removing the minor components. Biomethane can then be separated from the CO₂ by stripping out the CO₂ using pressure swing adsorption, absorption, membrane and cryogenic upgrading technologies.

Such upgrading systems are now commercially available and are being employed in a number of countries to produce transport fuels, notably in Germany, Sweden and the United States (where upgraded biogas qualifies as an advanced biofuel under the Renewable Fuel Standard).

Production of transport fuels

For convenience, biofuels can be categorised under two headings: conventional biofuels, including ethanol and biodiesel produced from sugar, corn, cereals and oil-based crops and processed using fully commercial technologies; and advanced biofuels.

In the sugar-to-ethanol process, sucrose is obtained from sugar crops such as sugar cane, sugar beet and sweet sorghum, and is subsequently fermented to ethanol. The ethanol is then recovered and concentrated by a variety of processes. Biodiesel and HVO are produced from raw vegetable oils derived from soybean, canola, oil palm, sunflower and other oil-producing crops, as well as animal fats and used cooking oil. The oils and fats are converted to biodiesel (FAME) using methanol or ethanol, or to HVO using hydrogen.

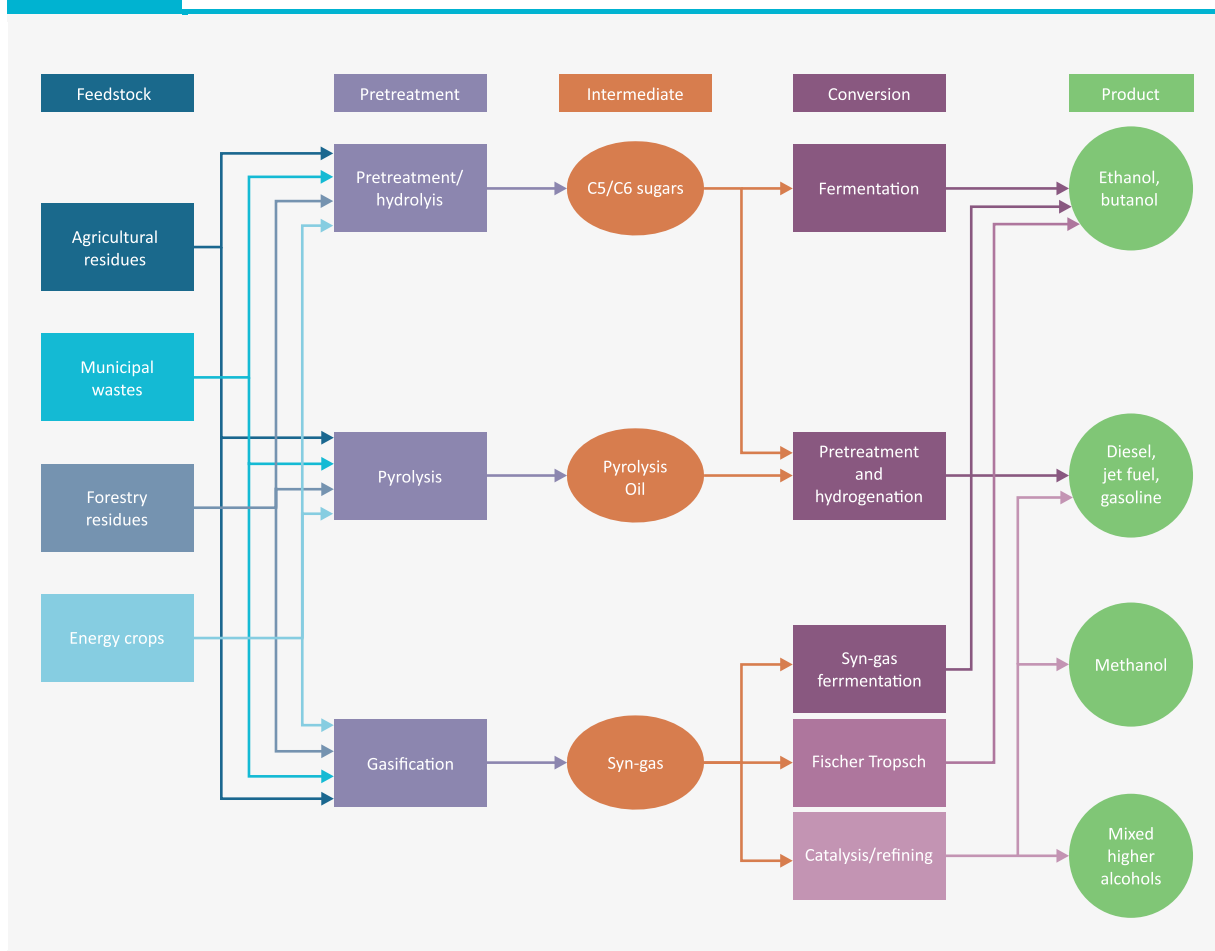
The production of HVO has been successfully commercialised in recent years. Fatty acid-containing materials, including waste products such as used cooking oils, animal fats and vegetable oils, and by-products from paper- and pulp-making processes such as tall oil, are pre-processed and then subject to a hydrogenation process that reduces the oxygen content. Isomerisation of the product can be controlled to produce a range of fuels including advanced biodiesel, naphtha and aviation fuels.

The rationale for the development of advanced biofuels is to produce fuels that have better overall GHG performance and that can use residues or non-food crops so as to minimise the impact of large-scale production on land use. A further objective is to produce fuels that are better suited to the end uses that will be a priority in the future, such as long-haul land transport, shipping and aviation.

The challenge of producing fuels from biomass with the same chemical composition and properties as fossil fuels should not be underestimated. In particular, biomass materials (and fuels such as ethanol and biodiesel) contain significant proportions of oxygen, which must be removed to make “drop-in fuels”.

A range of approaches to the production of advanced biofuels have been actively under development for around 40 years, using either biological or thermal routes (Figure 7.12). While advances in the development and commercialisation of these technologies have been slower than expected, promising signs of increasing maturity have emerged in the last five years, with a number of technologies successfully seeing advances in R&D, moving to early deployment and pilot-scale operations (IRENA, 2016a).

Figure 7.12. Some advanced biofuels pathways



Key point *A wide range of advanced technologies are under development.*

Biochemical processes for advanced biofuels concentrate on the conversion of lignocellulosic materials to sugars. These can then be turned into alcohols, or directly or indirectly into hydrocarbon fuels. Potential feedstocks include agricultural and wood residues; wood from forestry; short-rotation coppices and lignocellulosic energy crops, such as energy grasses and reeds; and waste fractions such as cellulosic fibres from cardboard and recycled paper.

This is the best developed of the various biological routes to biofuels, with more than 10 commercial-scale facilities having been constructed and now in operation, with a similar number of demonstration plants and over 40 pilot-scale plants. Most production is based on agricultural residues (which are easier to break down than woody materials).

A range of other processes are under development that take the sugar feedstock produced by lignocellulosic hydrolysis. Options include using sugars as a feedstock for fermentation directly to other chemicals that can be used as fuel components or as petrochemical replacements.

A number of routes are available for the thermal conversion of biomass to potential fuels and chemicals. For example, the synthesis gas produced by biomass gasification can be transformed into fuel and chemical products, including methane, methanol and di-methyl ether, which can be further processed to make bio-gasoline, or to co-produce gasoline, diesel and aviation fuels by the Fischer-Tropsch process. The gas emerging from the gasifier must be cleaned to remove troublesome tars and other components, especially sulphur and chloride compounds and other trace components that can poison catalysts

used in further processing. Another interesting alternative conversion is to treat the syngas with biological processes, using acetogenic microbes that can be tailored to transform a wide variety of carbon-rich gases, including CO and CO₂ with or without H₂, into ethanol, higher alcohols or hydrocarbons.

In a further option, oils produced by pyrolysis can be upgraded by feeding them as a small percentage of feedstock into the fluid catalytic cracking unit of a petroleum refinery. Larger molecules are broken down and reduced at high temperatures and with a catalyst. The resulting product streams contain a proportion of biomass-derived fuels. The necessary refinery modifications are minimal, so capital cost requirements are low. Alternatively the same type of process can be undertaken in a stand-alone plant.

Other low-carbon fuels

There are a range of other low carbon fuels which are under development. For example hydrocarbons and alcohols can be made from industrial waste gases. In addition “power to gas” and “power to liquid” technologies, in which hydrogen is produced by electrolysis and then combined with CO₂ catalytically to form methane or methanol. The source of the CO₂ can either be from a fossil source or from a biological source – for example from the gas produced in fermentation in a biofuels production plant.

These technologies are currently reaching demonstration scale. (European Commission 2017 For example:

- A consortium of Lanza Tech, ArcelorMittal Primetals Technologies and E4Tech are building a demonstration facility at a steel plant in Ghent, Belgium which will make ethanol from CO rich waste gases produced during the steel making process, using a gas fermentation process.
- Eon’s power to gas pilot plant in Germany uses renewable sourced electricity to produce hydrogen, which is then injected into the natural gas transmission system.
- SolarFuel GmbH, working with Audi, has developed a power-to-gas demonstration facility with a 6.3 MW_e capacity in Germany which produces methane using CO₂ from a nearby waste treatment biogas facility.
- In Iceland the largest power to methanol plant has been in operation for five years. This plant recycles CO₂ captured from a geothermal power plant, and hydrogen produced through electrolysis using electricity produced from hydro and geothermal sources.

Such processes can produce a range of fuels with similar carbon advantages to biofuels, depending on the source. Their use in conjunction with gases produced during bioenergy production can also “gear-up” the useful energy produced for each unit of bioenergy produced.

These technologies share many of the same barriers to commercialisation with bioenergy, and their commercialisation will require a similar policy and regulatory framework. If this is put in place, there are good prospects that these technologies could be scaled up quickly once successfully demonstrated. It is for example considered possible that between 1.2 and 1.7 of the European Union’s transport fuels could come from such sources by 2030. (European Commission 2017).

Biofuel costs

It is difficult to establish the costs of the various advanced biofuel options as the information is proprietary and the processes are at different stages of maturity and scale of operation. What is clear is that current production costs are generally significantly above those of both conventional biofuels and the fossil fuel equivalents that they seek to replace.

For example, the equivalent crude oil price at which current cellulosic ethanol production would be competitive (break-even oil price) is estimated to be in the region of USD 100 per barrel (bbl) to USD 130/bbl (IEA, 2016b). Limited lower-cost opportunities are available based on using wastes or other residues and byproducts as feedstocks, but the potential for replication is constrained.

The industry has significant room for innovation to deliver cost reductions and improve yields. Trends in cost reduction and efficiency improvement previously observed in the conventional biofuels industry can be replicated within advanced biofuels. For example, significant potential has been identified to reduce production costs for cellulosic ethanol fuels. Capital and operating costs can be reduced with experience, and process efficiency and yield can be improved. Taken together these have a significant effect on costs, since higher efficiency lowers both feedstock costs and the scale of plant needed for a specified output. It can also be assumed that more favourable financing conditions will be available for plants not considered first of their kind, therefore lowering investment costs, as long as a policy regime is in place that establishes a stable market outlook for the products. Achieving this potential could allow cellulosic ethanol plants to reduce break-even production costs to around USD 45/bbl to USD 70/bbl with the benefit of experience of building several successive large-scale plants.

Biorefineries

Biorefining is the processing of biomass into a range of marketable bio-based products, including bioenergy and biofuels. It is an innovative and efficient approach to using available biomass resources for the co-production of power, heat and biofuels alongside food and feed ingredients, pharmaceuticals, chemicals, materials and minerals. This matches the current approach of the petrochemical industry, which makes both higher added-value products and lower value fuels. Biorefining is one of the key enabling technologies of a circular economy, closing loops for biomass raw materials (through the reuse of agricultural, process and post-consumer residues), minerals, water and carbon (IEA Bioenergy, 2017a). While the circular economy principally focuses on the efficient use of finite resources and ensures that these are reused as long as possible, the bioeconomy integrates the production, efficient use and reuse of renewable resources, in particular renewable carbon. Bioenergy – fuels, power and heat – are often considered an important part of a sustainable bioeconomy.

Conventional biorefineries have commonly been found in the food, feed and dairy, and pulp and paper sectors. Bioenergy- and biofuel-based biorefineries are becoming more common and in these, heat, power and biofuels are the main products, with both agricultural and process residues used to produce additional bio-based products. Assessing the number of biorefinery facilities currently in operation globally is challenging. However, more than 100 commercial, demonstration and pilot facilities have been identified.

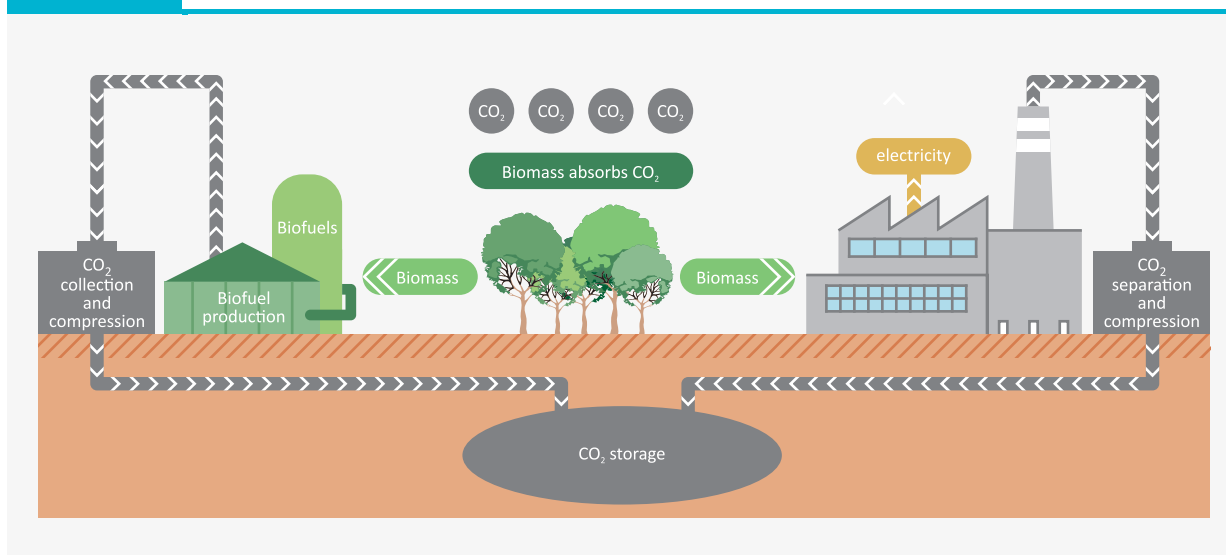
Combining bioenergy with CCS and CCU

CCS is mainly discussed in the context of avoiding CO₂ emissions from the combustion of fossil fuels, but the technology can also be deployed in bioenergy conversion plants as BECCS. In such a system the CO₂ emitted during bioenergy combustion or in the manufacture of biofuels is injected into long-term geological storage. This provides the possibility to remove “neutral” CO₂ from the atmosphere, thus providing “negative emissions” (Figure 7.13). This is one of very few demonstrated technologies able to deliver negative emissions – and the most mature. In a variant, BECCU, the CO₂ could be reused by combining it with hydrogen from renewable or other low-carbon sources to make, for example, a carbon-based fuel.

Potential applications of BECCS include:

- biofuel production facilities, including ethanol distilleries and gasification plants
- dedicated or co-firing of biomass in power, co-generation or heating plants
- pulp and paper mills
- lime and cement kilns using biomass or waste fuels.

Figure 7.13. The principle of BECCS



Key point *By capturing the CO₂ after biofuels or bioelectricity production, a net reduction in CO₂ emissions is possible.*

Five BECCS projects are known to be operating: three plants located in the United States, one in Canada and one in the Netherlands. All projects have an ethanol plant as the source of CO₂ since ethanol production processes produce a high-purity stream of CO₂. Three of the projects use the CO₂ for enhanced oil recovery. The largest project, ADM Illinois Industrial CCS project (Decatur), will capture up to 1 million tonnes of CO₂ per year from 2016.

While the technologies needed for CCS are available, it should be noted that there are significant efficiency and cost penalties associated with the technology. Work remains to be done to identify the optimum combinations of bioenergy technologies and CCS/CCU.

The route towards BECCS is not clear. Such deployment would be facilitated if CCS were widely deployed for fossil sources of CO₂, but this is currently not the case. A further important issue concerns the scale of bioenergy operations – often much smaller than fossil fuel equivalents. Further techno-economic studies are needed.

Short-term opportunities

While bioenergy is often seen as a controversial and complex area, it is clear that a number of technology options are available that:

- Are technically mature and already demonstrated at commercial scale.
- In many circumstances, have costs close to the fossil fuel alternatives.
- Can command adequately available resources that are either inherently uncontroversial regarding sustainability considerations, or for which sustainability can be assured under an effective certification or regulation scheme.

More rapid deployment of these solutions would lead to early GHG reductions while also delivering policy benefits, including increased energy diversity and security, and wider environmental and social benefits such as improved waste management or rural economic development. Wider deployment would also help stimulate the potential cost reductions associated with industrial growth and may provide an enabling environment for the next generation of bioenergy (and potentially other renewable) technologies, for example by building up experience in establishing sustainable biomass supply chains.

Examples include:

- production and use of biomethane from wastes and effluents in transport
- production of hydrotreated vegetable oil (HVO) and hydrogenated form wastes and residues in heavy duty road freight and aviation
- production and use of mid- and high-ethanol blends, E100 and ED95 in road transport
- biomass fuelled district heating, notably in areas with a consistent heat demand and substantial forestry industries
- maximising the efficiency of use of industrial biomass co-products and residues, notably for bagasse co-generation in the sugar and ethanol industry
- using energy from waste (EfW) solutions (landfill gas, sewage gas and biomass content of municipal solid waste), particularly in areas of rapid urbanisation where using the wastes as fuels can contribute to improved waste management (and help offset costs).

These and other opportunities will be discussed in more detail in the upcoming Bioenergy Technology Roadmap.

Challenges for the medium and long term

Looking ahead to the medium- and longer-term perspectives represented within the 2DS and B2DS, two questions come to the fore: what will be the energy context in which bioenergy systems will figure, and what are the technology priorities for development and deployment over this timescale?

In general, bioenergy will need to find roles in which it can make a contribution to sustainable energy supply and provide significant additional carbon savings in sectors that are hard to decarbonise in other ways. This is in a context where energy demand has been reduced through the adoption of an extensive range of energy efficiency measures and a wide variety of other low-carbon technologies.

At the same time, the potential constraints on the supply of sustainable biomass mean that it is essential that where biomass is used, its production is as efficient as possible – in respect to the use of resources or any land that is dedicated to producing biomass for energy purposes. Its use must also be as efficient as possible. This means that the beneficial use of the biomass must be maximised (for example by using the biomass to produce a range of energy products in an integrated way), and focus on applications where the carbon savings are optimised.

Bioenergy technology priorities for deep decarbonisation

The following section briefly identifies the main roles and technology requirements for the use of bioenergy in each end-use sector in the 2DS.

Buildings

Within the 2DS, traditional use of biomass is significantly reduced. This implies an extensive roll-out of more sustainable cooking and heating solutions in developing and emerging economies, including both efficient fossil fuel solutions as well as more sustainable ways of using biomass (linked to sustainable supply of fuelwood from managed wood fuel plantations) and the use of biodigesters at the community scale.

In residential and commercial buildings, the need for heating is significantly reduced through the use of energy efficiency measures, and other low-carbon solutions (such as heat pumps) are widely deployed. The role of biomass as a provider of individual building heating is therefore constrained except for buildings in remote or isolated situations. Bioenergy can play an important role in providing energy in highly integrated systems for urban heating and

cooling through district heating and cooling networks. These bring together sources such as heat from waste management operations and water treatment, and specifically supplies of bioenergy from heat and co-generation operations, alongside solar and/or geothermal energy, and waste heat recovered from cooling systems and industrial processes, using heat pumps as appropriate. Such systems can also play a role in balancing and facilitating electricity generation from systems with high levels of variable renewable energy generation by acting as a heat source and sink, as well as by modulating electricity output.

This evolution will not require specific new bioenergy technologies, but would benefit from the development of cost-effective heat storage and supply solutions. The key challenge is to increase experience of the design and operation of such integrated systems in areas with different seasonal energy demand profiles and potential energy supplies, building on examples such as that of Helsinki and other cities in the Nordic region. A key enabling factor is the availability of the necessary heating grid infrastructure.

Industry and agriculture

In the industrial sector, the 2DS implies an expanded role for bioenergy in providing energy for relatively low-temperature applications within the existing user sectors – paper and pulp, timber processing, and the food sector. However, bioenergy can also play a role in delivering energy to a broader range of sectors with significant low-temperature energy needs outside the bio-industrial sectors. Examples of such uses are so far rare. This will be most cost-effectively delivered in circumstances where the energy can be provided in an integrated way to different users via heating networks linked to biomass co-generation systems, making use of synergies between industries that are located within a particular zone.

An expanded role is also implied for bioenergy as an energy supply in high-temperature applications, such as the use of biogenic waste fuels in the cement industry and in other sectors, notably the iron and steel sector where such fuels are not currently used to any significant degree. A priority topic for RD&D is the identification and subsequent development and demonstration of efficient use of bioenergy as part of low-carbon manufacture in these sectors.

The 2DS also sees some expansion of the role of bio-feedstocks in supplying chemicals. This could also play an important role in the cost-effective production of biofuels through the development of biorefineries and the co-processing of bio- and fossil fuel-based feedstocks.

Electricity

The 2DS sees a large-scale shift to decarbonise the electricity sector, particularly through the widespread deployment of low-cost variable renewable energy (VRE) sources such as wind and solar along with other renewable generation technologies. In many cases, bioelectricity will face increasing competition from these other renewable sources of electricity, but it can still have an important role to play in particular in the following situations where:

- The resources for production from wind, solar or other renewables are relatively poor and so generation opportunities are constrained or the costs high.
- Low-cost biomass sources are readily available (for example at agro-industrial processing sites such as sugar mills or wood processing sites).
- Biomass electricity generation can be efficiently linked to the provision of heat or cooling.
- Dispatchable bioelectricity can play a role in balancing high levels of VRE generation.
- Bioelectricity can be linked to CCS (BECCS) or CCU (BECCU), maximising the carbon benefits of using bioenergy.

Cost competition will favour the generation of electricity from low-cost fuel supplies (such as processing residues) or where the generation brings other benefits that are valued (such as wastes where there will be an associated waste management benefit). In addition, the

requirements to use biomass as efficiently as possible will favour generation that is inherently efficient, but where the heat can also be effectively used. Given that heat demand in both buildings and industry will be considerably reduced in the 2Ds and the B2DS and that there will be more intensive efforts to recycle waste heat from a number of sources, the opportunities for using heat from bioenergy co-generation systems may in the longer term be more constrained.

This suggests that priority needs to be given to the development and demonstration of smaller-scale generation systems with higher electrical efficiency. Such systems based on gasification and ORC are currently being commercialised, but significant efforts are still needed to refine the systems and to bring down costs. SOFCs are also promising but are less well developed.

The huge expansion in electricity generated by VRE sources, such as wind and solar PV, will create a greater demand for flexible plants able to generate during times of low VRE generation to supply residual system loads, and then reduce generation when VRE generation is high (IEA, 2014). This will change the role that bioenergy can play and the value of the electricity it produces. This is now receiving increased attention and is already happening in certain European markets, such as Germany (IEA Bioenergy, 2017b).

Bioenergy technologies are inherently dispatchable. However, the technical ability of different technologies to operate flexibly in line with the needs of a VRE-intensive power system varies. Examples of technical flexibility include using the turndown ratio of boilers to modulate generation, the use of liquid biofuel generators to serve peak loads, and the thermal storage of biomass co-generation plants to operate flexibly where there is a heat and power demand mismatch. Biogas systems can increase flexibility by increasing the volume of gas storage and generator capacity, adapting feeding regimes to control gas production. Virtual power plant concepts can be used to control a larger number of systems in unison.

Fuel costs are a key consideration that will influence the willingness of bio-generators to provide such services. For example, EfW plants that receive a gate fee for each tonne of waste used have a strong incentive to continue to generate even when power prices and ancillary service income are low, while systems using fuels that are higher cost (for example pelletised wood fuels), will be more willing to respond to market signals.

Flexible operation also generally means that annual output, and so income, is reduced as generation is constrained or curtailed when VRE generation is high, and this means that the effective cost of generation increases. Given the high capital costs of many bioelectricity systems, reducing the output can significantly increase the cost of the electricity produced (Figure 7.14).

The investment needed to allow flexible generation, or the reduced income due to lower annual output, will need to be offset by increased revenue from flexible generation – for example by accessing additional revenue streams for balancing power and ancillary services, and by benefiting from peak power prices. Bioelectricity plants, along with other potential providers of flexibility, will therefore need to be able to participate in these markets if their flexibility capabilities are to be monetised.

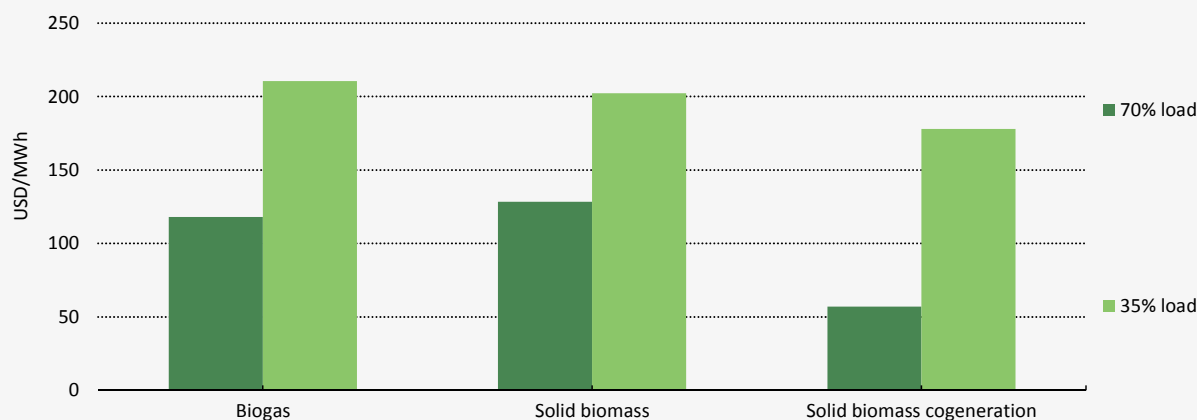
The value of such flexibility services will be very system-dependent and so it is difficult to generalise what level of additional revenue might be available. However, bioelectricity systems are already participating in such markets. For example, a premium for biogas flexibility has been included in the German Renewable Energy Act (Erneuerbare-Energien-Gesetz [EEG]) since 2012 (Szarka et al., 2013). As of early 2015, almost 3 000 plants had registered for the additional flexibility tariff (Thran et al., 2015). Just under 30% of solid biomass-fuelled steam and ORC power plants in Germany are offering flexibility, principally in the form of negative control power (Thran et al., 2015). Biomass plants have participated in the UK balancing mechanism, and two Canadian coal-to-biomass conversion plants are providing backup to hydropower and variable renewable generation in Ontario.

Further system studies and practical demonstrations of bioenergy systems playing such a facilitating role are needed to establish best practice (and these will need to be complemented by market rules that properly value such flexible generation).

Finally, the need will also grow for systems capable of large-scale efficient generation that is compatible with CCS or CCU. Options here include the development of biomass-fired integrated gasification and combined cycle systems, but currently this is not a highly active area of research, and producing affordable systems at scales compatible with biomass supply may be challenging. Fuel cell systems may prove to be another option.

Figure

7.14. Example LCOE values for bioenergy technologies at 70% and 35% load factors



Key point

Operating as flexible generation, bioelectricity load factors may be reduced, pushing up generation costs.

Transport

The 2DS sees the large-scale introduction and deployment of electric vehicles, notably in the passenger and urban transport systems, as well as a move to improved public mass transport systems. It also sees a very significant expansion of the supply of biofuels for this sector, notably for the supply of fuels to replace diesel, aviation and heavy fuels used in the maritime sector and also to complement gas-fuelled systems, with a move to fuels that offer higher levels of GHG savings, implying a move away from conventional biodiesel and bioethanol production.

This suggests that current efforts to produce fuels from lipid and cellulosic feedstocks and from the production of sugars from cellulosic materials by thermal and biological processes, along with those directed at other low carbon fuels based on waste gases or on “power to fuels” should be reinforced. There should be an increasing emphasis on “drop-in fuels” fuels with characteristics suitable for integration in the long-haul transport sectors, rather than on the passenger vehicle sector where most current efforts are focused. In addition, further efforts are needed to advance processes based on thermochemical routes, such as gasification and pyrolysis, towards the commercial demonstration scale and subsequent commercialisation.

Integrated approach

Integrated approaches to bioenergy generation need to be developed and demonstrated given the need to optimise the use of biomass feedstocks – both to improve the overall economics and to maximise the efficiency of use from a resource and land-use perspective. These can include the production of energy alongside higher value food, material and chemical products and integrated production of electricity, heat and transport

fuels or chemicals where possible. This implies not only further development of the biorefinery concept, but also a wider integration of bioenergy into the whole bio-economy.

Additional technology challenges for moving beyond the 2DS

Within the B2DS, the role of bioenergy and the resulting technology requirements are similar to those in the 2DS. The principal change is the much wider deployment of CCS linked to bioenergy use. A specific opportunity exists to capture the CO₂ released during the processes used to produce biofuels – via fermentation or gasification – since they tend to produce a highly concentrated and pure CO₂ stream amenable to capture. Further opportunities will exist in the production of electricity and in industrial sectors. This implies increased emphasis on the identification, development and eventual deployment of BECCS or BECCU solutions linked to biofuels and bioelectricity production, and also in the industrial sector (and notably within the cement and iron and steel sectors, where CCS/CCU will be widely deployed).

A further interesting possibility is to use sustainable biomass to produce energy (electricity, heat or transport fuels) with carbon capture, and then to recycle the captured carbon via chemical or biological processes to form fuels. As well as maximising the carbon capture value associated with BECCS, such processes could also reduce land-use requirements for energy production through re-use of the carbon components. Fuel manufacture would require provision of low-carbon sources of hydrogen, which could come from electrolysis powered by increasingly low-cost renewable electricity in regions with good solar and wind resources. Further analysis and techno-economic appraisal of such systems is required, and will need to take account of issues such as the siting of plants to make the best use both of biomass resources and of opportunities to produce low-carbon hydrogen.

Delivering sustainable feedstock for bioenergy

In developing the *ETP* scenarios, the use of biomass has been constrained, reserving its use for situations where it can play an important role in decarbonisation where other alternatives are difficult or expensive as well as bringing other benefits. As discussed earlier, the primary biomass demand associated with the range of end uses amounts to between 100 EJ in the RTS and around 145 EJ in the 2DS and B2DS.

Many low-carbon scenarios have similar contributions from bioenergy. In its Special Report on Renewable Energy and Climate Mitigation the IPCC examined a range of scenarios consistent with maintaining CO₂ levels below 40 ppm and found that bioenergy contributed between 120 and 180 EJ to such scenarios by 2050 (IPCC 2011).

However, bioenergy can play this important role in reducing carbon emissions from the energy sector only if its use leads to unequivocal and significant carbon savings, and does not lead to other unmanaged impacts on the environment or to social or economic issues.⁷ Without a broad social consensus that bioenergy can be delivered sustainably, it will be impossible to gain and maintain political support for the policy measures needed to promote sustainable bioenergy growth. Policy uncertainties create an unstable investment climate that inhibits investment both in deployment and in new technology development and commercialisation. There is experience of such instability – for example in Europe where concerns about sustainability have led to three major revisions to the policy framework supporting biofuels for transport. This has led to unused production assets (for biodiesel production in particular) and made the investment climate difficult for more advanced technologies (European Commission, forthcoming 2017).

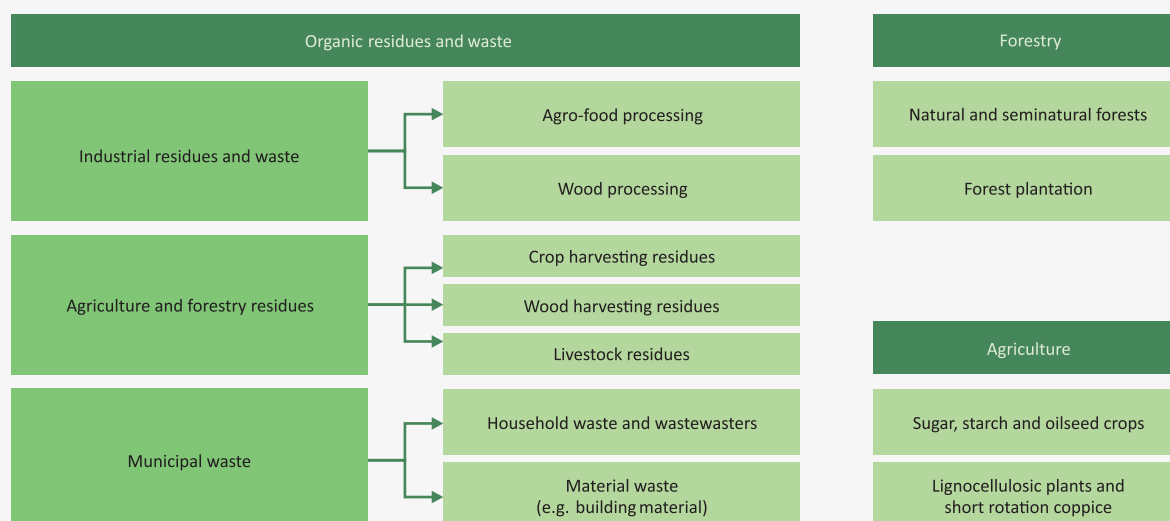
Well-designed sustainability policy and regulation is essential and should be designed to discourage or prevent bad practice. But it also needs to encourage and incentivise good practice and sustainable supply, given the need for a significant expansion of sustainable

7. The important issue of the sustainable supply of bioenergy will be more fully explored in the updated IEA *Bioenergy Roadmap*, due to be published shortly after *Energy Technology Perspectives ETP 2017*.

bioenergy if the 2DS is to be achieved. Striking a balance is difficult. An internationally accepted governance system, backed up by strong regional and national regulation, is a key requirement for substantial growth in bioenergy use in the coming years. Such a system would need to acknowledge that sustainability impacts of particular bioenergy chains are context-specific and complex. Sustainability management relies on good governance and strong institutional capacities, which vary from region to region.

Biomass resources can be classified into three main groups, determined by their origin (Figure 7.15): residues and wastes; forestry; and crops and fast-growing grasses.

Figure 7.15. Biomass types according to origin



Source: Adapted from FAO (2004), *Unified Bioenergy Terminology*.

Key point *A wide range of biomass materials can be used as bioenergy feedstocks.*

In addition, a number of potential new sources are being explored – in particular algae, which could provide a source of raw materials for a number of higher added-value applications as well for energy supply. (See for instance the recent IEA Bioenergy Technology Collaboration Programme [TCP] review of the state-of-the-art [IEA Bioenergy, 2016c]).

Each bioenergy chain – from feedstock to end use – has its own characteristics in respect to the overall contribution to emissions reduction, the sustainability risks that could arise and the measures needed to mobilise the necessary supply chain if these resources are to be available. These need to be optimised through the adoption of best practices in the application of technology and supply chain management. The IEA Bioenergy TCP has an ongoing project on sustainable bioenergy supply chains addressing all of these issues (IEA Bioenergy, 2015a).

Progress in understanding and managing bioenergy sustainability issues

Three main questions are raised about the sustainability of bioenergy:

- Does using bioenergy to replace fossil fuels reduce the net emissions of GHG, and by how much?

- What is the impact of increased levels of bioenergy production on global and local food availability and prices?
- Are there other significant issues involving bioenergy that have serious and unmanageable environmental, social or economic impacts?

A more detailed consideration of the main sustainability issues associated with bioenergy has been carried out by the Global Bioenergy Partnership (GBEP), an intergovernmental initiative that brings together 50 national governments and 26 international organisations. In order to facilitate the assessment and monitoring of bioenergy sustainability at a national level, GBEP produced a set of 24 indicators and related assessment methodologies (FAO, 2011). Consideration of these indicators can show up potential negative impacts but also highlight potentially positive environmental, social and economic impacts.

Although certain issues remain unresolved, much has been learned in the last ten years about the factors that influence sustainability and how to manage them. For example:

- The Scientific Committee on Problems of the Environment evaluated the potential expansion of bioenergy in the world and its impacts and benefits to assist policy decisions (Souza et al., 2015).
- A better appreciation has been gained of the issues associated with land-use impacts of bioenergy, how to include them within overall life-cycle analysis of bioenergy chains, and how to discriminate against fuel chains that have significant negative land-use change impacts.
- In addition there is now a better understanding of the issue of indirect land-use change (ILUC) and how to take it into account. For example, the EU Renewable Energy Directive obliges member states and fuel suppliers to report the estimated ILUC emissions of biofuels. Ways of producing bioenergy from land previously used for food production while minimising ILUC impacts have also been developed through managed intensification and by increasing productivity (Teixeira de Andrade and Miccolis, 2011; IEA Bioenergy, 2015b).
- Appreciation is improving of the role that forestry bioenergy systems, including the production of bioenergy, can play in carbon management, although this is one area still subject to ongoing debate, particularly over the timing of carbon savings and the role of active forest management (Berndes G. et al., 2016; Brack.D, 2017; European Commission, 2016a; IEA Bioenergy, 2017d).
- A much better appreciation has been gained of the complex links between bioenergy and its impact on food availability and prices (the “fuel versus food” debate), with an understanding that bioenergy is not by itself either good or bad from this perspective, as recognised by the Committee on Fuel Security and the Food and Agriculture Organization (FAO) (HLPE, 2013; FAO, 2013). It is clearly important that the impact of biofuels production on food security in a country is closely examined before major steps are taken in that direction, in particular relating to changes in land use and impacts on the staple crops used. Tools are now available to evaluate the interactions between food and fuel at a country level, such as the FAO Sustainable Bioenergy Support Package. This includes the Bioenergy and Food Security Rapid Appraisal, which consists of a set of easily applicable methodologies and user-friendly tools that allow countries to generate an initial indication of their sustainable bioenergy potential and of the associated opportunities, risks and trade-offs (FAO, 2014). The FAO, the International Renewable Energy Agency (IRENA) and IEA Bioenergy have recently published a memorandum summarising good practice in these areas (IEA Bioenergy, 2017c).
- There is a growing appreciation that many of the broader sustainability concerns apply not just to bioenergy, but also more widely to the whole bio-economy (such as land-use change for agricultural production or even beyond, for example issues relating to labour rights) and need to be managed in that expanded context.
- A number of comprehensive regulatory packages have been put in place that take into account issues relating to direct land-use change and ILUC and a broad range of other

sustainability concerns. These include the provisions under the EU's Renewable Energy Directive and the proposals for the directive that will apply to 2030 (European Commission, 2016b). These are complemented by a number of project-level certification schemes that aim to assure sustainable supply – for example the industry-led initiative Sustainable Biomass Programme and the Roundtable on Sustainable Biomaterials.

- A number of studies have narrowed the range of estimates of global sustainable bioenergy potential. These are complemented by detailed regional and national studies, including an update of the US “billion tonne study” (USDOE, 2016) and of the potential in Europe through the S2Biom Futures project (S2Biom, 2016).

While there is this improved understanding of the likely impacts of bioenergy, there are significant regional differences in the levels of concern about bioenergy sustainability and its management. For example, while in the European Union there are serious concerns about the use of food crops as feedstock for bioenergy, in the United States and Brazil such concerns are much less evident, and energy production from corn and sugar crops are actively promoted. Much of the understanding of sustainability impacts is so far based on modelling and theoretical considerations, and there is not yet much solid evidence on the real impact of large-scale bioenergy deployment, although some such studies are now under way. Further research to identify and quantify the impacts from practical large-scale deployment will be important to corroborate the results of more theoretical studies, for example by using satellite-based technologies to study land-use changes and the impact on carbon stocks.

Based on the emerging consensus about what would constitute a sustainable supply of biomass, the following criteria represent a range of the constraints that need to be applied when considering which sources of biomass might contribute to a long-term sustainable supply:

- municipal wastes available for fuel use taking account of the waste management hierarchy, which favours waste prevention and minimisation and recycling, and the likely growth in waste quantities and the gradual evolution of waste management systems in economies as they develop
- agricultural residues, consistent with leaving sufficient amounts on the field for soil/nutrient protection, for animal feed and for other productive uses
- wood and other agro-industry processing residues, consistent with other higher-value uses
- wood harvesting residues, consistent with maintaining nutrient levels and contribution to biodiversity
- forestry products where the life-cycle carbon balance is assured, for example by using thinnings from plantations where this promotes productivity and improved quality
- energy crops based on areas of land and yields consistent with minimising impacts on food production and using derelict and underutilised lands and avoiding high-biodiversity-value grass and forest lands.

Availability of sustainable bioenergy feedstocks

A wide range of estimates of the availability of biomass for energy purposes is apparent in the relevant literature, ranging from levels close to zero to levels well in excess of today's total energy use (1 500 EJ). The levels depend on what is included in the estimates (wastes, agricultural and forestry residues, other forestry materials, energy crops, algae, etc.) and on the constraints to biomass supply that are applied.

Despite the continuing or increasing need for a better appreciation of how much bioenergy might be available in the medium to long term, most papers making detailed global bioenergy resource assessments predate 2011 (perhaps reflecting the difficulty of such exercises and the inevitable need to make many assumptions). They were written before there was such a focus on the concerns over the impacts of direct land-use change and ILUC and the “food versus fuel” debate. However, more recent papers have tried to

understand the reasons for the widely differing estimates and to reduce the range by harmonising and updating the underlying assumptions (for example, Creutzig et al., 2014; Daioglou, 2016; IRENA, 2016b; Searle and Malins, 2014; Slade, R., et al.: (2011); Slade, Bauen and Gross, 2014).

This work starts to home in on what could reasonably be taken as a range of future potential, while identifying a range of the factors that will influence this sustainable supply potential. Analysis of the various studies and meta-studies cited above and more broadly suggests that:

- There seems to be consensus that up to 100 EJ could be delivered by 2050 without serious difficulties.
- Potential within the 100 EJ to 300 EJ range may still be considered reasonable, but the risks of delivery increase as the estimate rises and therefore a number lower down this range is to be preferred.

A workshop convened by the IEA and IRENA considered the contribution of bioenergy in a number of global energy scenarios and aimed to compare and understand the basis for a number of global potential estimates (Table 7.4). Where possible, the split between the types of feedstock is shown, but in many cases this is not indicated, and the classification of sources between these headings is not always consistent, making more detailed comparison difficult. In overall terms, the material is sourced roughly evenly between wastes and residues, and purpose-grown energy crops, grown either on agricultural land that may be available after food needs are met or from underutilised or derelict land that can be used for energy production.

Table

7.3. Range of estimates of sustainable bioenergy supply (EJ)

	Farm residues	Forest residues	Post-consumer waste	Energy crops	Total
IRENA Boosting Biofuels – 2050 Stretch Goal	46	50		191	287
Greenpeace Energy (R) Evolution Scenarios					76–77
Shell – New Lens Scenarios (Mountains and Oceans Scenarios)					97–133
World Energy Council Scenarios 2016 (Unfinished Symphony Scenario)					119
Searle and Malins	5	3	3	40–110	51–121
Daioglou		65–72		81–141	146–213

Sources: IRENA (2016b); Greenpeace (2015); (Shell (2016); IPCC (2011); WEC (2016); Searle, S. and C. Malins (2014); Daioglou V. (2016).

Further study of availability of sustainable biomass feedstock at a global level would be valuable in helping better understand the sustainable supply opportunities. Studies at a regional and national level when local resources and issues can be considered in detail would be even more valuable. Such studies should, where possible, apply common methodologies and transparent assumptions about the criteria applied in making potential estimates.

The amount of feedstock supply needed to meet the RTS, 2DS and B2DS (90 EJ to 145 EJ) is within the range of many of these estimates. Its delivery will require significant contributions from wastes and residues and from energy crops, and therefore measures will

be needed to mobilise all three resources while ensuring high levels of lifetime carbon benefits and avoiding other serious sustainability concerns.

The estimates of global potential are inevitably uncertain, given the many factors both inside and outside the bioenergy sphere that can influence availability and the long timescale. The likelihood that such a substantial sustainable resource for bioenergy would become available will be influenced by:

- The balance between increases in agricultural productivity and efficiency (especially the reduction of food waste) and food needs.
- Practical experience of monitoring effects of large scale bioenergy use that will influence constraints placed on biomass resources used for energy.

A number of factors and actions could make the required supply easier to achieve and potentially lead to biomass availability at the high end of these ranges or even higher. (IRENA, 2016b). These include measures to increase the potential for food production by increasing crop yields, using land more efficiently, and bringing some degraded lands back into production. They also include measures to ensure that resources are used as efficiently as possible. More specifically, measures could include:

- Improving food crop yields, through improved crop varieties and management practices, but especially by narrowing the “yield gap” between best practice and achieved food production, thus enabling more to be produced on less land and potentially freeing land for energy production.
- Improvements in the land efficiency of animal husbandry, which could make more efficient use of the land used to raise animals for meat and dairy products (nearly half of all productive agricultural land) by increasing intensity and so freeing land for other purposes.
- Improving the efficiency of food production, notably by reducing food waste. It is estimated that some 30% of the food produced globally is wasted. In developing and emerging economies such problems are largely due to problems during production (for example because of problems getting food to market in good condition and the lack of “cold chains” to preserve the quality of the products). In more developed economies waste is more related to sale to consumers and use of the products.
- Afforestation of derelict and abandoned land, which could provide significant resources for sustainable local food and energy use. The Bonn Challenge and New York Declaration on Forests seek pledges from countries to restore 350 million hectares of degraded land to productive use. The African Forest Landscape Restoration initiative launched at the 21st Conference of the Parties (COP21) in Paris aims to restore 100 million hectares, and this initiative has already been joined by 15 countries. When planted with mixtures of trees, grasses and food crops, such areas can provide food and bioenergy on a sustainable basis while improving land quality.
- Maximising the productivity of any land that it is decided should be dedicated to energy production by using energy crops that are best adapted to the land and climate so as to maximise energy yield, taking both production efficiency and energy conversion processes into account. In some cases this may involve crops that in other circumstances can be used as food crops. For example, in some climates crops such as palm and sugar cane can be the most productive crops to use. There is also scope for further enhancement of the yields of such crops – for example trials of “energy cane”, a variety of sugar cane designed to maximise overall biomass yield rather than sugar content – suggesting that very high overall yields can be obtained, opening the way to the production of energy on much smaller land areas than with other crops. Development of higher-yielding energy crops (such as “energy cane”, high-yielding oil crops and, in the longer term, algae suitable for efficient conversion to advanced biofuels warrants further attention (IEA Bioenergy (2016c).
- Improved waste management practices and rapid implementation of waste-to-energy systems as these practices evolve in each region. For example, the use of well-managed landfill sites is an affordable stage in the introduction of waste management practices, and

where this is implemented the capture and use of landfill gas forms part of best practice. Once more advanced waste management systems become adopted, then energy use of some fractions of the waste can accompany higher levels of reuse and recycling of materials.

- Co-producing food and energy either by efficient use of residues and co-products for energy purposes or by producing food and energy products by intercropping or crop rotation.
- Maximising the efficiency of use of bioenergy resources with respect to the fossil carbon saved – for example through co-generation and co-production of electricity, heat and fuels alongside biochemicals where appropriate. In certain cases energy production efficiency may need to be sacrificed to optimise carbon savings (for example by BECCS or to prioritise a reduction in coal use in co-firing applications). In the long run this may mean “recycling” the CO₂ from biomass-based energy production to produce fuels or other products.

Mobilising supply chains

Aside from the sustainability issues discussed above, mobilising the supply chains needed to deliver some 145 EJ of bioenergy supply will be extremely challenging. Current primary energy supply from bioenergy stands at around 60 EJ, but much of that (30 EJ) is from the traditional use of biomass whose sustainability of supply is doubtful. So the supply of genuinely sustainable material will need to rise by a factor of nearly five, from 30 EJ to 145 EJ. This will require feedstocks drawn from municipal and industrial sources, along with agricultural wastes and residues, sustainable forestry products, and energy crops. While many of the feedstocks can be supplied using conventional agricultural and forestry harvesting and processing and transport systems, these will need to be adapted and optimised to deliver bioenergy feedstocks from the variety of sources. This raises important questions about how this supply can best be mobilised and which needs to come first – a stable demand or a stable supply.

Evidence from recent experience shows that once strong demand is established, a supply chain is put in place to supply it. Examples include:

- The supply chain for wood pellets used in power generation in Western Europe, stimulated by economic support for such uses and which now draws in pellets from a wide range of sources within Europe as well as from the southern United States.
- The supply chain for corn residues established to support large-scale use in the production of cellulosic ethanol. For example, the DuPont plant in Iowa uses 375 000 tonnes of corn stover supplied by 500 farmers within a 50-kilometre radius of the plant (DuPont, 2016).

Developing these supply chains has not been easy, and the end users have had to make enormous efforts to establish them and to invest in the systems needed to transport and process the fuels. Once a more diversified user base has been established, it is possible that the challenge of supply will be taken up more strongly by players in the traditional bioindustries (the agricultural and forestry industries, for example) and a more liquid supply chain infrastructure will develop.

However, for these markets for sustainable bioenergy feedstocks to grow, a clear market framework is needed to give confidence that a sufficiently sized and stable market will endure so as to justify the investment in supply chain development, coupled with clear arrangements for governance of sustainability.

It is clear that many challenges remain in establishing the necessary supply chains and the right regulatory frameworks to manage sustainability issues. This will be achieved only through experience, as it is only through learning by doing that supply chains can be optimised. The same applies to the development and implementation of sustainability frameworks and regulation at regional and national levels and at the project level. For example, the large-scale trade in pellets referred to above has given rise to a number of sustainability concerns, which have led to a tightening of the regulatory framework in the countries where the fuel is used. It has also stimulated an industry initiative, the Sustainable

Biomass Programme, to develop a recognised sustainability certification system to provide assurance that woody biomass is sourced from legal and sustainable sources (SBP, 2017).

RD&D priorities

Table 7.4 highlights the main RD&D challenges that will need to be tackled in order to deliver the expanded production and use of bioenergy identified above, covering each end use and the sustainable supply of bioenergy.

While many of these challenges are currently being tackled in international, national and industrial research programmes, current efforts in several areas are likely to be insufficient to enable progress to be made towards commercialisation and deployment. These are highlighted in red in the table. Government and international initiatives should consider refocusing efforts to ensure that these topics are properly addressed in future RD&D initiatives.

Table 7.4. Priority RD&D needs

Sector/application	R&D requirements	Demonstration requirements
Buildings		
Sustainable cooking and heating solutions		Wider roll-out of sustainable bio- and fossil-based systems.
Bioenergy in integrated heating and cooling systems	Advanced heat storage systems.	Demonstration of integrated heating and cooling systems using bioenergy.
Industry		
Low-temperature applications		Demonstration of bioenergy use outside bio-based industry sectors.
High-temperature industry applications	Identification and development of bio-based systems for high-temperature sectors including iron and steel.	Demonstration of bio-based chemicals and co-processing of bio and fossil feedstocks.
Electricity		
Biomass co-generation linked to urban energy systems	Low-cost, high-efficiency, smaller-scale generation systems such as those based on ORC and fuel cells.	Demonstration of role of bioenergy co-generation within systems with high shares of VRE. Demonstration of flexible bioelectricity generation systems.
Large-scale efficient generation appropriate for BECCS	Feasibility studies on optimal generation configurations and development of BIGCC systems.	
Transport fuels		
Advanced biofuels	Development at laboratory and pilot scale of efficient “drop-in” biofuels technologies based on thermal routes such as pyrolysis and gasification and of “hybrid” thermal and biochemical processes.	Wider deployment of advanced biofuels solutions including HVO and cellulosic ethanol plants.
Integrated approaches		
Biorefineries	Identification of range of efficient integrated biorefinery approaches.	Demonstration of biorefinery and other systems co-

		producing different elements.
Integration of bioenergy into bio-economy	Further studies of the role of bioenergy within integrated bio-economy.	
BECCS and BECCU		
BECCS	System studies and techno-economic appraisals of optimum BECCS configurations for electricity and industry applications including siting studies.	
BECCU	System and techno-economic studies of options for combining bioenergy production with CCU.	
Sustainable supply		
Sustainability impacts	Studies of local impacts of bioenergy use on carbon stocks and other sustainability indicators such as ecological impacts and water use. Studies of real impacts of bioenergy deployment on land use (using satellite-based systems).	
Feedstock availability	Studies of feedstock availability at global and particularly regional level.	
Improved energy crop yields	Studies and trials on higher-yielding bioenergy feedstocks including energy crops and algae.	Larger-scale demonstrations of the production of such materials.
Note: Blue text = topics where further effort is particularly needed.		

International collaboration and initiatives

To accelerate the development and deployment of innovative energy technologies stakeholders from both the public and private sector can benefit from sharing knowledge, working collaboratively and, where appropriate, pooling resources to deliver integrated, cost effective solutions to common challenges. There are a number of international collaborations and initiatives aimed at improving the understanding of the many issues involved in bioenergy and in promoting the sustainable expansion of the sector. These are summarised below.

The IEA Bioenergy

The IEA Bioenergy Technology Cooperation Programme (TCP) is one of the best established of the 42 IEA TCPs, having been initiated in 1978. It has 23 countries as members including many IEA member countries plus the European Commission, Brazil, Croatia and South Africa. Its work focuses on the main RD&D challenges associated with bioenergy and is organised under ten active “tasks”. In addition are a number of cross-cutting tasks that are organised to deal with cross-cutting issues or to respond to particular issues of interest to participant members. For example, a cross-cutting task is currently ongoing in relation to bioenergy sustainability, and special tasks have been established to improve understanding of future market change-driven deployment of BECCS and BECCU technologies. The TCP produces a significant number of authoritative publications each year, as well as organising

workshops and conferences.⁸ The bioenergy TCP has been a co-operating partner in the production of the bioenergy roadmap, which will be published shortly after *ETP 2017*.

The IEA Bioenergy TCP has a comprehensive programme covering research in a wide spectrum of bioenergy technologies, applications and cross-cutting issues and has a membership that includes many of the key countries with strong interests and capabilities in bioenergy. There is further scope to enhance the bioenergy TCP's leading role by expanding its membership and its work programme, and this is a strong nucleus around which other international efforts should develop, building on its strengths and avoiding duplication.

IRENA

The International Renewable Energy Agency (IRENA)⁹ was founded in 2011, with 150 member countries as a hub for information on renewable energy. Its programme includes extensive activities on bioenergy, including estimates of biomass availability now and in the future, resource mapping, bioenergy statistics, and costs of feedstocks and conversion technologies. It is also working with partners to assess practical strategies for scaling up bioenergy.

Mission Innovation

The 23 governments that have joined Mission Innovation¹⁰ have each pledged to seek a doubling of their governmental and/or state-directed investment in clean energy R&D over five years. The initiative's research includes a challenge associated with biofuels: the objective is to develop ways to produce, at scale, widely affordable advanced biofuels for transport and industrial applications. It aims to accelerate biofuels RD&D in order to achieve performance breakthroughs and cost reductions with the potential to substantially reduce GHG emissions.

Biofuture Platform

The Biofuture Platform¹¹ is a new government-led, multi-stakeholder initiative designed to promote international co-ordination on advanced low-carbon fuels and bio-economy development. Government members include Argentina, Brazil, Canada, China, Denmark, Egypt, Finland France, India, Indonesia, Italy, Morocco, Mozambique, the Netherlands, Paraguay, the Philippines, Sweden, the United Kingdom and the United States. It is designed to complement the work of existing international institutions and initiatives (including the Clean Energy Ministerial, GBEP, IEA Bioenergy, IRENA, Mission Innovation and SE4ALL), and to formulate ways to best address existing gaps.

FAO

The Food and Agriculture Organisation (FAO) focuses its bioenergy efforts on making bioenergy development sustainable by trying to capture its potential benefits to rural development, climate and energy security. It promotes an integrated approach to address these links and promote both "food and fuel" and ensure that bioenergy contributes to sustainable development. This approach requires:

- An in-depth understanding of the situation and of the related opportunities, risks, synergies and trade-offs.
- An enabling policy and institutional environment, with sound and flexible policies and effective means to implement these.

8. See www.ieabioenergy.com/.

9. See www.irena.org.

10. See <http://mission-innovation.net/our-work/innovation-challenges/sustainable-biofuels-challenge/>.

11. See <http://biofutureplatform.org/>.

- Implementation of good practices by investors and producers in order to reduce risks and increase opportunities; and appropriate policy instruments to promote these good practices.
- Proper impact monitoring, evaluation and response.

In order to promote this sound and integrated approach, FAO, in collaboration with partners, has developed the FAO Support Package to Decision-Making for Sustainable Bioenergy. This support package includes different elements that can be used independently or together at different stages within the decision-making and monitoring processes of bioenergy development.

GBEP

The Global Bioenergy Partnership (GBEP)¹² is an intergovernmental initiative that brings together 50 national governments and 26 international organisations. It was established to implement the commitments taken by the Group of Eight major world economies (G8) in the 2005 Gleneagles Plan of Action to support “biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent”.

One important GBEP activity has been the development of a set of 24 indicators and related methodologies in order to facilitate the assessment and monitoring of bioenergy sustainability at a national level (FAO, 2011). These indicators, which are based on a series of relevant themes under the three pillars of sustainable development, address the production and use of liquid, solid and gaseous biofuels for heat and power and for transport. They are intended to inform policy makers about the environmental, social and economic sustainability aspects of the bioenergy sector in their country and guide them towards policies that foster sustainable development.

Summary

Other international initiatives directed at market implementation of bioenergy solutions have an understandable emphasis on the development of solutions for sustainable advanced biofuels and on related sustainability issues, given the importance of such issues in a low-carbon future. In these areas there is a strong need to co-ordinate closely to avoid duplication of effort.

There is also scope for some additional international efforts to enhance market deployment of a range of other solutions (such as the short-term deployment opportunities identified in an earlier part of this chapter) and some consideration might be given to measures to promote such technologies, for example under the Clean Energy Ministerial initiative.

Policy requirements for increased bioenergy

Short-term policy requirements

An appropriate policy and regulatory environment is needed to support the introduction of technologies which are mature at least in their leading markets. This enabling framework should have the features that have been identified as desirable in a supportive enabling framework for low-carbon technologies in general (Barnsley et al., 2015):

- a stable and predictable policy environment
- clear and specific targets
- appropriate mechanisms to reward low-carbon energy production
- measures to avoid non-financial barriers to deployment, such as appropriate and clear regulations relating to planning, environmental permitting and energy market access.

12. See www.globalbioenergy.org/.

These requirements stem particularly from the capital-intensive nature of low-carbon technologies, with often very low operating costs, which means that the cost of delivered energy is strongly influenced by the financing conditions, which in turn are sensitive to perceived policy risk. Bioenergy has the added complexity that its operating costs can also be substantive depending on the cost associated with the feedstock used.

For bioenergy technologies, particular issues include the need:

- for stable regulations relating to the sustainability of feedstock supply and technology deployment
- for transparent and appropriate environmental safeguards (such as emissions standards)
- to recognise and, where possible, monetise non-energy benefits and the enhanced flexibility of certain bioelectricity options
- for appropriate regulations relating to the integration of bioenergy (for example the regulations and standards that apply to biofuel/gasoline or diesel blends).

Deep decarbonisation policy framework

The general policy principles discussed under the section on short-term options apply to both established and newly commercialising technologies that will be needed to deliver the 2DS vision for bioenergy. But this scenario depends heavily on these new technologies, and appropriate policy and regulatory measures will be needed to help these technologies to mature and avoid the “valley of death” between prototype or pilot plant operation and full commercial deployment.

Significant barriers stand in the way of the investment needed to build and operate the series of plants necessary to demonstrate the technology at scale and to identify and incorporate technology learning. These include the technical risks associated with scaling up to full-size commercial plants, and commercial/financial barriers due to early plants not having benefited from technology learning, causing their outputs to be more expensive than both their fossil fuel competitors and other more established bioenergy technologies. This means that technology-neutral measures (such as an increased price for carbon emissions), while useful by discriminating against fossil options, are unlikely to promote the commercialisation of the technologies needed to meet longer-term needs, and on their own may lock in less desirable technology choices (e.g. conventional rather than advanced biofuels).

Bioenergy has specific characteristics that make a number of these barriers more significant than for other new sustainable energy technologies. For example, the technologies are not modular (as they are for solar PV or wind), and so very large sums are needed to invest at risk in full commercial-scale plants for biofuels and large-scale power generation (of the order of USD 1 billion). This is beyond the balance sheet capabilities of even the largest companies (and also beyond the budget of many national RD&D programmes). Bioenergy plants also generally face significant costs for feedstocks (unlike other renewable energy technologies) – so even if built, the plants cannot operate for long periods unless a sufficient revenue stream is available to cover operating and fuel costs.

Deploying advanced biofuels is the most significant challenge in the 2DS. Investment from industry is necessary to expand capacity and invest in the development and commercialisation of new technology and to drive down costs. This will happen only with supportive enabling policy environments, which may include:

- A long-term stable policy and regulatory framework that provides certainty about the market for an extended period (10 to 15 years) sufficient to justify investment in a series of production plants.
- Mandatory obligations for deployment of sustainable low-carbon fuels, with separate obligations established for advanced biofuels a whole, and for specific subcategories that are at different stages of technical and market maturity.
- Appropriate and dedicated financial mechanisms and instruments for advanced fuels to facilitate technological development and market deployment.

The same principles will need to apply if the other large-scale technologies (such as more efficient large-scale power generation and BECCS and BECCU technologies) are to find their place in the market.

Policy implications for going beyond the 2DS

More ambitious deployment policies associated with the B2DS goals mean first of all that the measures associated with the 2DS must be accelerated. This implies a very high level of ambition and financial commitments from governments and industry, since that the policy initiatives required above must be introduced earlier and more widely to achieve faster progress in both existing and new technology deployment.

There will also be a need for strong policy measures to drive the other significant difference between the 2DS and the B2DS – the earlier and much more extensive uptake of BECCS and BECCU. One element of this will be the need for an unprecedented policy support given the higher costs of BECCS deployment. Carbon pricing mechanisms coupled with other policy measures will need to reward the “double carbon benefits” of BECCS, taking account of both the low-carbon production of energy and the additional carbon saved through CCS.

In addition, technology-specific measures will be needed in order to promote specifically BECCS and BECCU technologies. Apart from measures to support studies of optimised systems and early examples of the technologies in practice, longer-term measures could include limits on emissions from biomass power plants and other similar sources of CO₂ emissions from bioenergy. There will also need to be an early start to CCS infrastructure planning, and this will need to specifically take into account the potential for BECCS.

While the large-scale deployment of BECCS and BECCU is likely to be later in the scenario period, early action to stimulate the uptake of BECCS and BECCU will be essential to stimulate the interest and investment necessary to demonstrate and deploy the technologies.

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Chapter 8



Unlocking the potential of carbon capture and storage

Carbon capture and storage (CCS) is vital for reducing emissions across the energy system in both the *Energy Technology Perspectives (ETP) 2°C Scenario (2DS)* and the *Beyond 2°C Scenario (B2DS)*. The potential for CCS to generate negative emissions when coupled with bioenergy is integral to energy use becoming carbon dioxide (CO₂) emissions-neutral in 2060. Building CO₂ transport and storage infrastructure is critical to unlocking large-scale CCS deployment.

Key findings

- CCS currently plays a growing but still niche role in emissions reductions. The number of large-scale CCS projects in operation has grown to 17, capturing over 30 million tonnes of CO₂ (MtCO₂) per year globally, with 2 more projects expected to come on line in 2017. Currently, most CO₂ is captured from natural gas processing, but CCS has now also been applied to the production of coal-fired power, steel, hydrogen, fertiliser and bioethanol, and coal gasification.
- Under the Reference Technology Scenario (RTS), the role of CCS remains modest through to 2060, resulting in 1.3 gigatonnes of CO₂ (GtCO₂) captured and stored per year by 2060, nearly 60% of which would be from energy-intensive and process industries. The slower deployment in the RTS reflects the lower climate ambition and the resulting lack of incentives to invest in CCS.
- CCS is deployed far more widely in the 2DS, with 6.8 GtCO₂ captured from facilities across the power generation, fuel processing and transformation, and industrial sectors in 2060. As climate ambitions increase, CCS features more heavily as it can reduce hard-to-mitigate emissions from industrial processes, lower the emissions from remaining fossil fuel use and potentially result in net-negative emissions when combined with bioenergy.
- The public sector will need to take a leading role in supporting development of the transport networks and storage resources necessary to take the large quantities of CO₂ captured in the 2DS. In the 2DS, CCS is applied in a range of sectors that cannot reasonably be expected to develop and operate the necessary storage resources on a purely commercial basis. Transport and storage infrastructure, including for shipping CO₂, will enable CO₂ capture for a range of processes and be particularly helpful for capture projects in industry, but is unlikely to be developed without strong public support.
- CCS is deployed yet more widely and more rapidly in the B2DS to further reduce emissions from industry and to generate negative emissions through bioenergy with carbon capture and storage (BECCS). In 2060, 11.2 GtCO₂ are captured in the B2DS,

66% higher than the level in the 2DS. Capture from industrial processes more than doubles from 1.8 GtCO₂ in the 2DS to 4.2 GtCO₂ in the B2DS. Similarly, capture from bioenergy increases from 2.7 GtCO₂ in the 2DS to 4.9 GtCO₂ in the B2DS, as net emissions from the power sector move below zero.

- **Higher CCS penetration rates in the B2DS mean CO₂ being captured from smaller, more diluted streams, requiring further technological innovation and research and development (R&D).** The need for deeper emissions reductions in the B2DS means CO₂ is captured from a wider range of point sources, including some smaller or more diluted streams, an activity that is at present more costly and energy intensive. The development of new technologies that reduce the costs and energy penalty of capture, making it feasible for smaller, more diluted streams of CO₂, would greatly assist in reaching the levels of CCS foreseen in the B2DS.

Opportunities for policy action

- **Strong public–sector leadership in developing CO₂ transport and storage infrastructure will be needed for CCS to achieve the level and rate of CCS development set out in the 2DS and B2DS.** As with the roll–out of much infrastructure historically, extensive CO₂ transport and storage infrastructure is unlikely to be developed privately given the lack of commercial incentives and the commercial risk in the absence of strong policy pricing the negative externalities of CO₂ emissions.
- **Strategic and co–ordinated planning of CO₂ transport infrastructure will reduce the cost and challenge of scaling CCS up to the levels envisaged in the 2DS and B2DS.** Local, regional and national governments will all have a role, as will international co–operation in planning CO₂ transport networks.
- **Government investment in storage is critical now, given the long lead times for the development of storage resources in certain regions.** Furthermore, government investment in storage will indicate long–term policy commitment to CCS and give the private sector the confidence to invest.
- **Carbon pricing is vital, but CCS deployment at the pace and scale required in the 2DS and B2DS will need additional policy support targeted at the various elements of the CCS chain, recognising the differences between the sectors in which CO₂ capture is being applied.** Having storage available and accessible allows government to implement a range of other more targeted policies.
- **Government can reduce the commercial risks involved in integrating the elements of the CCS chain through policy that differentiates among and insulates the three separate elements – capture, transport and storage.** The commercial integration of the three elements has proven challenging in individual projects – the counterparty and integration risk makes it difficult to secure investment and financing. Government can play a role in reducing the commercial risks associated with integrating different parts of the process through policy that differentiates between capture and storage operators and insulates them from the risks associated with other parts of the chain.
- **In addition to the policies necessary for meeting the 2DS, achieving the levels of CCS in the B2DS will require policy driving more accelerated deployment.** The B2DS calls for 66% more CO₂ captured and stored than in the 2DS to reach the levels of CCS foreseen in 2060. By 2060 CCS becomes standard in certain processes, making facilities without CCS become the exception. Meeting the more rapid and extensive ramp–up rate in the B2DS is likely to require much more aggressive policy setting, including mandatory CCS or the equivalent for certain processes.

- **The penetration of CCS in industry, fossil fuel and bioenergy power generation, and fuel processing and transformation increases substantially between 2DS and B2DS.** The application of CCS to a larger proportion of facilities will most likely mean applying CO₂ capture to plants that are outside the corridors that would represent the early opportunities for CO₂ transport networks.

Overview

This chapter aims to highlight the importance of CO₂ storage in allowing the application of CO₂ capture across the energy and energy-intensive sectors, and the role of government in leading this deployment. It examines CCS deployment options in the context of three scenarios that look to 2060 with varying levels of ambition to achieve climate change goals.¹

- **RTS**, in which CCS deployment is very modest, and is in line with current pace of deployment and some growth in the lowest-cost applications.
- **2DS** relies heavily on CCS. CCS is used extensively to reduce emissions from industrial processes, fuel production and transformation, and power generation from fossil fuels and bioenergy to keep emissions to the levels compatible with limiting the rise in global mean temperature to 2°C by 2100.
- **B2DS** pushes CCS deployment more widely and rapidly in order to aim for the “well below 2°C” target of the Paris Agreement. There are particularly large increases in the application of CCS in the industrial sector, and on power generation and fuel production from bioenergy. The combination of CCS and bioenergy allows for the generation of negative emissions critical in reaching the emissions targets in the B2DS.

Since 1996, the Sleipner offshore project in Norway has been separating CO₂ from a natural gas production facility and injecting it in the Utsira sandstone formation some 800 metres (m) to 1 100 m beneath the seabed. To date, the project has safely and permanently stored 17 MtCO₂. Sleipner is significant because it was the first large-scale CO₂ capture and injection project to have permanent, dedicated CO₂ storage with associated CO₂ monitoring.

The number of large-scale CCS projects in operation has since expanded to 17, with 2 more expected to come on line in 2017. CO₂ capture has now been applied at scale to coal-fired power plants, and steel, hydrogen, fertiliser and bioethanol production plants, as well as natural gas processing and coal gasification facilities. The size of dedicated CO₂ storage projects is also growing, with the world’s largest CCS project from the natural gas feed at the Gorgon liquefied natural gas plant in Australia expected to begin injecting more than 3 MtCO₂ per year from 2017.

On a technical level, the three elements in the CCS chain – capture, transport and storage – are well understood and demonstrated. R&D efforts have reduced the energy requirements of capture technologies and resulted in a better understanding of the behaviour of CO₂ once it has been stored. But despite these technical advances, CCS deployment has been slow.

The 2DS and B2DS rely extensively on CCS to reduce the emissions from industrial processes and ongoing fossil fuel use, and as a CO₂ removal technology that can lead to net-negative emissions. Retrofitting CCS to existing assets can also reduce the lost value in the write-down of fossil fuel generation assets, particularly in non-member countries of the Organisation for Economic Co-Operation and Development (OECD). The value of CCS to the energy system can be greater than simply the difference in technology costs, as CCS is not an energy-generating technology, but rather a suite of technologies that reduce CO₂

1. For additional information on the three scenarios, see Chapter 1, “Global outlook.”

emissions from a range of sources. Without CCS, it looks highly likely that industrial production and other hard-to-mitigate emissions sources would prevent the achievement of the Paris Agreement goals.

Yet deployment of CCS has been slower than the international community expected and much slower than envisaged in the 2DS or B2DS, as a litany of projects have fallen before final investment decision (FID) and many even before moving from desktop to actual development. Many potential projects have struggled with commercial challenges, including a lack of revenue, the allocation of risk across project partners and the difficulty in securing financing. Other obstacles involve gaining public acceptance, including from local communities, and the challenge of finding, developing and operating an underground CO₂ storage site.

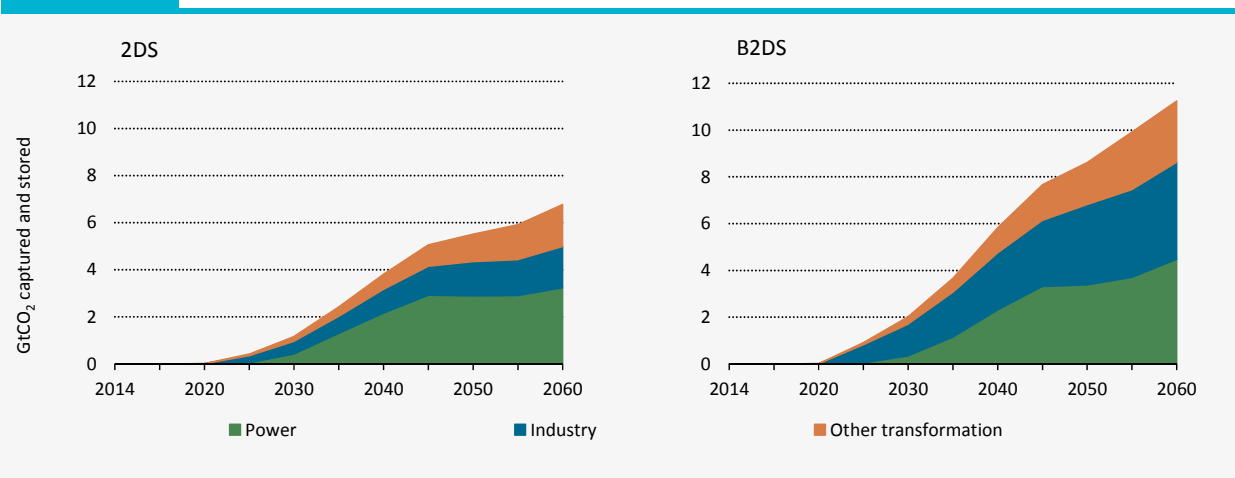
An evolution in the policy approach to deploying CCS, as well as an increase in public-sector commitment, will be needed to reach ambitious climate targets such as those behind the 2DS and B2DS. Deploying CCS at the pace and scale envisaged in the 2DS and the B2DS requires targeted support for the different elements of the CCS chain and responses to the commercial, financial and technical challenges. Governments can encourage the uptake of CCS and leverage private investment by recognising and supporting CO₂ transport and storage as common user infrastructure, critical to a low-carbon economy.

The role of CCS in decarbonising the energy sector

As has been established previously, CCS is a crucial technology in reducing emissions to a level consistent with 2DS targets (IEA, 2015a; IEA, 2016a; IPCC, 2014). In the 2DS, CCS is used extensively to reduce emissions from industrial processes, fuel production and transformation, and power generation from fossil fuels and bioenergy. In 2060, 6.8 GtCO₂ are captured and stored from these sectors. Cumulatively, 142 GtCO₂ are captured and stored between 2015 and 2060 in the 2DS.

Figure

8.1. CCS deployment rates – 2DS and B2DS



Key point

Deployment of CCS increases significantly in the B2DS, with over 11 GtCO₂ captured and stored in 2060.

As climate ambition increases from a 2DS to a B2DS trajectory, so CCS plays a proportionately greater role in reducing emissions. In moving from the RTS to the 2DS, CCS accounts for 14% of the emissions reductions. However, CCS accounts for 32% of the reduction in emissions between the 2DS and the B2DS (see figure 1.9 in Chapter 1). CCS is

increasingly used to reduce emissions from hard-to-reach sources where there are few or no other options. If the energy system moves towards and beyond net-zero emissions, it is necessary to generate negative emissions to offset the remaining emissions in the energy sector. In the 2DS, BECCS generates a cumulative total of 37 GtCO₂ in negative emissions, while in the B2DS, this figure increases to a total of 72 GtCO₂ (Box 8.2).

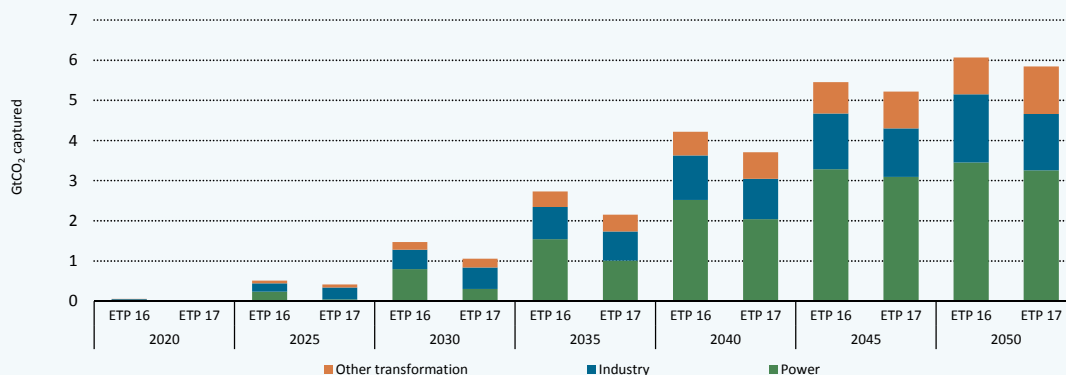
As such, CCS is deployed far more extensively and more rapidly in the B2DS than in the 2DS (Figure 8.1). In 2060, the annual rate of CO₂ capture and storage is 11.2 GtCO₂, 66% higher than at the same point in the 2DS. By 2030, CO₂ captured and stored is 73% higher than in the 2DS. In total, across the period 2015–60, 227 GtCO₂ are captured and stored in the B2DS, 60% more than the cumulative amount captured under the 2DS.

Box

8.1. Changes to the 2DS since 2016

The medium-term deployment of CCS in the 2DS has been revised downwards since 2016 due to the lack of projects entering the development pipeline over the past year (Figure 8.2). Annual capture rates in 2030 under the 2017 2DS are 20% lower than in the 2016 2DS. There will be a peak in the number of projects coming on line in 2017; however, no projects achieved FID in 2015 or 2016. Furthermore, the pipeline of projects in the conception and early stages of design has fallen from 33 at the beginning of 2015 to 17 at the beginning of 2017 (GCCSI, 2017a).

8.2. Figure: 2DS CCS deployment curves – ETP 2016 and ETP 2017



Key point: CCS deployment is lower in the 2017 2DS than in the 2016 2DS.

As CCS projects have tended to experience long lead times, particularly those that include development of a storage site, the slowdown in projects entering the pipeline has led to a decrease in CCS in the early years of the 2DS period. The reduction in CCS from the 2016 2DS is most pronounced in the power sector, where the level of CO₂ captured per year in 2030 in *ETP 2017* amounts to a third of that in *ETP 2016*.

By 2050, levels of CCS activity in the 2DS set out in *ETP 2017* are consistent with those in *ETP 2016*. CCS will eventually need to be deployed on a wide scale given its essential role in mitigating hard-to-abate emissions, and the slower initial rate leads to a faster ramp-up rate for CCS towards the end of the modelling horizon.

While CCS starts more slowly, its eventual rise to the same level of capture per year highlights its importance. It also illustrates the importance of acting soon to deploy CCS. Any delay in deployment now will necessitate faster deployment rates in the future, potentially straining resources and driving up prices of key materials and services.

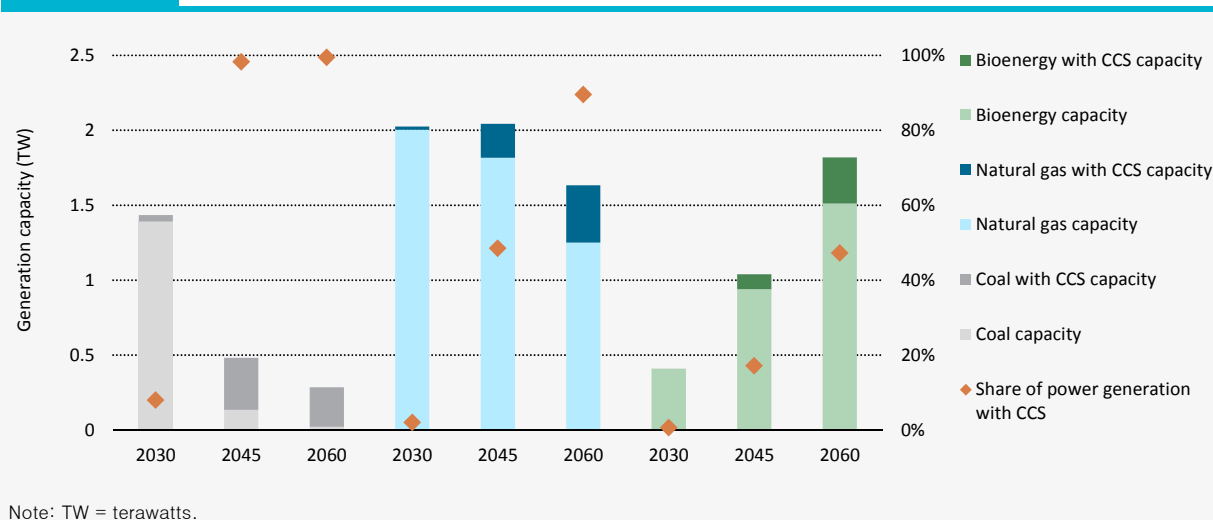
The role of CCS in the power sector

CCS plays a critical role in the power sector under the B2DS over the period to 2060, reducing emissions from the ongoing, albeit declining, use of fossil fuels in power generation and generating negative emissions from bioenergy generation. Fossil fuels continue to be used in both the 2DS and the B2DS, initially as a significant fleet is already constructed and operating, and then to continue to provide flexible and dispatchable generation. The use of fossil fuels to provide these services is possible only through the application of CCS, which significantly reduces the emissions intensity of fossil fuel-based power.

In the 2DS, CO₂ capture from the power sector reaches 3.2 GtCO₂ in 2060, with a total of 72 GtCO₂ captured cumulatively between 2015 and 2060. CCS is used much more extensively in the power sector in the B2DS, increasing to 4.5 GtCO₂ captured in 2060 and a cumulative total of 85 GtCO₂ captured and stored between 2015 and 2060.

The growing share of electricity supplied by variable renewable energy (VRE) sources makes it more difficult to match electricity supply and demand. A system with a higher share of VRE may require more balancing capacity from the rest of the power system to maintain reliable electricity supply. Fossil fuel plants can also provide other system services, such as frequency control and reserve capacity. Applying CCS allows these plants, which provide balancing capacity and other system services, to continue operating despite severe restrictions on emissions. In the 2DS, the share of fossil fuelled power generation with CCS increases from 4% in 2030 to 62% in 2060. Even higher shares are achieved in the B2DS, with 4% in 2030 and 93% in 2060. Over time, fossil fuel CCS plants shift from mainly providing baseload to providing more flexible and reserve capacity with declining full-load hours, particularly during times of variation in the availability of VRE (Figure 8.3).

Figure 8.3. Share of CCS in power generation and capacity – B2DS



Note: TW = terawatts.

Key point

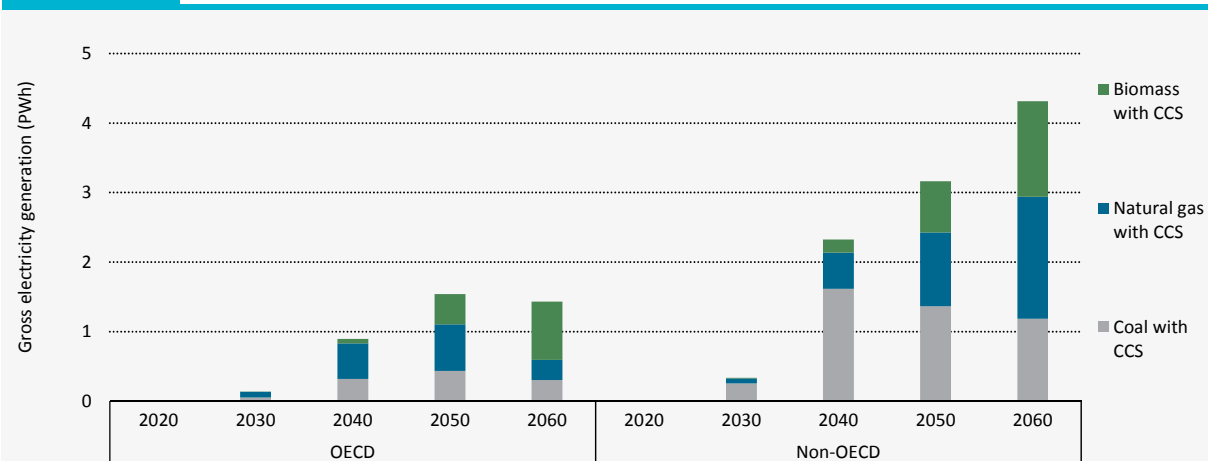
While some fossil fuel capacity remains without CCS under the B2DS, almost all fossil fuel power generation is from plants with CCS.

As the emissions intensity of power generation in the B2DS declines from the current level of 519 grammes of CO₂ per kilowatt hour (gCO₂/kWh) in 2014 to below zero after 2050, fossil fuel generation, even with CCS, becomes a high-emissions generation option. Based on current technologies with capture rates of between 85% and 95%, the emissions intensity of power from coal with CCS is around 100 gCO₂/kWh to 140 gCO₂/kWh, and that of gas with CCS is 45 gCO₂/kWh to 60 gCO₂/kWh. Therefore the role of CCS in the power sector changes over the course of the B2DS. As the share of fossil fuel generation declines,

CCS is applied extensively to bioenergy power generation, particularly later in the period, to provide negative emissions and move the energy sector to net-zero emissions.

Figure

8.4. CCS in power generation by fuel in OECD and non-OECD countries – B2DS



Note: PWh = petawatt hours.

Key point

The mix of generation from plants with CCS shifts away from fossil fuels towards bioenergy, particularly in OECD countries.

Box

8.2. BECCS: A first large-scale project in Illinois, United States

The Illinois Industrial CCS Project, owned and operated by Archer Daniels Midland Company in Decatur, Illinois, is the first large-scale project to combine CCS with a bioenergy feedstock. The project started operating in early 2017 and will capture 1 MtCO₂ per year from the distillation of corn into bioethanol. The CO₂ is then compressed and dehydrated, after which it is injected, on site, for permanent storage in the Mount Simon sandstone formation at approximately 2.1 kilometres (km) depth.

The project has received 140 million United States dollars (USD) in capital support from the United States Department of Energy and will also be able to access CO₂ storage credits of USD 20 per tonne of CO₂. The relatively modest level of support (compared, for example, to the application of CCS to power generation) highlights that in the right circumstances, ethanol production with CCS is an example of a relatively low-cost CCS application. The favourable economics of the project are, in part, due to the earlier investment in geological storage characterisation, which was undertaken as part of a pilot project, as well as the fact that no transport of CO₂ is required. Aspects of this project have the potential to be replicated in other areas of the United States, with the bioethanol mandate currently supporting production of 50 billion litres of ethanol each year.

Power generated from bioenergy with CCS therefore surpasses both gas and coal generation with CCS in 2055. In 2060, bioenergy generation with CCS accounts for 4% of total electricity generation and 47% of CO₂ captured in the power sector.

These trends are, however, not universal. In non-OECD countries, CCS with fossil fuel generation remains greater than BECCS through to 2060 (Figure 8.4). While the trend in both OECD and non-OECD countries is to shift away from fossil fuel generation and see an increase in bioenergy generation with CCS, the transition is not as advanced in non-OECD countries in 2060.

CCS is retrofitted extensively in China

The option of retrofitting CCS to existing plants allows for the preservation of a proportion of the economic value of existing coal-fired power generation assets, an impact most keenly felt in non-OECD countries. In the B2DS, 170 gigawatts (GW) of coal-fired capacity is retrofitted with CCS, avoiding the need for these plants to be retired before the end of its technical life. Of the retrofitted capacity, 81% is in the People's Republic of China (hereafter, "China") and 8% is in India, reflecting the importance of retrofitting for preserving the value of existing assets in regions with relatively young coal fleets. In total, 137 GW of coal capacity in China is retrofitted with CCS across the period. The extent of retrofitting in China is consistent with an earlier International Energy Agency (IEA) study, which found that 310 GW of coal capacity would be technically attractive for retrofitting (Box 8.3) (IEA, 2016b).

Retrofitting CCS to this capacity extends its operating lifetime by preventing its retirement before the end of its technical life. In total, the retrofitting of CCS avoids the loss of 7.9 million gigawatt hours of generation from existing assets in China, and the associated electricity sales revenue of over USD 500 billion.²

It should be noted that the option of retrofitting CCS does not avoid the need to phase out fossil fuel power generation in the 2DS or B2DS. Even with the availability of CCS retrofitting, over 1 700 GW of fossil fuel capacity is nonetheless retired before the end of its technical lifetime in the B2DS.

Box

8.3. The opportunity of retrofitting CCS to existing coal-fired power stations

The option of retrofitting CCS to existing coal-fired power plants can be a valuable opportunity to avoid the long-term "lock-in" of emissions from these facilities. CCS can reduce the emissions from a state-of-the-art hard-coal power plant from around 800 gCO₂/kWh to around 100 gCO₂/kWh if 90% of the emissions are captured and stored, and even lower with higher capture rates or in combination with bioenergy co-firing.

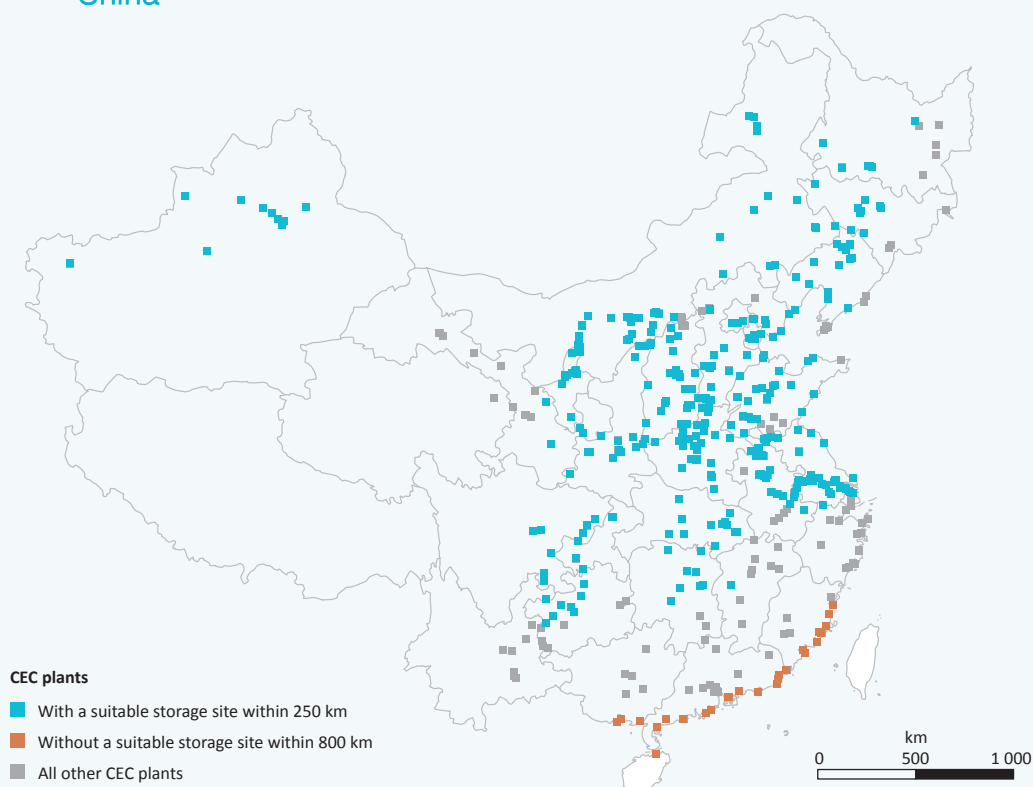
Access to suitable storage sites is a prerequisite for any retrofit. This entails a high level of certainty about the suitability of an identified storage site before a retrofit project can begin. Plant age, size, efficiency, load factor and availability of space for capture equipment are other key criteria for deciding whether a plant is suitable for retrofitting. The following criteria were used to identify the plants that are most suitable for retrofit:

- plant age: ≤40 years in 2035
- unit size: ≥600 megawatts (MW) or ≥300 MW if in a cluster of units
- load factor: ≥50%
- location: not located in a province with a coal phase-out plan
- access to CO₂ storage: ≤800 km.

2. Lost hours of generation in China based on the capacity-weighted average age of China's coal fleet and a 40-year technical lifetime. Lost electricity sales revenue is in nominal 2014 USD and is based on B2DS power prices at the point of retrofit.

According to IEA analysis, in total some 310 GW of existing coal-fired power capacity in China would meet basic criteria for being suitable for a retrofit (IEA, 2016b). Plant size is of particular importance in China, where many smaller plants are likely to be retired before CCS retrofitting is widely deployed.

8.5. Figure: Proximity of coal-fired power plants to CO₂ storage in China



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: CEC = China Electricity Council.

Source: IEA (2016b), *Ready for CCS Retrofit: The Potential for Equipping China's Existing Coal Fleet with Carbon Capture and Storage*.

Key point: 310 GW of coal capacity in China meets the technical criteria for being suitable for retrofitting CCS, including being accessible to a potential storage site.

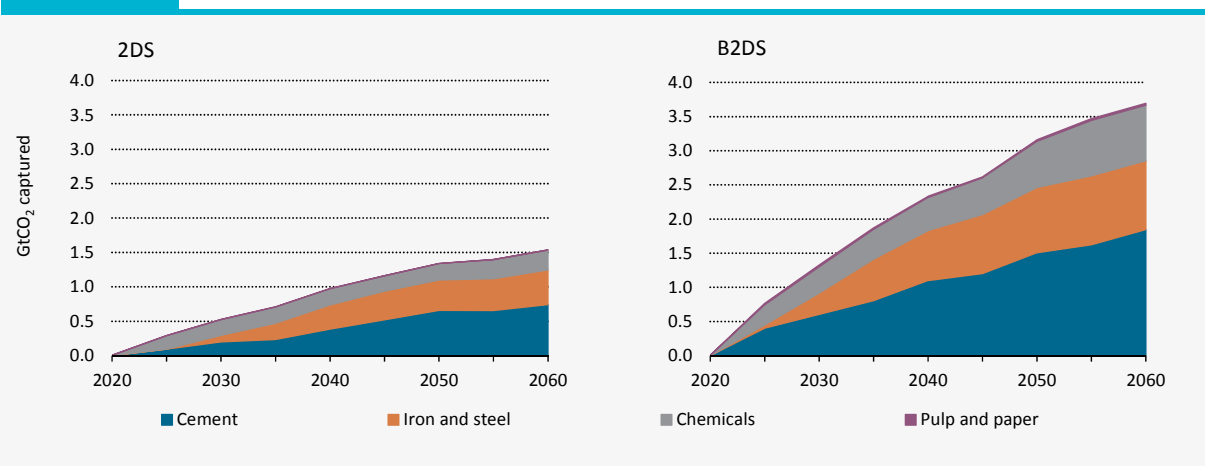
CCS in industrial processes

CCS is one of the few options available for achieving deep emissions reductions in the production of key primary materials. Accordingly, there is a greater deployment of CCS to reduce emissions from industry in the B2DS than in the 2DS, notably in the production of cement, chemicals, iron and steel, and to a lesser extent, pulp and paper. The application of CCS in the industrial sector grows from 1.8 GtCO₂ in the 2DS to 4.2 GtCO₂ in the B2DS in 2060 (Figure 8.6). In moving from the 2DS to the B2DS, the deployment of CCS increases more in the industrial sector than in the power or fuel transformation sectors. As a proportion of total CO₂ captured in 2060, CO₂ captured from industrial processes increases from 26% in the 2DS to 39% in the B2DS.

As further emissions reductions are needed in the B2DS, CO₂ capture is also applied to smaller CO₂ streams with lower concentrations in this scenario, despite the higher cost. These streams of CO₂ are generally more difficult and costly to capture; however, the very tight carbon budgets in the B2DS necessitate reducing even the hardest-to-reach emissions and highlight the challenge of achieving CCS deployment rates in the B2DS.

In the 2DS, CCS is applied to 21% of crude steel production in the iron and steel sector in 2060, which corresponds to 506 MtCO₂ captured annually (see box 8.4). A much wider deployment of CCS can be observed in the B2DS, in which 55% of production is equipped with CCS, resulting in an annual amount of CO₂ captured of 1 007 million tonnes in 2060. Over time, blast furnaces are replaced by direct reduced iron steelmaking and smelting reduction processes, both of which have CCS applied extensively. Under the B2DS, CCS is applied to almost all production that requires CCS to be low carbon (Figure 8.7). (For further discussion of emissions reductions in the industrial sector, please refer to Chapter 4).

Figure 8.6. CO₂ captured from industry by subsector

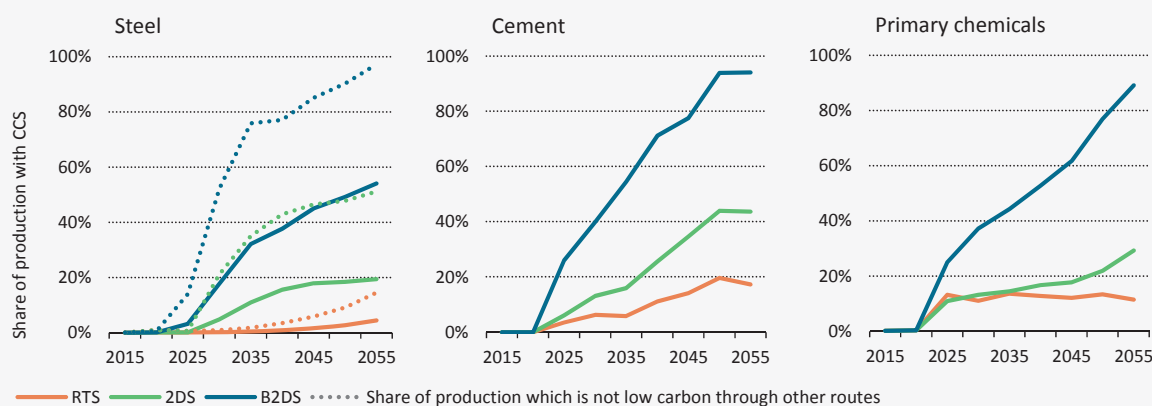


Key point *CO₂ captured from industry more than doubles by 2060 between the 2DS and the B2DS, as deeper emissions reductions are needed.*

By 2060, 98% of cement production globally is equipped with CO₂ capture in the B2DS, up from 47% of production in the 2DS. The extensive application of CCS in the B2DS reflects the current scarcity of options other than CCS for deep emissions reductions in cement production. As well as overall penetration of CCS being higher in the B2DS than in the 2DS, the capture rates in plants are higher due to the use of 90% post-combustion capture technologies and 90% oxy-combustion in the B2DS, as well as 60% partial oxy-combustion, which is the dominant capture technology in the 2DS. This shift to higher capture rate technologies generally comes at greater cost and complexity. The higher capture rates and deeper CCS penetration in the B2DS lead to 1847 MtCO₂ being captured in 2060 compared with 741 MtCO₂ in the 2DS.

The use of CCS to reduce emissions from chemicals production also increases substantially between the 2DS and the B2DS. In the 2DS, CCS is applied to 60% of ammonia production and 48% of methanol production. The rate of CCS penetration in the production of these chemicals increases substantially in the B2DS, reaching 93% of production for ammonia and 100%, for methanol in 2060. This results in 226 MtCO₂ being captured annually from the ammonia production process and 247 MtCO₂ from methanol production in 2060. The step change in ambition between the 2DS and the B2DS is even more marked in the level of CCS penetration in high-value chemicals (HVC) production. In the 2DS, CCS is hardly used in the production of HVC, as it is less cost-effective than in ammonia or methanol production; in the B2DS, however, CCS is applied to around 91% of HVC production, again reflecting the depth of emissions reductions necessary in this scenario.

Figure 8.7. Share of CCS in industrial production



Key point *Under the B2DS, CCS is applied to almost all cement and chemicals production, and to almost all steel production that is not low carbon through other routes.*

As well as a large increase in the level of CCS captured in 2060, the B2DS also calls for a much more rapid ramp-up, which reaches a higher penetration in all three sectors in the B2DS than in the 2DS. This emphasises the need for policy that drives capture uptake more quickly, as well as the necessary storage reserves.

Box 8.4. Al Reyadah CCS project

Al Reyadah, a joint venture between Masdar and Abu Dhabi National Oil Company (ADNOC), has developed a project that takes captured CO₂ from the Emirates Steel Factory in Abu Dhabi and transports it to the ADNOC-operated oilfield for the purpose of enhanced oil recovery (EOR) (MIT, 2016).

ADNOC is a United Arab Emirates (UAE) state-owned oil company, and Masdar is a wholly owned subsidiary of the Abu Dhabi government-owned Mubadala Development Company. The project began operations in November 2016.

The project scope includes operation of a greenfield CO₂ compression facility adjacent to the Emirates Steel Factory. CO₂ is transferred at low pressure to the compression facility, where it is dehydrated, compressed, metered and exported to the CO₂ pipeline. The CO₂ is transported 43 km through an eight-inch pipeline for injection into ADNOC reservoirs (GCCSI, 2017c).

The project is the Middle East's first commercial-scale carbon capture, use and storage facility and will sequester up to 800 000 tonnes of CO₂ annually. The engineering, procurement and construction contract for the facility and pipeline was valued at USD 122 million (450 million UAE dirham) (Masdar, 2017).

CCS in fuel production and transformation

In 2060, 1.8 GtCO₂ is captured and stored from fuel production and transformation in the 2DS and 2.3 GtCO₂ in the B2DS. A significant increase in demand for biofuels is seen in both the 2DS and the B2DS, including biodiesel, hydrogen and ethanol, as they offer an energy source with net-neutral emissions. The combination of CCS and bioenergy allows for

the generation of negative emissions. Accordingly, CCS is applied widely to the biofuel production sector, capturing 1.6 GtCO₂ in the 2DS and 2.2 GtCO₂ in the B2DS.

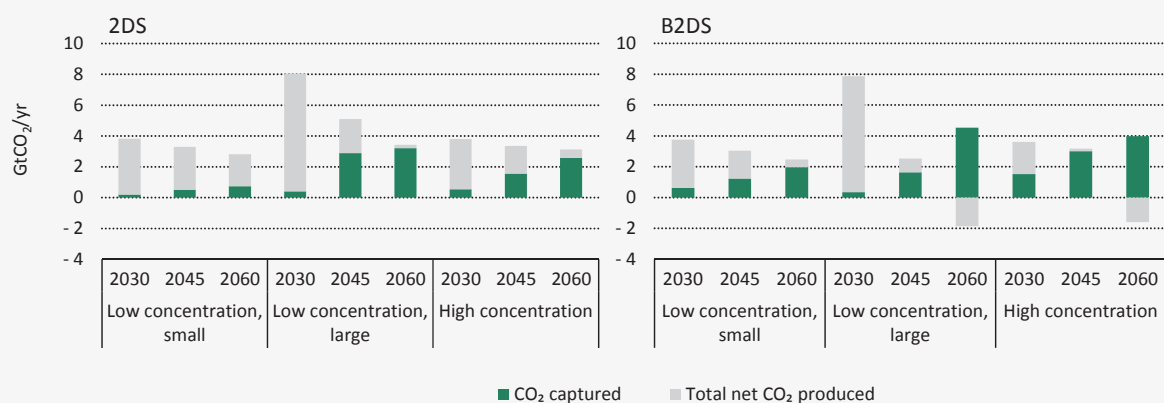
Capturing CO₂ from natural gas and hydrogen production is well understood and an established technology. Many of the early applications of CCS have been in natural gas processing, as the separation of CO₂ is often already an inherent part of the process. Hydrogen production has also been a leader in the early deployment of CCS. Accordingly, these upstream processes account for much of the early CCS activity. In the 2DS, 5% of all CO₂ captured and stored is from natural gas processing in 2025, but by 2060, capture from natural gas production and processing is incidental to total CO₂ captured.

CO₂ capture projects in fuel transformation can drive early investment in CO₂ transport and storage and are among the vanguard of early CCS projects. The technologies involved are well understood and often quite mature. Also, applying CCS in this sector has a lower impact on the competitiveness of facilities, owing to the particular market and pricing dynamics. Furthermore, many of the companies involved in the upstream fuel sector have experience of operating in the subsurface and are therefore more likely to develop the initial storage sites.

Challenges for the deployment of carbon capture in the B2DS

Both the 2DS and the B2DS show a widespread deployment of CCS from industrial and energy-related point sources, which differ according to their size and the CO₂ concentration in their gas streams (Figure 8.8). The B2DS involves more CO₂ capture from small point sources with dilute CO₂ streams (3% to 12% CO₂ by volume) such as industrial boilers, and decentralised co-generation plants (see box 8.5 for a discussion of CO₂ capture technologies).³ Separating CO₂ from these point sources is often more energy intensive and costly, as the capture equipment benefits less from economies of scale than in the case of large-scale sources. Moreover, creating space for capture equipment around small point sources on cramped industrial sites, such as complex refineries, may increase costs further.

Figure 8.8. CO₂ captured by size and concentration of stream



Note: GtCO₂/yr = gigatonnes of CO₂ per year.

Key point *More CO₂ is captured from more expensive, lower-concentration and smaller sources in the B2DS.*

To realise widespread deployment of CCS, as envisaged in the B2DS, technological development is required to reduce the costs of CCS technologies. The necessary conditions

3. Co-generation refers to the combined production of heat and power.

for this can be summarised as a convergence of two factors that reduce the costs and risks associated with CCS projects and capture technologies (IEA, 2015b):

- **Learning-by-doing** reduces technology costs and raises performance, especially in early opportunities for industrial applications where the learning rate can be expected to be steepest. These early opportunities open a path for CCS deployment in an increasing number of sectors and point sources, including the power sector and small point sources with dilute CO₂ streams.
- **Learning-by-researching** in laboratories, research institutions and industry-led projects introduces lower-cost and better-performing technologies.

Box

8.5. Carbon capture technologies

Carbon capture involves the separation of CO₂ from industrial processes and energy-related CO₂ point sources. Separating the CO₂ requires energy and often involves modifications to existing processes by adding extra process steps. Some industrial processes already produce reasonably pure CO₂ streams as part of the current production process (e.g. hydrogen or methanol production). In both cases, the CO₂ stream can be further purified and compressed to make it ready for transport.

CO₂ capture is typically divided into four main categories. In certain cases, these categories can be combined to create hybrid routes to capture.

Post-process capture. CO₂ is separated from a mixture of gases at the end of the industrial or energy process, for example from combustion flue gases. This route is referred to as post-combustion capture in power generation applications. Most post-process capture technologies used in demonstration projects today are amine-based absorption systems.

Syngas/hydrogen capture. Fossil fuels or bioenergy can be processed with steam and/or oxygen to produce a gaseous mixture called syngas, consisting of carbon monoxide and hydrogen (a process referred to as reforming or gasification). The former is reacted with more steam (water-gas shift reaction) to yield additional hydrogen and convert the carbon monoxide to CO₂. The CO₂ can be separated from the high-pressure gas mixture, yielding a raw syngas for chemical production or energy feedstock for the generation of heat (in a boiler or furnace) or electricity (in a combined-cycle gas turbine [CCGT] or fuel cell).

Oxy-fuel combustion. Instead of air, (nearly) pure oxygen can be used to combust fuel. This way, virtually all the flue gas will be composed of CO₂ and water vapour. Part of the flue gas is recycled to the combustion chamber to control the combustion temperature, while the remainder is dehydrated to obtain a high-purity CO₂ stream. Oxygen is commonly produced by separating oxygen from air, often produced in an air separation unit (ASU).

Inherent separation. Certain processes in industry and fuel production generate high-purity CO₂ streams as an intrinsic part of the process (e.g. gas processing, synthetic fuel production). Without CO₂ capture, the produced CO₂ is vented to the atmosphere.

Oxy-fuel and pre-combustion capture systems require drastic changes to the power and industrial processes, while post-combustion capture is an add-on technology. This could make the demonstration of complete oxy-fuel and pre-combustion capture systems more challenging. The individual components of the four approaches are well understood, and in some cases, technologically mature. For example, there is commercial experience with natural gas processing, oxygen and hydrogen production, and oxy-fuel combustion in the iron and steel industry. The CO₂ capture system may be added as a retrofit or included in the design of the energy plant or industrial application.

CO₂ capture is generally the largest single cost element in the CCS chain due to the high capital costs of the equipment and the energy use involved. Exceptions are industrial processes where CO₂ separation is already an integral part of the process. In these industrial processes, CO₂ separation costs are a part of total production costs. In

conventional fossil fuel power generation and industry, CO₂ separation is less developed at scale, although several power plants have been retrofitted with CCS technologies in recent years.

Allocation of R&D resources should consider how new technologies might affect capital costs and raise flexibility and energy efficiency. It is currently unclear which CO₂ capture technologies will be most effective in delivering cost reductions and performance improvements. Balanced portfolios include technologies representing both lower-risk, incremental improvements and higher-risk, more radical improvements. Furthermore, novel approaches to carbon capture from low CO₂ concentration gas streams from small point sources merit further research. The main technological developments by capture route are briefly described below.

- *Post-process capture.* Past research into solvents has already reduced the energy required to separate CO₂ from flue gas by 50% since 1990. Several technological approaches are on the horizon with the potential to improve post-combustion capture, covering the full range of technological maturity. The most promising separation routes are based on solvent- or sorbent-based processes, membranes, or liquefaction (IEAGHG, 2014).
- *Syngas/hydrogen capture.* Considerable research has been conducted into novel technologies that aim to separate the CO₂ or hydrogen from the gas mixture during the water-gas shift reaction by using membranes or absorbents. Both options have good prospects for energy and cost reductions. Other promising technologies include low-temperature separation, and fuel cells in conjunction with integrated gasification combined-cycle (IGCC) power plants. Fuel cells have higher part-load efficiencies than conventional thermal power plants, such as a CCGT, and are able to inherently capture CO₂, resulting in low additional costs.
- *Oxy-fuel combustion.* Research efforts focus mainly on improving the large and costly ASUs used to separate out pure oxygen to use in combustion, as well as their integration into the heat generation or industrial process. Over time, membranes for air separation are expected to become a cost-effective alternative as well. Several advanced oxy-fuel technologies (e.g. chemical looping, pressurised oxy-fuel and fuel cells in combination with IGCC) are currently being developed and show large energy reduction potentials, but are still in their infancy. The advent of alternative oxy-combustion turbine-based cycles, integrating advanced turbines and novel CO₂ separation technologies, is another promising concept. In these alternative power cycles, a gaseous fuel is combusted with oxygen and recycled flue gases. The combustion products, consisting of water and CO₂, are expanded through a modified turbine, which drives a generator. The use of water and CO₂ as a working fluid eliminates the need for CO₂ separation processes. These cycles aim to optimise the total system, comprising power generation and CO₂ capture, in order to reduce the cost per megawatt hour, rather than simply focusing on the capture system. Several designs of these alternative power cycles demonstrate efficiency comparable with CCGTs (without CO₂ capture) at similar capital cost.

Certain capture technologies are more suited than others to capturing CO₂ from small and low-concentration CO₂ streams. In particular, post-combustion capture technologies involving amines and precipitating solvents perform well, as do adsorbents in combination with temperature swing processes.

Next to improvements in the cost and energy consumption of capture technologies, novel configurations involving flue gas recirculation or a combination of capture technologies constitute another route to lower the energy demand and spatial footprint. For instance, membranes (or flue gas recirculation) can be used to boost the CO₂ concentration in a diluted gas stream (e.g. 3% to 4% in flue gas of a gas-fired furnace), resulting in a reduced gas volume, after which an amine solvent is used to separate the CO₂. A

downstream solvent system would have a smaller spatial footprint and lower energy penalty than conventional post-combustion systems (GCCSI, 2014).

In places where multiple small sources are clustered closely together, sharing CO₂ capture equipment is another possibility to curtail capture and transport costs by exploiting economies of scale, especially for smaller CO₂ emitters. For instance, a post-combustion capture configuration in which absorbers are placed on each industrial plant site (i.e. decentralised), and large-scale desorbers and compressors are placed at a more centralised location, is likely to be more cost-effective than a set of individual capture systems at the plant level. Similar observations were made for centralised oxy-fuel and pre-combustion capture configurations (Berghout et al., 2015; Berghout, van den Broek and Faaij, 2017).

The B2DS not only implies higher CCS deployment rates, but also necessitates higher CO₂ capture rates. Many current and emerging capture technologies are designed to remove around 80% to 90% of the CO₂ from the feed gas. The remaining CO₂ emissions in the feed gas are vented to the atmosphere. Over time, these emissions will have to be abated as well. This can be done by increasing the capture rate to (nearly) 100%. In current amine-based capture systems, capture rates over 90% result in higher specific energy consumption, especially when they approach 98% to 99% (Enaasen Flø, Kvamsdal and Hillestad, 2016). Specific energy consumption would also increase for oxy-fuel combustion with capture rates of nearly 100%.

With growing CCS penetration rates, advanced capture technologies with improved performance at high capture rates can be expected to become available. Aside from improving capture technologies, new industrial process designs that produce gas streams with higher CO₂ concentration, and designs with integrated CO₂ separation, could be means to reduce the cost of CO₂ capture from small, diluted point sources.

Building a CCS system

Reaching the levels of deployment envisaged in the B2DS will require a marked increase in government commitment to deploying CCS, including substantial financial investment. In practice this will mean enacting specific support mechanisms tailored to CCS, to ensure effective early deployment. Experience to date demonstrates that CCS policy would be more effective with a shift in focus from supporting full-chain integrated projects to targeted intervention, to develop, support and incentivise investment in each of the three components of CCS – capture, transport and storage.

A comprehensive policy framework to support the development of CCS should be built on government leadership and clear commitment to decarbonisation, with CCS as a critical component, in order to encourage private-sector investment. CCS policy frameworks need to recognise the nature of CCS, in particular:

- CCS is a suite of technologies that offers the potential to reduce CO₂ emissions, rather than being an energy generation technology. In this sense, CCS is more akin to other environmental control technologies than to power generation technologies.
- There is no commercial driver for CO₂ capture or storage in the majority of sectors and regions. There are exceptions, such as in North America where demand for CO₂ exists for EOR, or in the natural gas industry where the removal of CO₂ is often a necessary step in the production process.
- The three elements of CCS – capture, transport and storage – are different activities with different risk and investment profiles and technical capacity requirements. Policy to drive CCS deployment needs to recognise and address the challenges specific to each of these elements.
- The integration of the three elements of the chain can bring complex commercial risks. As CCS is not a profit-generating process in the current policy environment, no incentive exists for parties to absorb the risks.

Separate models for separate businesses

The CCS chain comprises distinct processes of capture, transport and storage, each of which has contrasting attributes. The differences among the parts of the CCS chain necessitate distinct or decoupled business models and approaches to developing them, including differentiated policy drivers. On the one hand, CO₂ capture will be a standard, in most cases chemical, technology that can be applied to a number of industrial and power generation processes. On the other hand, transport and storage are much more akin to regular infrastructure activities. The transport and storage of CO₂ differ from CO₂ capture with regard to the required competencies, risk profiles and commercial models, and therefore must be understood as separated but inter-related activities.

The vast majority of sectors applying CO₂ capture will be unlikely to have the skills for or interest in developing dedicated CO₂ transport and storage options, and will have a strong preference for relying on external transport and storage services that can be purchased “at the gate”. Most companies applying CO₂ capture will have little or no experience of operating underground. Indeed, for most companies in the power and industrial sectors, operating a CO₂ storage facility are outside their corporate mandate. Therefore most CCS will require access to dedicated CO₂ transport and storage services.

Box

8.6. Alberta Carbon Trunk Line

The Alberta Carbon Trunk Line (ACTL) is an example of public-sector leadership in developing CO₂ transport infrastructure, enabling capture from a number of sources in an industrial cluster. The total costs for the initial phase of the project, which includes the pipeline and two capture sources, are of the order of USD 906 million (1.2 billion Canadian dollars [CAD])* . The Canadian and Alberta governments will provide a total of USD 421 million (CAD 558 million) to the project. The Province of Alberta will provide USD 374 million (CAD 495 million) over 15 years from the Alberta CCS Fund, with the Canadian government providing USD 48 million (CAD 63 million, comprising CAD 30 million from the Clean Energy Fund and CAD 33 million from the EcoENERGY Technology Initiative).

The project consists of the transport of CO₂ from a number of sources in Alberta’s industrial heartland, near Redwater, to declining oil fields in central Alberta for the purpose of EOR. Developed in Alberta by Enhance Energy Inc., ACTL consists of a 240 km pipeline, employing a proven technology to gather, compress and store up to 14.6 MtCO₂ per year at full capacity (Enhance Energy, 2017).

The initial sources of CO₂ for the ACTL come from the Agrium fertiliser plant and the North West Sturgeon bitumen refinery currently under construction, both close to Redwater. The combined capture of CO₂ from these sources is between 1.6 MtCO₂ and 2.0 MtCO₂, only 12% to 13% of the pipeline’s capacity (GCCSI, 2017b).

The ACTL is designed under the financing agreements to be oversized and is incentivised to allow access to other CO₂ sources in the region at a competitive price.

* Exchange rate – USD: CAD 1.325 (OECD, <https://data.oecd.org/conversion/exchange-rates.htm>).

CCS chain integration models

Three generic models can be identified for the integration of CO₂ capture projects with CO₂ transport and storage (Esposito, Monroe and Friedman, 2011).

- The **self-build** model refers to operators who are fully vertically integrated and are able to develop and operate the capture, transport and storage facilities. The self-build model relies on the operating company having the core competencies necessary to manage all three

aspects. Oil and gas companies are examples of companies likely to be vertically integrated, allowing them to control all aspects of the CCS chain.

- The **joint venture** model involves less vertical integration within single companies, but rather the formation of joint ventures incorporating the capture host facility operator and the companies responsible for transport and storage. The joint venture model avoids the need for a single company to hold the competencies necessary to operate all elements of the chain. At this stage of CCS experience and with current policy and regulatory settings, it has proven difficult to overcome the commercial challenges of establishing a successful joint venture. All participants face commercial risks for which there is usually insufficient compensation, making risk allocation within the structure difficult.
- The third approach is a “**pay at the gate**” model in which transport and storage services are supplied by an external third party. This model involves the CO₂ being purchased or taken from the capture facility. The question of who is responsible for the CO₂ once it passes the gate will vary between jurisdictions. A “pay at the gate” model is particularly attractive for industrial processes or smaller capture applications, where capture host companies are unlikely to enter into joint venture arrangements or have the capacity to keep transport and storage in house.

To date, CCS policy in many countries has tended to focus on progressing projects that undertake all three elements within a fully integrated single project structure, either as a single entity self-build or more commonly following the joint venture model.

Such a fully integrated approach has proven challenging and has required projects to be undertaken by a consortium comprising the necessary competencies, but without a strong revenue stream to serve the commercial arrangements. Consortia incorporating the full project chain have had a very low success rate due, among other factors, to the complex commercial challenges of integrating the three elements of the chain. So far almost all projects that have taken FID have relied on existing CO₂-EOR operations (where CO₂ is injected into oil reservoirs to enhance oil recovery) as takers of the captured CO₂, or have had large corporate project sponsors able to manage the various elements of the projects. These large sponsors have mostly been oil and gas companies, which routinely undertake the separation of CO₂, pipeline transport of gas and liquids, and underground operations. Thus, by and large, successful projects have either been able to store CO₂ themselves, or have delivered it into a CO₂ network.

The first wave of projects currently in operation or under construction have been of either the self-build or “pay at the gate” model. A majority of projects have provided CO₂ for EOR through a “pay at the gate” contract. Five projects are in construction or operation globally that are not supplying CO₂ for EOR, all of which are fully integrated in the self-build model in which the operator of the capture facility also operates the storage well. While a number of joint venture projects have been developed and progressed, none has yet taken FID.

Lack of access to CO₂ transport and storage has been an obstacle for many projects in development, and conversely, access to transport and storage has been a critical enabler for all operating CCS projects. This highlights the importance of infrastructure development. The following parts of this section discuss various aspects of infrastructure, and the role that governments could take in enabling its development.

The strategic need for CO₂ transport and storage infrastructure

The CCS system will be a critical part of a decarbonised economy in 2060 under the 2DS and B2DS, comprising widespread application of CO₂ capture on a range of power generation and industrial plants, an extensive network of CO₂ pipelines or shipping lanes, and a portfolio of storage sites. However, the widespread deployment of CCS will require a shift from a policy approach of incentivising individual projects to one that focuses on developing the transport and infrastructure that will enable CCS, together with sector-specific policy settings necessary to push the uptake of CO₂ capture. A multipronged approach that targets the individual elements in the CCS chain will create the environment in which CCS can be rapidly adopted.

The development of public common user transport and storage infrastructure would greatly accelerate the uptake of CO₂ capture. The availability of CO₂ storage has proven to be one of the key determinants in the success of CCS projects, and accordingly, the deployment of CCS will require the upfront development of storage resources given the lack of a business case. To achieve the rapid deployment of CCS necessary to meet ambitious climate targets, governments must prioritise the development of storage resources. In an emissions-constrained environment such as the B2DS or 2DS, extensive transport networks and storage resources will form essential infrastructure critical to the operation of emissions-intensive industries, bioenergy power generation, and remaining fossil fuel production and consumption processes.

The deployment of CCS to date has been concentrated in regions where storage options are easily accessible and in industries where CO₂ storage is a manageable undertaking. The 2DS and B2DS require CCS to be deployed extensively in regions currently without developed storage resources. Further, most CCS will be applied in sectors currently without the skills and commercial profile to undertake storage. This will highlight the need to speed up the development of a CO₂ transport and storage infrastructure system.

A majority of CO₂ capture projects globally have been developed in the United States, where CO₂-EOR operators take CO₂ either directly or through an extensive dedicated pipeline network. EOR operators have been a source of revenue that has driven the development of CO₂ capture and transport infrastructure, but also a ready and accessible CO₂ off-take option. Such off-take arrangements reduce the commercial risks facing potential capture project proponents, as they avoid the need to develop and operate an underground storage site.

Successful CO₂ injection projects have also drawn from more than one capture project. For example, the Weyburn and Midale fields began injecting CO₂ from the Great Plains Synfuel plant in North Dakota, United States, in 2000, and this injection continues to date. In addition, CO₂ captured from Boundary Dam Unit 3 is now also being sold to Cenovus through the existing pipelines to be injected in the Weyburn and Midale fields.

In the B2DS, the availability of storage becomes much more critical, with the pace of storage availability forming the upper limit on CCS deployment and penetration. As CCS deployment accelerates over the period to 2060, the large quantities of CO₂ being captured and requiring storage will become a significant logistical challenge. This will not be met through individual point-to-point projects, but will require the co-ordinated and strategic development of transport and storage systems able to receive CO₂ from a variety of sources.

Infrastructure development

In 2060, CCS will not be a series of individual projects, but rather will require a system comprising extensive pipeline networks, a diverse portfolio of CO₂ storage resources and CO₂ capture applied to a range of processes. The construction of CCS systems will be driven by the development of well-located storage resources and common user transport networks, which will reduce the barriers to facilities deploying CO₂ capture. The development of CCS infrastructure could follow the model of other similar large-scale infrastructure systems, characterised by local or regional leadership with increasing levels of co-ordination and centralisation between different systems, leading to national or transnational systems.

Investment in infrastructure is generally assessed on its societal benefits as well as its potential to spark economic development. Historically, governments have led the development of new infrastructure when there is a public good to be pursued or a public burden to be addressed, and insufficient incentive exists for the private development of the infrastructure. As is common with large infrastructure projects, ownership can become more weighted to the private sector as the market develops. In this case, as CO₂ capture is more widely adopted, the demand for transport and storage services will drive greater private investment.

CO₂ transport and storage networks offer a service of greater value to society than can be realised through their commercial operation at the current low CO₂ prices or emissions penalties. In addition, in certain jurisdictions a range of risks and

uncertainties surround responsibility for the CO₂, acting as a disincentive to the private development of transport and storage.

Infrastructure investment has often been justified by its potential to generate or enable additional economic activity. CO₂ transport networks will open avenues for economic activity in the B2DS or even the 2DS. In the B2DS, the cost of CO₂ emissions will be prohibitive for high-emissions processes, meaning that only plants with CO₂ capture will be built.

Therefore plants will be built only where they have access to transport and storage.

Accessible CO₂ transport and storage can help create low-carbon industrial clusters. In such a scenario, CO₂ transport and storage facilities will be almost as critical to industrial facilities as other key services, such as power, water and waste disposal.

A CCS system that provides these services can be considered a public good, given its ability to decarbonise various forms of economic activity, the current lack of a commercial case for its development, and the challenges of and potential savings from co-ordinated development across countries and regions. Current climate policies do not adequately reflect the societal costs of CO₂ emissions and as such provide little incentive for the removal of CO₂. The market for CO₂ storage will not become commercial until a given region sees the widespread adoption of CO₂ capture; however, paradoxically, CO₂ capture will not be widely deployed until transport and storage options are available. Government leadership will be critical to breaking this deadlock.

The next wave of CCS deployment in OECD countries could feature the development of integrated CO₂ transport and storage projects in an area with a well-understood storage site accessible from a cluster of high-emissions industrial and power facilities. They may also be built out from a single large-scale fully integrated project. Several examples of such projects can be found, such as the Teesside collective in the United Kingdom and the Rotterdam industrial area in the Netherlands; these are in the development pipeline, although none has yet taken FID. As more facilities in the local region apply CO₂ capture, the model will shift to a “pay at the gate” model whereby the owner of the original project will offer transport and storage services to neighbouring capture projects.

The developer of the initial pipelines will face significant commercial risk of other capture plants failing to come on line or not delivering the promised quantities of CO₂, underlining again the importance of government support. If the revenue flowing to the operator of the pipeline is based on volumes, the project economics will rely on a certain amount of CO₂ from a certain number of capture sites. This risk is likely to make the construction or oversizing of these trunk lines commercially unviable, and the project will therefore need some form of public underwriting of this risk.

In the early phase, access to storage would enable capture from a range of processes where capture is relatively straightforward and low cost. Access to a transport and storage network would drive the uptake of capture with little extra cost or need for subsidy, or at a relatively low CO₂ price. Easily realisable capture opportunities would further support investment in transport and storage, further reducing the costs and technical and commercial uncertainties.

Government can drive CCS by building CO₂ transport and storage infrastructure

Governments have a central role to play in developing CO₂ transport and storage infrastructure. They should go further than precompetitive screening of sites to leading the development of transport and storage infrastructure. Governments have traditionally supported storage resource development through the precompetitive stages of exploration. Different global regions have differing levels of geological understanding. Regions with extensive oil and gas production will have areas with well-understood geology, whereas other regions will need to begin assessment at the base level. Governments have undertaken, or helped to undertake, assessment and characterisation of basins to a precompetitive level for the oil and gas industry. In such cases the assumption has been that the private sector will then drive exploration, appraisal and site development to the point at which CO₂ can be injected.

Precompetitive exploration programmes reduce the uncertainty in storage exploration; however, further appraisal of a potential site still requires significant investment, which is

lost if the site is subsequently deemed to be unsuitable. The oil and gas industry manages this uncertainty in oil and gas exploration, as a discovered resource will deliver a significant rate of return. This risk–reward proposition does not exist for CO₂ storage, as no market is present for CO₂ storage services. A market for CO₂ storage may develop as the cost of CO₂ emissions increases over the period of the B2DS or the 2DS.

A private market for CO₂ storage services is unlikely to emerge without government intervention, given the challenge in sequencing the development of CCS. The market for CO₂ storage will develop only once CO₂ capture is widespread, creating demand for transport and storage services. In many cases, however, projects will invest in CO₂ capture only when accessible transport and storage networks are available. This sequencing challenge will greatly hamper and slow CCS development, but can be overcome through the creation of public transport and storage infrastructure.

The pipelines, shipping networks and extensive CO₂ storage resources needed to handle the volumes of captured CO₂ in the B2DS can be most effectively and efficiently developed as public infrastructure. Over time, the commercial case for private investment will grow, leading at least to the partial privatisation of the networks, but initially the majority of investment and development will come from the public sector, as with the roll–out of other large infrastructure programmes, such as advanced waste management.

CO₂ storage

The effectiveness of CCS as a climate mitigation technology relies on the captured CO₂ being permanently prevented from entering, or re–entering, the atmosphere. Geological storage is the most effective method of preventing captured CO₂ from entering the atmosphere and the only option of a scale sufficient to accommodate the large volumes of CO₂ captured in the 2DS or B2DS. By 2060, over 11 GtCO₂ will be captured annually in the B2DS, which means the portfolio of storage resources globally will need to be able to take CO₂ at a rapid rate. In total, 227 GtCO₂ are captured across the B2DS by 2060, necessitating a global portfolio of storage resources with sufficient capacity.

The safe and effective long–term storage of CO₂ requires a good understanding of basic subsurface processes, careful selection of storage sites, effective engineering and operation of the actual storage sites, and appropriate risk management, monitoring and modelling.

How is CO₂ stored underground?

Geological storage involves the injection of captured CO₂ into deep underground geological reservoirs of porous rock for permanent storage. Current volumetric estimates of total global storage capacity in sedimentary basins range from 5 000 GtCO₂ to 25 000 GtCO₂ (de Coninck and Benson, 2014), more than sufficient to contain the 227 GtCO₂ captured in the B2DS. However, significant uncertainty surrounds the global storage estimates, and work is needed to better appreciate the geographical distribution of storage to allow for more effective planning.

Suitable storage formations

Several types of underground formation offer the potential for deep geological storage, both onshore and offshore. The geological requirements for CO₂ storage include a large porous and permeable sandstone or limestone reservoir, overlain by an extensive layer of mudstone, shale or other impermeable formation, such as rock salt, forming a “cap rock” or “seal”. The reservoir must also be at a depth that can retain the CO₂ in a dense phase for maximum efficiency (see Box 8.7 for discussion of CO₂ trapping mechanisms).

The major classes of underground formation that can potentially be used for CO₂ storage are as follows:

- **Saline aquifers** are layers of porous and permeable rocks saturated with salty water (brine), which are fairly widespread in both onshore and offshore sedimentary basins.

- **Depleted oil and gas reservoirs** are porous rock formations containing either mainly crude oil or gas that has been physically held in stratigraphic or structural traps for millions of years.
- **Unmineable coal:** coal is considered unmineable if it is not economically, geologically and/or technically extractable. In that case, CO₂ can be adsorbed in the coal. CO₂ can replace methane, which is naturally found in coal seams and can be extracted by depressurisation/dewatering of the coal seams. This process of using injected CO₂ to enhance methane recovery is called enhanced coalbed methane recovery (ECBM). To date, CO₂ storage in deep unmineable coal seams (including ECBM) is under development, with only small-scale field and pilot projects under way.
- **Basalt formations** are typically geological formations of solidified lava (classified as basalt). They have a wide geographical distribution around the world, but storing CO₂ in basalts is yet to be demonstrated on a large scale.

Saline aquifers and depleted oil and gas reservoirs in sedimentary basins are the main geological media being considered for large-scale CO₂ storage. Depleted oil and gas reservoirs are likely to be the first resources to be exploited, as they are well understood geologically and operationally, and therefore will require less time to develop into storage reserves than greenfield saline formations, which are completely undeveloped. While depleted oil and gas fields may provide important intermediate-scale storage, the level of CO₂ capture in the 2DS or B2DS will require large-scale CO₂ injections into deep saline aquifers due to the volumes of CO₂ to be stored, and due to saline aquifers being much more commonly occurring geographically.

Box

8.7. CO₂ trapping mechanisms

In suitable underground geological formations, CO₂ is trapped to ensure storage for geological timescales. The trapping of CO₂ in the formations happens through a combination of the following mechanisms:

- **Structural or stratigraphic trapping:** CO₂ is physically trapped below a cap rock, which prevents it from migrating to the surface.
- **Residual trapping:** CO₂ is trapped at the irreducible saturation point, segregating the CO₂ bubble into droplets that become trapped in individual or groups of pores.
- **Solubility trapping:** a portion of injected CO₂ can also dissolve in the brine water that is present in the pore spaces within the rock.
- **Mineralisation or mineral trapping:** CO₂ that has been dissolved in brine reacts with the reservoir rocks to form carbonate minerals. Mineral trapping is the most secure form of storage, but reactions usually occur slowly on the geological timescale, with the exception of the CarbFix project where mineralisation occurs a lot more quickly due to Iceland's specific geological setting.

For CO₂ storage in coal seams, the trapping mechanism is slightly different: a form of geochemical trapping takes place, with preferential adsorption of CO₂ onto the coal matrix because of its higher affinity to coal than that of methane.

The nature of the trapping will vary within and across the life of a site, and will depend on the geological conditions, the type of rock formations where CO₂ is injected and the injection phases. During the injection phase, the hydrodynamic force of pressure from the injection of large amounts of CO₂ is usually the dominant physical force in the system, favouring the structural trapping mechanism. But for the post-injection phase, buoyancy is usually the dominant driving force for plume migration, enhancing chemical trapping (residual, solubility and mineral trapping), which is affected by the slope and topography of the top of the injection formation.

CO₂ storage capacity

The vast majority of the estimated capacity is in deep saline aquifers, which have an estimated storage potential ranging from 4 000 GtCO₂ to 23 000 GtCO₂, consistent with storage capacity range in the IPCC report (2005). Oil and gas reservoirs offer further CO₂ storage capacity of the order of 1 000 GtCO₂ (Benson et al., 2012). A high degree of uncertainty surrounds estimates of global storage volumes, particularly in saline aquifers given that they have yet to be deeply explored or characterised. CO₂ storage capacity is estimated by calculating the total pore volume of a formation and then multiplying that volume by a storage efficiency factor. Storage efficiency is the volume proportion of pore space within the target storage complex that can be filled with CO₂. High-level storage volume assessments estimate the storage efficiency of a given reservoir; however, a high degree of uncertainty remains until detailed assessments are undertaken. The storage efficiency is a function of a number of factors (Bachu and Bandilla, 2015), including:

- The storage aquifer parameters, such as pressure, temperature, water salinity, displacement characteristics of the CO₂/brine system, depositional environment, lithology and hydrogeological parameters (porosity and permeability, heterogeneity and anisotropy, compressibility, areal extent, thickness, dip, topography at the top of the aquifer, faults, and aquifer boundaries).
- The specifics of the storage operation, including rate of injection, duration of injection, number, design and spacing of injection wells, and proximity of legacy wells.
- Regulatory constraints, such as maximum allowed bottom hole injection pressure, area where pressure is impacted (area of review) and duration of tenure.
- Dynamic capacity takes into account the rate at which CO₂ can be stored, which will change over the life of the project, as well as the total volume that can be stored. In addition to ensuring that the anticipated overall volume of CO₂ can be stored, it is important to establish how much CO₂ can be injected per year in a given storage resource and how that compares with the captured CO₂ of a given region. Numerical simulations have recently shown that dynamic storage capacity estimates involving various operational strategies and aquifer characteristics have always resulted in lower estimates of storage capacity than straightforward volumetric capacities (Thibeau et al., 2014; IEAGHG, 2016). This is mainly because storage efficiency has a temporal dependency, and volumetric methods do not take in consideration the effects of initial pressure limitations and pressure build-up over time.

However, even if storage capacity estimates based on a volumetric capacity estimation method remain inherently uncertain, recent findings have concluded that sufficient capacity is available worldwide, mainly in deep saline aquifers, to store the emissions captured in the B2DS or 2DS.

CO₂ storage costs and economics

CO₂ storage costs vary significantly depending on the rate of CO₂ injection and the characteristics of the storage reservoirs, as well as the location of CO₂ storage sites. These are all subject to significant uncertainty, particularly in regard to reservoir properties and characteristics. Trade-offs among storage asset quality, transport distance and risk can present themselves. Beyond being site-specific and subject to a large range of reservoir uncertainties, comparing CO₂ storage costs between studies can be complicated by the application of different unit costs, economic factors and cost estimation methodologies and assumptions (Rubin et al., 2015).

Box

8.8. Zero-Emissions Platform storage costs and economics study

The European Zero-Emissions Platform (ZEP) study of CO₂ storage costs in Europe estimates a range of 1 euro (EUR) to EUR 2 per tonne for onshore storage and EUR 2 to EUR 20 per tonne for offshore storage, with the cheapest storage option being onshore depleted oil and gas fields using legacy wells (EUR 1 to EUR 7 per tonne), and offshore saline aquifer being the most expensive (EUR 6 to EUR 20 per tonne) (ZEP, 2011). The study also shows that the cheapest storage option contributes the least to total available capacity, while larger reservoirs with high injectivity have the lowest CO₂ storage costs. Pre-FID costs for saline aquifers are higher than those for depleted oil and gas fields, reflecting the need for more exploration of saline aquifers for CO₂ storage given that less is known of them than depleted oil and gas fields. The study concluded that field capacity estimates have a large effect on CO₂ storage costs, and therefore reducing CO₂ storage costs can be achieved by selecting reservoirs with the highest capacity. In addition, well costs contribute 40% to 70% of the total storage costs, meaning saline aquifers with high injectivity, which require the lowest number of injection wells, have the lowest CO₂ storage costs.

8.1. Table: Storage costs in Europe by formation type

Case	Medium cost estimate (EUR per tonne)
Depleted oil and gas field – onshore (with legacy wells)	3
Depleted oil and gas field – onshore (no legacy wells)	4
Saline aquifer – onshore	5
Depleted oil and gas field – offshore (with legacy wells)	6
Depleted oil and gas field – offshore (no legacy wells)	10
Saline aquifer – offshore	14

Selecting suitable CO₂ storage sites

The appropriate selection of a site for CO₂ storage is the single greatest factor determining the safety of CO₂ storage and reducing the storage risks to acceptable levels. This process can take up to ten years for greenfield sites or formations, and requires significant investment in CO₂ storage assessment prior to any FID on a storage project.

Critical features of suitable storage sites

Four critical generic features must be considered when assessing suitable CO₂ storage areas or sites. These are:

- **Containment.** The most important attribute to ensure is containment: any injected CO₂ and the displaced brine should not migrate to any critical subsurface zones, including groundwater aquifers and other subsurface resource locations, or to the atmosphere.
- **Capacity.** The injection target must be able to store the total amount of CO₂ that needs to be stored (capacity). The capacity depends essentially on the porosity – the proportion of the pore space (already filled with a fluid, which is commonly brine or salt water) that CO₂

can occupy once injected compared with the total volume of the rocks. Porosity can range from 0% for a cap rock (pores are filled with solid material) to up to 40% for a high-quality sandstone reservoir.

- **Injectivity.** The selected storage site must also be able to accept the CO₂ being injected at the rate at which it is delivered via transport (injectivity is measured in million tonnes per year). Injectivity is driven by permeability (expressed in millidarcies), and is the ability of a fluid such as CO₂ to flow through the rock formation via the interconnection of one pore space with its adjacent pore spaces.
- **Monitorability.** Finally, monitorability is a further factor determining the suitability of a site for CO₂ storage. It is the ability to monitor the CO₂ plume and associated pressure propagation over time, during CO₂ injection and after CO₂ injection ceases.

CO₂ storage site selection and characterisation

As with oil or gas, CO₂ storage capacity is a natural resource requiring exploration and appraisal based on a portfolio approach, with more than one option to allow for exploration “failures”. During the site characterisation process, this necessitates a large amount of expensive data gathering, and while success rates might be higher than in the oil and gas exploration sector, failure rates, costs and delays are likely to be significant. Such CO₂ storage data acquisition and study programmes must focus on reducing large geotechnical uncertainties. It is crucial to develop clear storage decision criteria, with both confidence levels and performance targets, which will drive the CO₂ exploration and appraisal programme and ultimately future investment in the CCS project.

The storage assessment process usually progresses from regional screening to successive refinement through data acquisition and modelling, leading to the selection of a suitable CO₂ storage sites (CO₂GeoNet, 2013). This assessment is based on a fundamental understanding of the geological, hydrological, geo-mechanical, and geochemical processes controlling the fate and migration of CO₂ in the subsurface.

First, site identification and selection begins with a process of site screening in order to evaluate, based on existing data, the potential for CO₂ geological storage in a given region through the identification of appropriate sedimentary basins. More detailed basin assessments allow the appraisal of the prospective sites as to their overall suitability for CO₂ storage.

A number of sites within the basin will then be further characterised, which involves appraising prospective storage sites in detail and developing a well engineering concept that provides the required capacity, injectivity and containment. This is the most time-consuming and costly part of the process, as it usually involves re-evaluation of well and seismic data and acquisition of new data and/or updating of existing data. These include static and dynamic pressure and fluid composition data, with static data comprising core, logging and seismic data, and dynamic data comprising well testing, production and/or injection test simulation and injection pressure data.

During site characterisation, the ultimate objective is to develop a field development plan for the selected sites. This will optimise engineering practices to ensure injection performance via a specified number, type and location of transport and injection facilities, and reservoir monitoring and integrity through the monitoring and verification plan. This process also takes account of legal and regulatory regimes, environmental constraints and economic conditions pertaining to the site.

Storage performance and assurance

After a suitable storage site is selected and developed, it is imperative to ensure that it performs in a safe and predictable manner. This includes an adequate risk assessment framework and practice, as well as employing monitoring and modelling techniques to understand the behaviour of the CO₂ in the reservoir.

Risk assessment and management

Risk assessment for CO₂ storage is an essential process used to examine and evaluate the potential for adverse impacts on health, safety and the environment of any potential leakage or seepage of CO₂ from the storage site. CO₂ storage risk assessments follow the same principles, methodologies and processes as those used in the oil and gas industry.

The primary risks in CO₂ storage result from the consequences of unintended CO₂ leakage and possibly brine displacement from the storage formation into overlying resource-bearing strata, protected groundwater aquifers, underground resources (coal, gas, geothermal, etc.), shallow soil zones and the atmosphere. Potential leakage pathways can occur through transmissive or undetected faults and fractures, insufficient top seal capacity, leaking legacy wells, or well failures (Anderson, 2016).

CO₂ storage risks are managed through a combination of site selection and characterisation, well completion design and practices, storage engineering, best practice assessment for abandoning wells, and monitoring (baseline, injection and post-injection). These processes are used to ensure that the probability of a significant risk event associated with long-term CO₂ storage remains very low.

Pressure management is a critical part of any storage operation, to avoid overpressurisation of the formation (more so for saline aquifers) and hence prevent fractures being created or reactivated in the cap rock. Brine production can play an important role in maintaining pressure below the maximum bottom hole injection pressure (a certain fraction of the estimated rock fracturing pressure), which is determined by the relevant regulatory authorities. Thermal and pressure stresses might also cause induced seismicity. However, proper site characterisation and active pressure management allow the reduction of the risk of seismic events. The risk of overpressurising the reservoir will also change over time. After CO₂ injection stops, the pressure will begin to decrease, reducing the risk of the CO₂ leakage or brine migration.

Measurement, monitoring and verification

CO₂ storage site monitoring allows for the ongoing observation of the performance of the storage site and the early detection of warning signs of unexpected behaviour. Monitoring is essential not only in observing CO₂ behaviour, but also in calibrating and validating predictive models, and in allowing the monitoring tools and plans to be improved. Monitoring is required through all phases of the project: establishing monitoring baselines before injection, and then monitoring performance during injection, after injection ceases and in the final site closure process.

Each CO₂ storage project will typically need to employ a monitoring programme that best suits its individual characteristics (Benson and Cole, 2008), with a combination of monitoring techniques:

Geophysical methods track movement of the CO₂ to monitor plume migration. To date, seismic imaging is the most extensively and successfully used, both offshore and onshore.

Geochemical methods sample fluid from the target and adjacent reservoirs through observation wells to detect changes in gas and brine composition (alkalinity and composition) or introduced tracers (such as isotopes), which signal the arrival of the CO₂ plume.

Surface and near-surface monitoring detects and measures potential CO₂ leakage through changes in the concentration of CO₂ in shallow ground, on the surface or in the atmosphere through gas or water sampling. Near-surface monitoring requires a well-established baseline profile of CO₂ levels as natural concentrations may vary significantly, for example due to microbial respiration and photosynthesis at the surface, potentially leading to false positive detection of CO₂ leaks to the atmosphere.

Satellite imaging is used to map induced ground motion caused by CO₂ injection underground and potential pressure build-up.

Modelling

Computer simulation of storage reservoir dynamics uses modelling to assess the mechanisms that control the behaviour of injected CO₂ underground, based on understanding of the processes that are active in the reservoir and on the available injection, production and monitoring data. The aim of modelling is different in each phase of the CO₂ storage project. During the pre-operational phase, simulation models are used to predict CO₂ plume migration and the effectiveness of trapping mechanisms, while during operations, comparison between simulated and monitored plume migration is used to refine and calibrate the model and then update forecasts of plume migration. This approach is iterative and requires the development of confidence in the prediction of plume behaviour. During the post-operational phase, a similar approach is used to predict post-injection plume behaviour.

CO₂-EOR

The vast majority of CO₂ that has been injected underground to date has been used to enhance the production of oil from ageing oilfields. CO₂-EOR has been undertaken in the United States on a commercial scale for nearly 50 years, predating concerns over CO₂ emissions and the subsequent push for geological sequestration of CO₂. Today, of the 31 MtCO₂ that is captured annually worldwide, 29 MtCO₂ (95%) is injected for CO₂-EOR (GCCSI, 2017a). However, the majority of the CO₂ used in CO₂-EOR is extracted from naturally occurring underground deposits rather than being captured from anthropogenic CO₂ sources.

CO₂-EOR typically involves a closed-loop process. Injected CO₂ mixes with oil, improving its flow properties and allowing it to move more easily to production wells. A proportion of the CO₂ is trapped underground, while the remaining CO₂ is extracted with the oil. As CO₂ is a valuable commodity for CO₂-EOR operators, care is taken to ensure that virtually all of the CO₂ produced with the oil is recovered and reinjected. Over the life of the project the CO₂ that stays underground, i.e. is not recovered, remains stored in the subsurface (see box 8.9) (IEA, 2015a).

Traditionally, CO₂-EOR projects have not undertaken monitoring to verify the permanent retention of CO₂ and detect CO₂ leaks. The IEA Greenhouse Gas R&D Programme (IEAGHG) Weyburn-Midale CO₂ Monitoring and Storage Project was an early exception, involving an extensive pilot programme to monitor and verify the storage of CO₂ between 2000 and 2012. More recently, the Uthmaniyah project in Saudi Arabia and the Petra Nova project in Texas both apply monitoring techniques to CO₂-EOR, with the aim of ensuring that CO₂ behaves as expected.

Box

8.9. Combining EOR and CO₂ storage

CO₂-EOR has been an important business driver for several CO₂ capture projects in recent decades. EOR offers further opportunities as the largest single use of CO₂, both today and in the foreseeable future. Today's CO₂-EOR is an oil production enhancement technique, aimed solely at increasing the production of oil from existing fields. "Storing" the utilised CO₂ happens incidentally, and is typically not verified. Furthermore, as CO₂ constitutes a cost for the operator, the quantities injected are naturally minimised and recycling of CO₂ is maximised. Conventional EOR has been practised for over 50 years, primarily in North America. Most CO₂-EOR projects today use naturally occurring CO₂ extracted for EOR purposes – a practice without any net benefit for the climate.

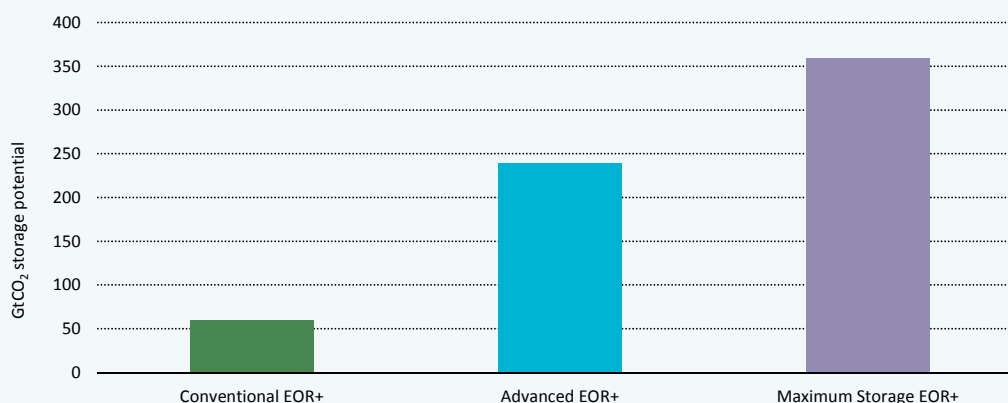
In contrast to conventional practices, the concept of EOR+ aims to exploit both oil production and geological CO₂ storage. EOR+ differs from conventional EOR in two key areas:

- The CO₂ must be anthropogenic.
- Operators undertake a number of key additional activities to ensure long-term retention of CO₂ from the atmosphere: 1) site characterisation; 2) measurement of fugitive emissions from the EOR+ operations site; 3) monitoring and verification of the field itself; and 4) field abandonment practices aimed at ensuring long-term storage. Such activities can be undertaken using existing technologies.

From a global perspective, CO₂ storage through EOR+ represents a significant opportunity. According to IEA analysis (2015a), the technical potential of EOR+ practices to store CO₂ in suitable oilfields worldwide ranges from about 60 GtCO₂ using current practices to potentially 360 GtCO₂ globally (Figure 8.9). The global potential for storage available through CO₂-EOR depends on the rate of net CO₂ utilisation per barrel of oil produced, and the incremental recovery of the original oil in place (OOIP). The three scenarios assume the following representative values:

- conventional EOR+: net utilisation of 0.3 tonnes of CO₂ per barrel (tCO₂/bbl) and incremental recovery of 6.5% OOIP
- advanced EOR+: net utilisation of 0.6 tCO₂/bbl and incremental recovery of 13% OOIP
- maximum storage EOR+: net utilisation of 0.9 tCO₂/bbl and incremental recovery of 13% OOIP.

8.9. Figure: CO₂ storage potential of EOR+



Sources: EA (2015a), "Storing CO₂ through enhanced oil recovery: Combining EOR with CO₂ storage (EOR+) for profit".

Key point: CO₂ storage through EOR holds significant technical potential – the amount will depend on the way the EOR is undertaken.

CO₂-EOR has been an important catalyst for CO₂ capture projects, which can generate revenue either by selling the captured CO₂ to a third party or directly by enhanced oil production. Furthermore, the United States has an extensive network of pipelines into which CO₂ capture projects can deliver their CO₂ without the cost or complication of developing dedicated transport and storage options.

CO₂ utilisation

CO₂ can be used as a feedstock or working fluid in a number of processes, creating a market for CO₂ as a commodity. Carbon capture and utilisation (CCU) offers a number of potential routes for replacing the use of fossil fuels with captured CO₂, reducing fossil fuel consumption. CCU can be attractive due to its potential environmental or climate benefits, or because of the innate chemical and physical properties of CO₂ (Bennett, Schroeder and McCoy, 2014). CCU has often been discussed as also providing an alternative route for captured CO₂ to geological storage, being particularly attractive to sectors that are unlikely to undertake storage. However, beyond CO₂-EOR, it is more likely to be a niche application limited to a few process routes that have the potential to be realised at scale, achieve net emissions reductions, and be economically viable in a given market.

CCU as an alternative to geological storage

The utilisation of CO₂ as a feedstock or as a working fluid has been put forward as an alternative to geological storage of CO₂; however, most utilisation routes do not permanently retain the CO₂. While mineralisation involves the permanent trapping of CO₂ comparable to geological storage, the CO₂ used in the production of fuels or urea is released to the atmosphere when the end product is used. CO₂ used as a working fluid is often recycled, and in the case of EOR may result in storage over time.

From a technical perspective, few process routes effectively and permanently store CO₂. Other CO₂ reuse routes rely on displacing fossil fuels to achieve a life-cycle emissions benefit. Therefore climate benefits accrue only if the process emissions are lower than competing products or if the product displaces the use of fossil fuel. In any case, detailed life-cycle assessment will be needed to determine the emissions reduction potential of different utilisation pathways.

Nonetheless, CCU can support early deployment of CO₂ capture as it avoids the complexity of storage and may provide a revenue stream. This simplifies the process, particularly for smaller CO₂ capture demonstration projects.

CO₂ utilisation pathways

The most common application of CO₂ currently is for EOR (as described above). In similar but far less mature applications, CO₂ can also be used in enhanced gas recovery or for extracting methane from coal seams. CO₂ is also being proposed as the working fluid in several new supercritical power cycles, although these technologies remain in the early stages of development.

CO₂ can be used as a source of carbon in the production of petrochemicals in place of hydrocarbon chains from fossil fuels. It can be converted to various chemicals, including polymers and carbonates, through reaction with other molecules or chemicals. These processes generally require significant amounts of energy to break the bonds of the otherwise stable CO₂, and therefore rely on abundant cheap renewable electricity to keep life-cycle emissions low. Therefore R&D is being conducted around the world to find technologies that efficiently use CO₂.

Urea, typically used as fertiliser, is produced by reacting ammonia with CO₂. Urea production is the second most common application of CO₂ today and is a mature and widely used technology. However, most of the CO₂ used in urea production is captured from ammonia production, often on the same site, limiting its potential to take other captured CO₂. Furthermore, CO₂ in urea is ultimately released to the atmosphere. Urea production with CO₂ is economic due to its proximity to, and the concentrated CO₂ streams from, the ammonia production point.

A number of processes can convert CO₂ into transport fuels, most commonly through the production of methanol or syngas. Methanol is produced by reacting hydrogen and CO₂ using a catalyst. As with all CO₂ conversion to chemicals, the process requires a substantial energy input, usually from renewable electricity, and the CO₂ is eventually released to the atmosphere when the fuel is combusted.

Markets for CO₂

Global demand for CO₂, outside of EOR, is estimated at around 200 MtCO₂ per year (Aresta, Dibenedetto and Angelini, 2013). The market for CO₂ in current applications is mature; however, other process routes may emerge. While there is the prospect of growth in demand for CO₂ from EOR if undertaken in other regions, it is yet to be established whether there will be significant growth in other applications.

Storage availability allows government to regulate and support CO₂ capture

Once storage is available and accessible in a given region, the scope widens for government to drive the deployment of CO₂ capture through a range of policy and regulatory instruments targeted at specific sectors. The availability of storage overcomes one of the key barriers to deployment for projects in most industries, creating the ability to promote CCS without asking companies to undertake storage, an activity outside their corporate risk profile. While storage may not be the largest cost component of CCS, it brings a high degree of uncertainty and is a hurdle for many prospective applications of CO₂ capture.

Government can address the increased operational costs of running CO₂ capture in the transition to a high CO₂ price environment with direct operational or cash flow support. This can be in the form of direct subsidies, contracts for difference between a benchmark price and the cost of production with CCS, tax credits, or other measures, and will be particularly important during the transition from the current policy environment to one in which the externalities of CO₂ emissions are fully priced. The importance and extent of government support will vary depending on the ability of the producer to absorb or pass on the added costs. In highly competitive industries with low margins, government support will need to cover the majority of the cost of capture until capture becomes standard for all production. In other sectors where costs can be more easily absorbed or passed through to consumers, government operating subsidies may not be necessary. For many CO₂ capture projects, operational support can be the most effective form of assistance if it provides a cash flow against which capital can be borrowed.

Capital investment grants partially address the cost of installing CO₂ capture equipment. Capital support will need to be complemented by operational support except in industries that are able to absorb the operational costs. Many governments have channelled public investment into CCS through capital grant programmes; however, projects have not reached FID owing to a lack of operational support.

Regulation can drive the adoption of emissions reduction technologies, including CCS. Measures such as emissions performance standards, which effectively mandate drastic reductions in emissions, can address the impacts on competitiveness of low-carbon technologies by requiring all participants in a given market to comply. These measures have been particularly successful in sectors that are not heavily exposed to international trade. The availability of storage allows regulators to set aggressive emissions performance standards at a level that effectively requires the application of CO₂ capture.

Policy actions to support CCS deployment

In the near term, governments should focus on developing storage resources that are strategically located near clusters of emissions point sources. A first step would be to develop infrastructure plans that set out a strategic and phased roll-out of transport networks and identify a pathway for providing the necessary storage resources.

Based on historical analogies of creating infrastructure in the absence of commercial drivers, the roll-out of extensive infrastructure over the coming decades is most likely to be achieved if undertaken by the public sector. To achieve the CCS deployment rates envisaged in the 2DS or the B2DS, governments should consider going beyond support for precompetitive assessment of basins to the development of storage resources to the point of operation.

Ultimately, governments should also consider mechanisms to commercially insulate CO₂ capture from CO₂ storage and vice versa. At present, the significant counterparty risk of one element of the chain not performing threatens the viability of the whole chain and indeed the activity underlying the capture of CO₂. Such mechanisms could go as far as creating a publicly backed intermediary, aggregator or market maker, which could absorb price and volume risk to some extent.⁴ Policy and support mechanisms could also be designed to allow plants flexibility to continue operating should an outage occur elsewhere along the chain, avoiding the need to vent CO₂. On the storage side, support mechanisms can be structured as “fee for service” arrangements rather than being based on tonnes of CO₂ stored, ameliorating the revenue risk associated with a lack of CO₂.

This level of investment creates an environment in which industry can invest in CO₂ capture, and ultimately over time, in CO₂ transport and storage. Experience to date has shown that when the storage challenge can be overcome, well-designed public investment can leverage multiples in private investment.

If transport and storage are available and are sufficiently de-risked, governments can easily put in place the combination of regulation and support necessary to drive the uptake of CO₂ capture. Regulatory measures such as emissions performance standards currently risk driving industry out of business, but can be much more effective if CCS is a viable and available option, and is within the risk and competence profiles of the operators. In certain sectors, such measures will need to be paired with support schemes designed to cushion the impact on competitiveness, which can also prove fatal, particularly in low-margin sectors.

Policy implications for the B2DS

The increase in CCS deployment from the 2DS to the level foreseen in the B2DS necessitates policy to drive faster and further. Two-thirds more CCS capacity would be needed in total. Achieving these rates of deployment would entail highly co-ordinated CCS implementation, with the public sector taking a lead role in building and operating transport and storage systems. The rate at which storage sites are developed would have to increase markedly.

The rates of CCS penetration in fossil fuel power generation and industrial production imply policy measures that go beyond incentivising and driving CCS uptake, and in addition mandate its application in certain processes with few exceptions.

Continued investment in R&D will be needed in any CCS deployment scenario; however, under the B2DS, efforts will need to focus on developing capture technologies that can more effectively and economically capture CO₂ from smaller and more dilute streams, and that have capture rates approaching 100% to avoid residual emissions from current technologies.

Policy will need to recognise and support the capture of CO₂ from bioenergy in the 2DS, but this becomes much more important in the B2DS, in which the negative emissions generated through BECCS are vital in offsetting other remaining emissions in the energy sector. CO₂ reduction schemes, such as carbon prices and emissions trading schemes, will need to be designed to account for the generation of negative emissions.

4. A market maker is proposed by ZEP (ZEP, 2014).

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Analytical approach

Energy Technology Perspectives 2017 (ETP 2017) applies a combination of “backcasting” and forecasting over three scenarios from now to 2060. Backcasting lays out plausible pathways to a desired end state. It makes it easier to identify milestones that need to be reached or trends that need to change promptly in order for the end goal to be achieved. The advantage of forecasting, where the end state is a result of the analysis, is that it allows greater consideration of short-term constraints.

The analysis and modelling aim to identify an economical way for society to reach the desired outcome, but for a variety of reasons the scenario results do not necessarily reflect the least-cost ideal. Many subtleties cannot be captured in a cost-optimisation framework, such as: political preferences, feasible ramp-up rates, capital constraints, and public acceptance. For the end-use sectors (buildings, transport and industry), doing a pure least-cost analysis is difficult and not always suitable. Long-term projections inevitably contain significant uncertainties, and many of the assumptions underlying the analysis are eventually likely to turn out to be inaccurate. Another important caveat to the analysis is that it does not account for secondary effects resulting from climate change such as adaptation costs. By combining varied modelling approaches that reflect the realities of the given sectors, together with extensive expert consultation, *ETP 2017* obtains robust results and in-depth insights.

Achieving the *ETP 2017* 2°C Scenario (2DS) and Beyond 2°C Scenario (B2DS) does not depend on the appearance of unforeseen breakthrough technologies. All technology options introduced in *ETP 2017* are already commercially available or at a stage of development that makes commercial-scale deployment possible within the scenario period.¹ Costs for many of these technologies are expected to fall over time, making a low-carbon future economically feasible.

The *ETP 2017* analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasises a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

To make the results more robust, the analysis pursues a portfolio of technologies within a framework of cost minimisation. This offers a hedge against the real risks associated with the pathways: if one technology or fuel fails to fulfil its expected potential, it can more easily be compensated by another if its share in the overall energy mix is low. The tendency of the energy system to comprise a portfolio of technologies becomes more pronounced as carbon emissions are reduced since the technology options for emissions reductions and their potential typically depend on the local conditions in a country. At the same time, uncertainties may become larger, depending on the technologies' level of maturity and the risk of not reaching expected technological development targets.

1. For more information on the technologies considered in *ETP 2017*, see the “Technology approach” section below.

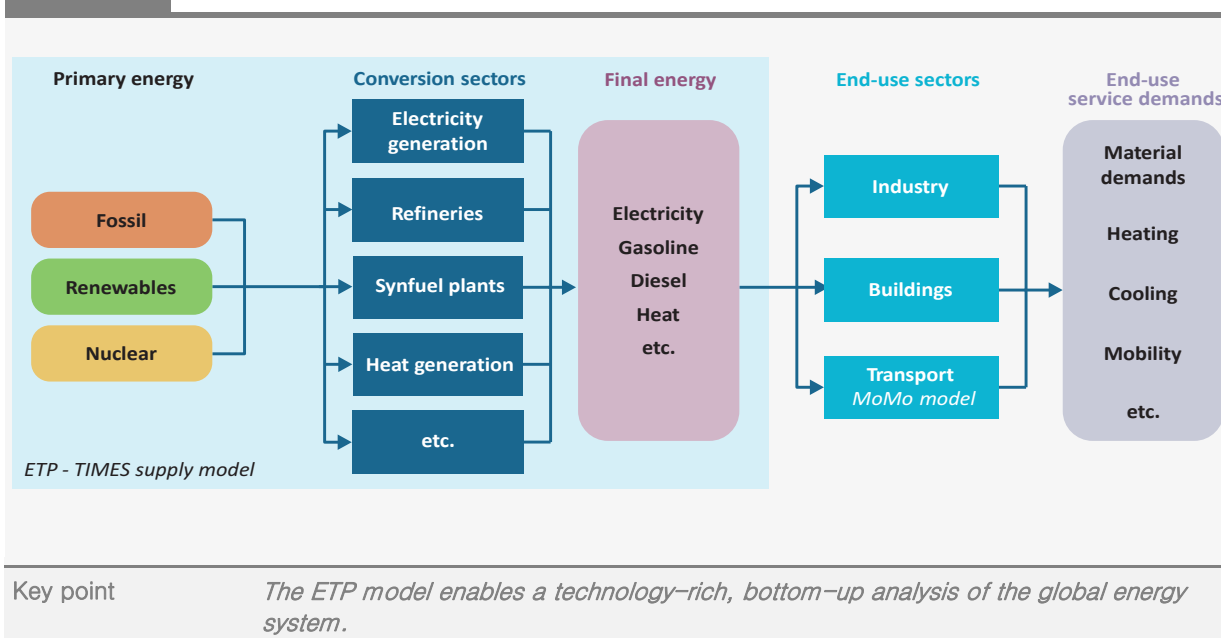
ETP model combines analysis of energy supply and demand

The ETP model, which is the primary analytical tool used in *ETP 2017*, supports integration and manipulation of data from four soft-linked models:

- energy conversion
- industry
- transport
- buildings (residential and commercial/services).

It is possible to explore outcomes that reflect variables in energy supply (using the energy conversion model) and in the three sectors that have the greatest demand and, hence, the largest emissions (using models for industry, transport, and buildings). The following schematic illustrates the interplay of these elements in the processes by which primary energy is converted to the final energy that is useful to these demand-side sectors (Figure A.1).

Figure A.1. Structure of the ETP model



ETP-TIMES Supply model

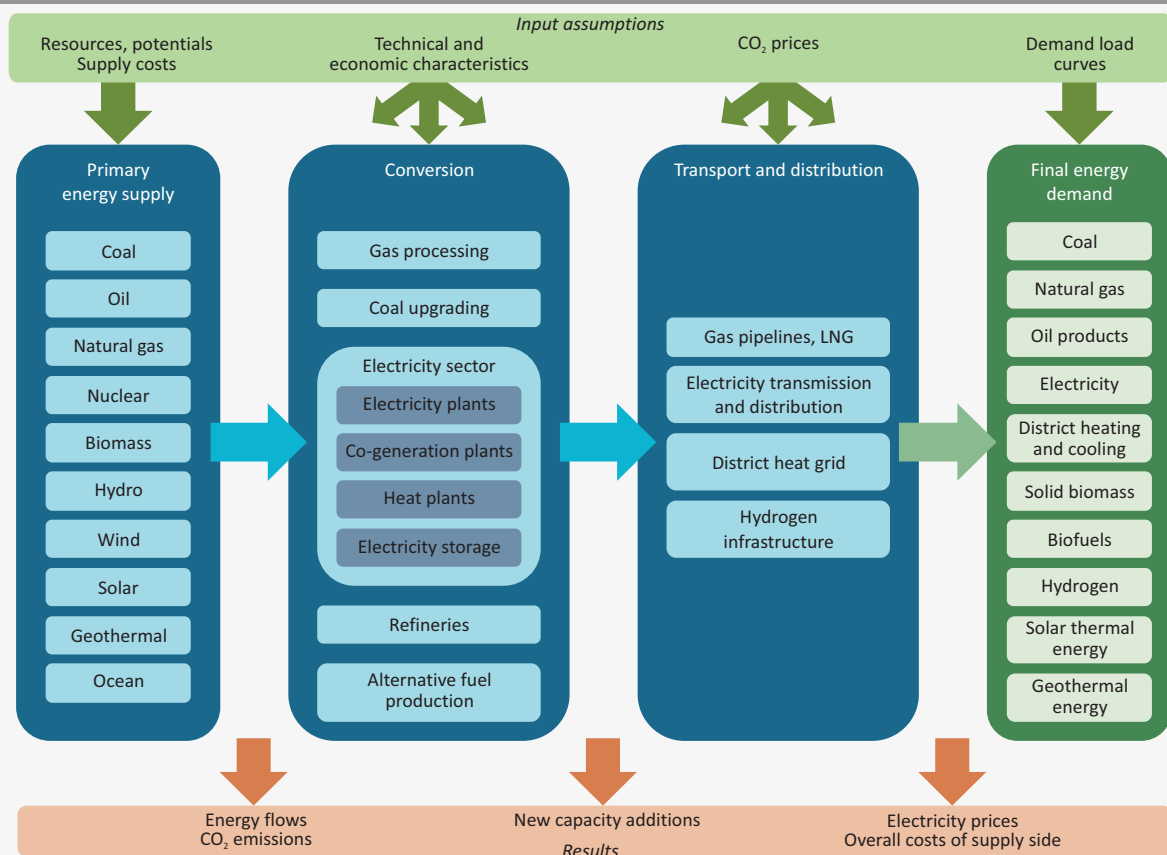
The global ETP-TIMES Supply model is a bottom-up, technology-rich model that depicts a technologically detailed supply side of the energy system. It models from primary energy supply and conversion to final energy demand up to 2060. It is based on the TIMES (The Integrated MARKAL-EFOM System) model generator, which was developed by the Energy Technology Systems Analysis Programme (ETSAP) Technology Collaboration Programme

(TCP)² of the International Energy Agency (IEA) and allows an economic representation of local, national, and multiregional energy systems on a technologically detailed basis (Loulou et al., 2005).

The model covers 28 regions, representing either individual countries, such as the People's Republic of China (hereafter, "China") or India, or aggregates of several countries, such as the Association of Southeast Asian Nations (ASEAN). The model regions are linked by trade in fossil energy carriers (crude oil, petroleum products, coal, pipeline gas, or liquefied natural gas [LNG]), biofuels (biodiesel, bioethanol), and electricity.

Starting from the current situation in the conversion sector (e.g. existing capacity stock, operating costs, and conversion efficiencies), the model integrates the technical and economic characteristics of existing technologies that can be added to the energy system. The model can then determine the least-cost technology mix needed to meet the final energy demand and calculated in the ETP end-use sector models for agriculture, buildings, industry and transport (Figure A.2).

Figure A.2. Structure of the ETP–TIMES model for the conversion sector



Notes: CO₂ = carbon dioxide; *co-generation* refers to the combined production of heat and power.

Key point *ETP–TIMES determines the least-cost strategy using supply-side technologies and fuels to cover the final energy demand from the end-use sector models.*

2. Further information on the TIMES model generator, its applications, and typical energy technology input data assumptions can be found on the ETSAP website at www.iea-etsap.org.

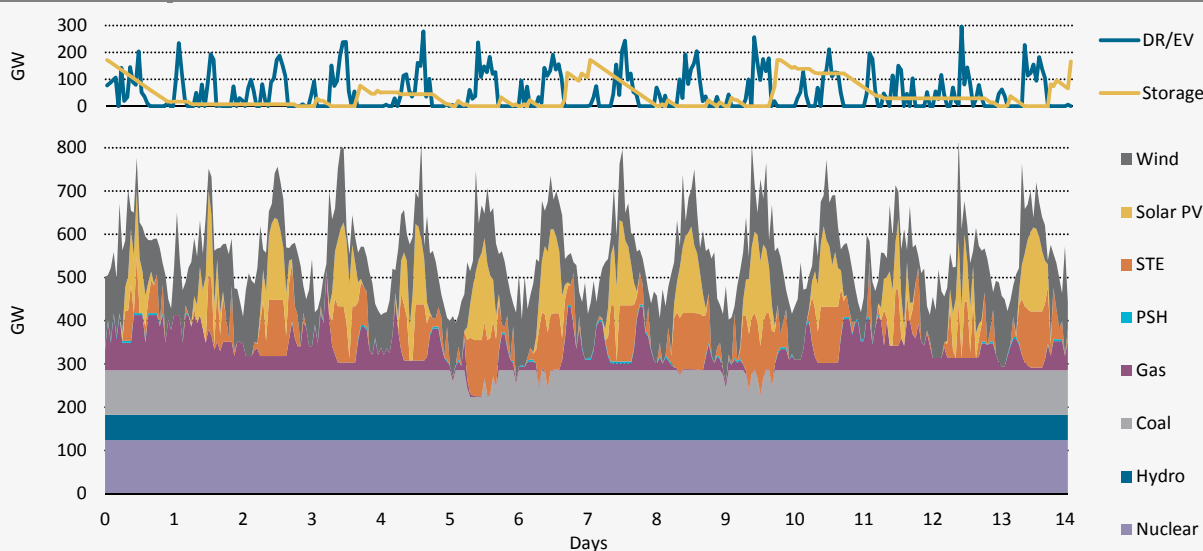
Technologies are described by their technical and economic parameters such as conversion efficiencies or specific investment costs. Learning curves are used for new technologies to link future cost developments with cumulative capacity deployment. Overall, around 550 technologies are considered in the conversion sector. Electricity demand is divided into non-urban and urban, with the latter further divided into five city classes by population size to reflect local differences in the technical potential for rooftop solar photovoltaics (PV) and municipal solid waste (IEA, 2016a; IEA, 2016b). Renewable energy sources — onshore and offshore wind, solar PV and solar thermal electricity (STE) — are differentiated according to their potential, based on their capacity factor (in addition for offshore wind by water depth and distance to the coast) and by their distance to the city classes (five distance categories) as an approximation for the transmission costs needed to use these resources. The ETP-TIMES model also takes into account additional constraints in the energy system (such as emissions reduction goals), and its results provide detailed information on future energy flows and their related emissions impacts, required technology additions, and the overall cost of the supply-side sector.

To capture the impact on investment decisions of variations in electricity and heat demand, as well as the variation in generation from certain renewable technologies, a year is divided into four seasons, with each season being represented by a typical day, which again is divided into 12 daily load segments of two hours' duration.

For a more detailed analysis of the operational aspects of the electricity sector, the long-term ETP-TIMES Supply model has been supplemented with a linear dispatch model. This model uses the outputs of the ETP-TIMES Supply model to generate the electricity capacity mix for a specific model region and year. This allows for detailed analysis of an entire year with one-hour time resolution using datasets for wind production, solar PV production, and hourly electricity demand.

Figure

A.3. Dispatch in the United States over a two-week period in 2050 in the 2DS



Notes: GW = gigawatt; DR/EV = demand response/electric vehicles; PSH = pumped storage hydro.

Key point

The linear dispatch model analyses the role of electricity storage, flexible generation and demand response.

Given the hourly demand curve and a set of technology-specific operational constraints, the model determines the optimal hourly generation profile, as illustrated in Figure A.3 for the 2DS in 2050 over a two-week period. To increase the flexibility of the electricity system, the

linear dispatch model can invest in electricity storage or additional flexible generation technologies (such as gas turbines). Demand response from electricity use in the transport and buildings sectors is a further flexibility option included in the dispatch model analysis.

This linear dispatch model represents storage in terms of three steps: charge, store, and discharge. The major operational constraints included in the model are capacity states, minimum generation levels and time, ramp-up and -down, minimum downtime hours, annualised plant availability, cost considerations associated with start-up and partial-load efficiency penalties, and maximum storage reservoir capacity in energy terms (megawatt hours [MWh]).

Model limitations include challenges associated with a lack of comprehensive data on storage volume (MWh) for some countries and regions. Electricity networks are not explicitly modelled, which precludes the study of the impacts of spatially dependent factors, such as the aggregation of variable renewable outputs with better interconnection.

Industry sector model

For the purposes of the industry model, the industrial sector includes International Standard Industrial Classification (ISIC) Divisions 7, 8, 10–18, 20–32 and 41–43, and Group 099, covering mining and quarrying (excluding mining and extraction of fuels), construction, and manufacturing. Petrochemical feedstock use and blast furnace and coke oven energy use are also included within the boundaries of industry.

Industry is modelled using TIMES-based linear optimisation models for five energy-intensive sectors (iron and steel, chemicals and petrochemicals, cement, pulp and paper, and aluminium). These five sub-models characterise the energy performance of process technologies from each of the energy-intensive subsectors, covering 39 countries and regions. Typically, raw material production is not included within the boundaries of the TIMES models, with the exception of the iron and steel sector, in which energy use for coke ovens and blast furnaces is covered. Due to the complexity of the chemicals and petrochemicals sector, the technology detail of the sub-model focuses on five products that represent about 46% of sector's energy use:³ ethylene, propylene, BTX (benzene, toluene, and xylene), ammonia and methanol. The remaining industrial final energy consumption is accounted for in a simulation model that estimates energy consumption based on activity level.

Demand for materials for the duration of the model time horizon is an exogenous input to the model, estimated on the basis of country- or regional-level data for gross domestic product (GDP), disposable income, short-term industrial capacity, current materials consumption, regional demand saturation levels derived from historical demand intensity curves, and resource endowments (Figure A.4). Total production is simulated by factors such as process, age structure (vintage) of plants, and stock turnover rates. The 2DS considers improvements in recycling in several sectors, leading to reduced primary chemicals demand for plastics, and a shift toward secondary production of metals and pulp. The B2DS considers additional material efficiency strategies that affect overall production levels for certain materials. For example, improvements in production yields reduce overall demand for crude steel in the B2DS compared with the other scenarios.⁴ Table 4.1 describes the material efficiency strategies considered in each scenario, and Figure 4.5 gives a high-level view of global material production levels.

Each industry sub-model is designed to account for sector-specific production routes for which relevant process technologies are modelled. Industrial energy use and technology portfolios for each country or region are characterised in the base year using relevant energy use and material production statistics for each energy-intensive industrial subsector. Changes in the technology and fuel mix, as well as efficiency improvements, are driven by exogenous assumptions on the penetration and energy performance of best available

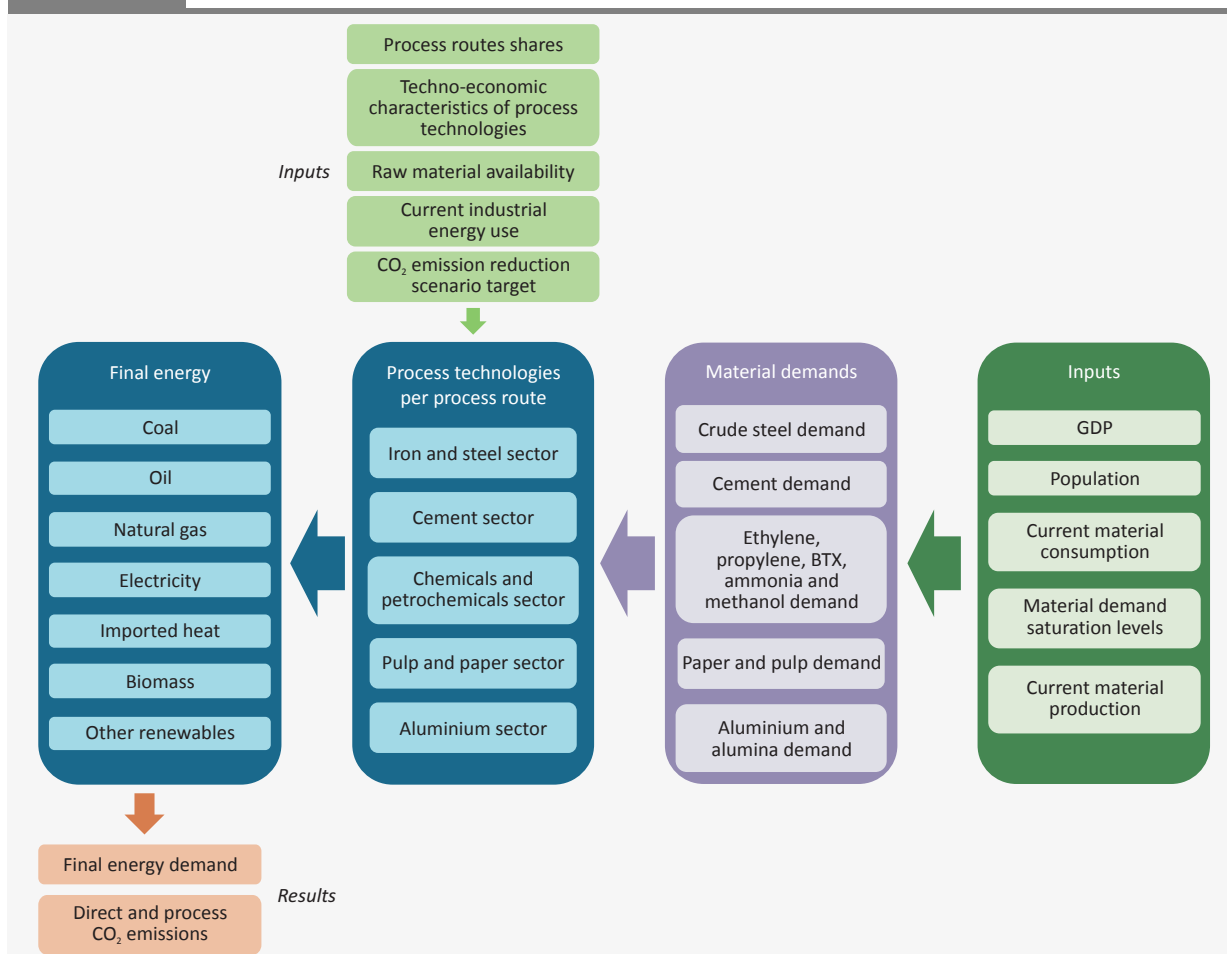
3. Including energy use as petrochemical feedstock.

4. Descriptions of *ETP 2017 2°C Scenario (2DS)*, *Beyond 2°C Scenario (B2DS)* and *Reference Technology Scenario (RTS)* are available in the "Global Outlook" chapter.

technologies (BATs), constraints on the availability of raw materials, techno-economic characteristics of the available technologies and process routes, and assumed progress on demonstrating innovative technologies at commercial scale. Thus the results are sensitive to assumptions on how quickly physical capital is turned over, on relative costs of the various technology options and fuels, and on incentives for the use of BATs for new capacity. Fuel costs are based on outputs from the ETP conversion sector model.

The industry model allows analysis of different technology and fuel-switching pathways in the sector to meet projected material demands within a given related CO₂ emissions envelope in the modelling horizon and in least-cost fashion.

Figure A.4. Structure of ETP industry model



Key point

Based on socio-economic assumptions, historical trends, expert views and statistical information, exogenous material demand projections are used to determine the final energy consumption and direct CO₂ emissions of the sector, depending on the energy performance of process technologies and technology choice within each of the available production routes.

Global buildings sector model

The buildings sector is modelled using a global simulation stock accounting framework, split into the residential and non-residential subsectors across 35 countries and regions (Figure A.5). The residential subsector includes all energy-using activities in apartments and houses, including space and water heating, cooling, ventilation, lighting, and the use of appliances and other electrical plug loads. The non-residential subsector includes activities related to trade, finance, real estate, public administration, health, food and lodging,

education, and other commercial services. This is also commonly referred to as the commercial and public services sector. It covers energy used for space and water heating, cooling, ventilation, lighting, and a range of other miscellaneous energy-consuming equipment such as commercial appliances, office equipment, cooking devices, and medical equipment.

For both subsectors, the model uses socio-economic drivers, such as population, GDP, income (approximated by gross national income [GNI] per capita), urbanisation, and electrification rates, to project the major building energy demand drivers, including residential and non-residential floor area, number of households, and residential appliance ownership. As far as possible, country statistics are used for historical energy balances by end use, floor area, appliance ownership rates, and other building-related technical data and efficiency rates (e.g. technology stock and sales data). These data can be difficult to obtain across many developing countries, so in several cases the historical driver parameters for the ETP buildings sector model have been estimated using a series of applied logistic functions relative to GDP, GNI per capita, urbanisation, and electrification, or another combination of proxies as defined by multilinear regressions. Those functions are applied to individual countries, or, in cases where few data are available, to country clusters designed to be as homogeneous as possible within the cluster and as heterogeneous as possible between cluster categories. The functions differentiate the applied energy indicators by year to 2060 and across the 35 model countries and regions. The indicators are then applied within a stock accounting framework, which is distinguished by annual vintages, and the technology (or building stock) lifetimes are spread using a Weibull distribution.

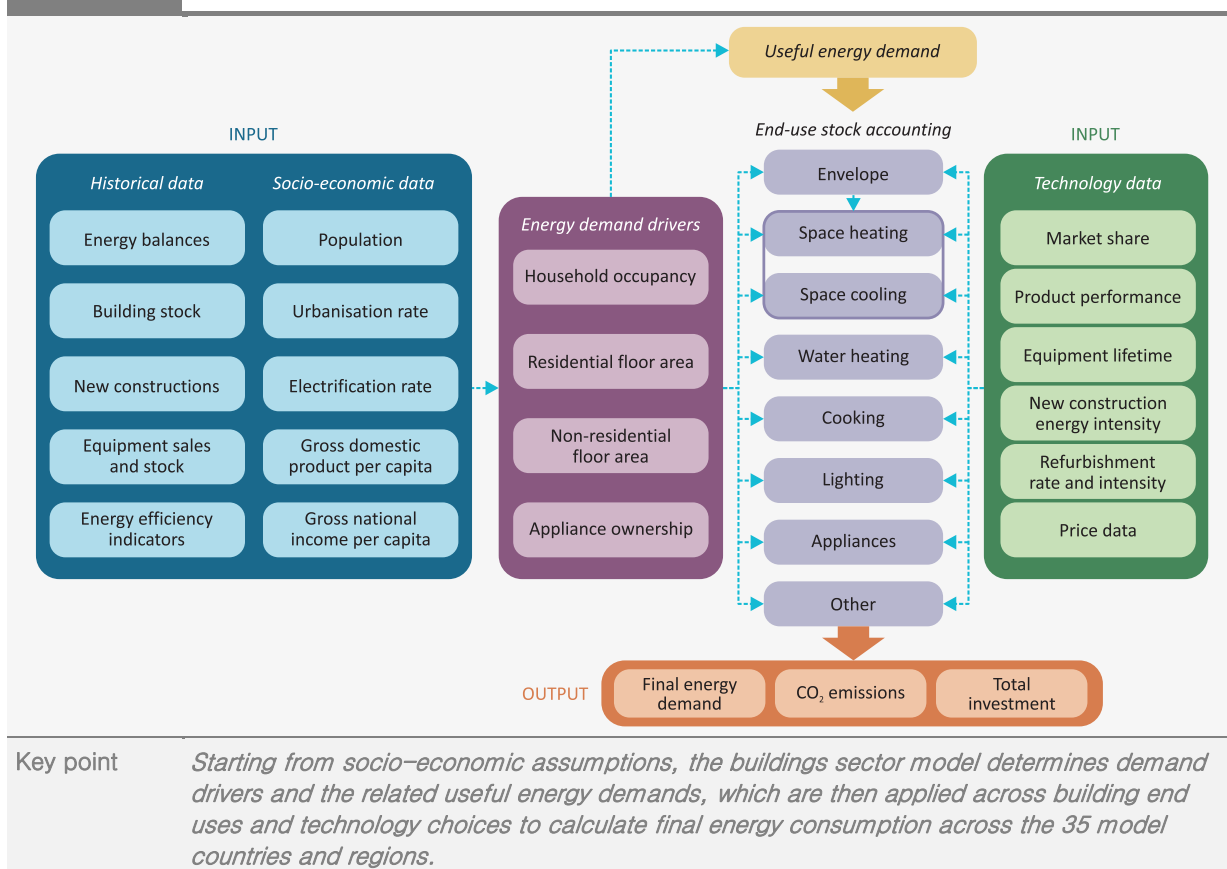
Whenever possible, historical data and buildings sector information, such as building energy codes or minimum energy performance standards for end-use equipment, are applied within the model. Depending on the end use or technology, multiple categories are included (or estimated) within the model. For example, the global building stock is broken down into three categories, including near-zero energy buildings (nZEBs), code-compliant buildings, and buildings that do not meet code or do not have an applicable building energy code. Building end-use technologies (e.g. major household appliances) are similarly broken down into categories where applicable, such as best-in-class, median market performance and minimum energy performance technologies.

Using the annually differentiated stock accounting framework by country or region, historical useful energy intensity is estimated across the various building end uses based on assumed technology shares and efficiencies. Building stock characteristics (e.g. nZEB and code-compliant building energy intensity) are applied with heating and cooling equipment to estimate historical and then projected annual demand for space heating and cooling per unit of floor area (i.e. useful energy service delivered). The model also takes into account the ageing, refurbishment or reconstruction of buildings through degradation, improvement, renovation rates, or specific lifetime distributions. For the other end uses (e.g. water heating, lighting, appliances, and cooking), the useful energy demand is similarly estimated through a differentiated stock accounting framework to determine the useful (or delivered) energy service by end use. Across all end uses and countries/regions, useful energy demand can vary over time (e.g. relative to average GNI per capita growth), where some convergence (in useful energy service) is assumed across similar countries/regions, depending on the building energy technology and policy scenario.

For each of the derived useful energy demands, a suite of technology and fuel options are represented in the model reflecting current techno-economic characteristics (e.g. efficiencies, costs, and lifetimes) as well as their assumed evolution to 2060 in the applied ETP scenario. Depending on the current technology stock, as well as assumptions on the penetration and market share of new technologies in the future, the ETP buildings sector model allows exploration of strategies that meet the different useful energy demands and the quantification of the resulting developments by final energy consumption and related CO₂ emissions. Detailed annual results from the model are also applied within a logarithmic mean Divisia index (LMDI) analysis, allowing in-depth tracking of changes in activity, technology, and energy performance over time with respect to the various scenarios.

Figure

A.5. Structure of the buildings sector model



Modelling of the transport sector in the Mobility Model

Overview

The Mobility Model (MoMo) is a technical-economic database spreadsheet and simulation model that enables detailed projections of transport activity, vehicle activity, energy demand, and well-to-wheel greenhouse gas (GHG) and pollutant emissions according to user-defined policy scenarios to 2060.

MoMo comprises:

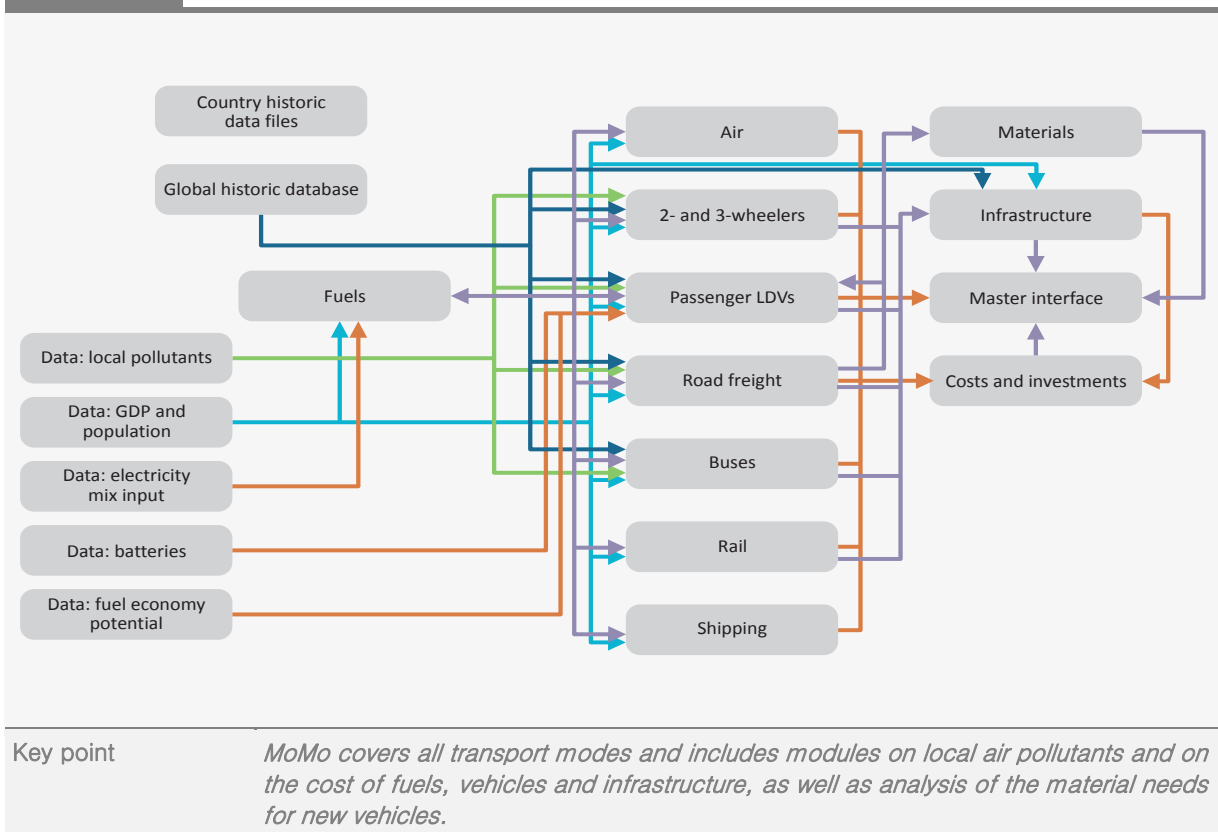
- 27 countries and regions, which are aggregated into four Organisation for Economic Co-operation and Development (OECD) regional clusters and 11 groups of non-OECD economies.
- Historical data from 1975 to 2014 (or 1990 to 2014 for certain countries).
- A simulation model in five-year time steps, for creating scenarios to 2060 based on “what if” analysis and backcasting.
- Disaggregated urban versus non-urban vehicle stock, activity, energy use and emissions (for methodological details, see *ETP 2016* Annex F at www.iea.org/etp/etp2016/annexes).
- All major motorised transport modes (road, rail, shipping and air), providing passenger and freight services.
- A wide range of powertrain technologies: internal combustion engines, including gasoline, diesel, and compressed natural gas (CNG) and LNG; as well as hybrid electric and electric vehicles (including plug-in hybrid electric and battery-electric vehicles) and fuel-cell electric vehicles.

Associated fuel supply options: gasoline and diesel, biofuels (ethanol and biodiesel via various production pathways) and synthetic alternatives to liquid fuels (coal-to-liquid and gas-to-liquid); gaseous fuels, including natural gas (CNG and liquefied petroleum gas) and hydrogen via various production pathways; and electricity (with emissions according to the average national generation mix as modelled by the ETP-TIMES model in the relevant scenario).

MoMo further enables estimation of scenario-based costs of vehicles, fuels, and transport infrastructure as well as the primary material inputs required for the construction of vehicles, related energy needs, and the resultant GHG emissions.

To ease the manipulation and implementation of the modelling process, MoMo is split into modules that can be updated and elaborated upon independently. Figure A.6 shows how the modules interact with one another. By integrating assumptions on technology availability and cost in the future, the model reveals, for example, how costs could drop if technologies were deployed at a commercial scale and allows fairly detailed bottom-up “what-if” modelling, especially for passenger light-duty vehicles (PLDVs) and trucks (Fulton, Cazzola and Cuenot, 2009).

Figure A.6. Structure of MoMo



Data sources

The MoMo modelling framework relies upon compiling and combining detailed data from various sources on vehicles in each of the countries/regions to estimate aggregate energy consumption, emissions, and other energy-relevant metrics at the country/regional level.

Historical data series have been collected by MoMo modellers from a wide variety of public and proprietary data sources for more than a decade. National data are gathered primarily from the following organisations: 1) national and international public institutions (e.g. the World Bank, the Asian Development Bank and Eurostat); 2) national government ministries

(e.g. departments of energy and transport, and statistical bureaus); 3) federations, associations and non-governmental organisations (e.g. Japan Automobile Manufacturers Association, Korea Automobile Manufacturers Association and National Association of Automobile Manufacturers of South Africa); 4) public research institutions (e.g. peer-reviewed papers and reports from universities and national laboratories); 5) private research institutions (e.g. International Council on Clean Transportation); and 6) private business and consultancies (e.g. IHS Automotive/Polk, Segment Y, and other major automotive market research and analysis organisations, in addition to major energy companies and automobile manufacturers themselves). Full details on data sources on a national or regional basis are documented in the regional data files of MoMo.

Calibration of historical data with energy balances

The framework for estimating average and aggregate energy consumption for a given vehicle class i can be neatly summarised by the ASIF identity (Schipper, Marie-Lilliu and Gorham, 2000):

$$F = \sum_i F_i = A \sum_i \left(\frac{A_i}{A}\right) \left(\frac{F_i}{A_i}\right) = A \sum_i S_i I_i = F$$

where: F = total fuel use (megajoules [MJ] per year); A = vehicle activity (vehicle kilometres [vkm] per year); I = energy intensity (MJ/vkm); S = structure (shares of vehicle activity [%]); and I is an index of vehicle modes and classes (MoMo models vehicles belonging to several modes). Vehicle activity can also be expressed as the product of vehicle stock (vehicles) and mileage (kilometre [km] per year). The energy used by each mode and vehicle class in a given year (MJ per year) can, therefore, be calculated as the product of three main variables: vehicle stock (S) (vehicles), mileage (M) (km/year) and fuel economy (FE) (MJ/vkm).

To ensure a consistent modelling approach is adopted across the modes, energy use is estimated based on stocks (via scrappage functions), utilisation (travel per vehicle), consumption (energy use per vehicle, i.e. fuel economy) and emissions (via fuel emission factors for CO₂ and pollutants on a vehicle and well-to-wheel basis) for all modes. Final energy consumption, as estimated by the “bottom-up” approach described above, is then validated against and calibrated as necessary to the IEA energy balances (IEA, 2016c).

Vehicle platform, components and technology costs

Detailed cost modelling for PLDVs accounts for initial (base year) costs, asymptotic (i.e. fully learned-out) costs and an experience parameter that defines the shape of cost reductions. These three parameters define learning functions that are based on the number of cumulative units produced worldwide. Cost functions define various vehicle configurations, including vehicle component efficiency upgrades (e.g. improved tyres or air-conditioning controls), material substitution and vehicle downsizing, conventional spark and compression ignition engine improvements, conventional and plug-in hybrid powertrain configurations, batteries, electric motors, and fuel cells. These configurations are added to a basic glider cost. The ratios of differences in vehicle technologies deployed in PLDVs are extrapolated to other road vehicle types (i.e. 2- and 3-wheelers and freight trucks).

The primary drivers of technological change in transport are assumptions on the cost evolution of the technology, and the policy framework incentivising adoption of the technology. Oil prices and the set of policies assumed can significantly alter technology penetration patterns. For each scenario, the model supports a comparison of marginal costs of technologies and aggregates to total cost across all modes and regions.

Infrastructure and fuel costs

MoMo estimates future (2017–60) infrastructure costs according to scenario-based projections on modal activity and fuel use. Infrastructure cost estimates include capital costs, operations and maintenance, and reconstruction costs — split by geography into urban and non-urban regions according to the location of the investments. Fuel costs are also estimated based on scenario-specific projections of urban and non-urban consumption, and include all fuel types (fossil-derived fuels, biofuels, electricity and hydrogen).

Elasticities

Key elasticities have been included in MoMo from 2012. Price and income elasticities of fuel demand, for light-duty (passenger) road activity as well as road freight, based upon representative “consensus” literature values, are used to model vehicle activity and fuel consumption responses to changes in fuel prices — which are themselves driven by projections and policy scenarios (i.e. GHG or fuel taxes). Elasticities also enable vehicle ownership to vary according to fuel prices and income, as proxied by GDP per capita. *ETP 2016* included updates for an expanded treatment of the above elasticities to encompass the urban/non-urban split, and to include the potential for municipal-level policies to reduce transport energy use.⁵

Changes from *ETP 2016*

ETP 2017 scenarios have been updated since 2016, particularly on key assumptions underlying the analysis such as energy prices, technology development, and projections for socio-economic drivers of population and GDP. Further details on key changes to the end-use sector models are described below.

Buildings

The *ETP 2017* building scenario results are taken from the ETP buildings sector model, which has been revised since 2016 to include a full stock-sales accounting framework for building envelopes and building end-use equipment across the major building end uses. The ETP building team is also working closely with partners to gather and update end-use data on product deployment across global markets, as well as building energy policy information through its Buildings Energy Efficiency Policy (BEEP) database. Those data and information, along with the most recent base year energy balances and statistics, are included in the *ETP 2017* buildings sector model results. Additional changes that have affected the outcome of the analysis include:

- Collaboration with the Tsinghua University Building Energy Research Centre, IEA Energy Data Centre, and National Bureau of Statistics in China to improve assessments on traditional use of biomass in China, which are reflected in the *ETP 2017* analysis and are anticipated to be revised in the 2017 IEA *World Energy Statistics and Balances*.
- Updates to overall sectoral activity projections, including floor area, household size (i.e. occupancy rates) and appliance ownership, with respect to changes in demographic and global economic outlooks.
- Revisions in global cooling estimates, in conjunction with the IEA Energy Efficiency in Emerging Economies (E4) programme, to reflect improved assessment of cooling energy demand in IEA key partner countries, including in particular Mexico, Indonesia, India, and Brazil.
- Changes to global lighting scenarios to reflect updates in market sales of residential lighting technologies (e.g. halogens and light-emitting diodes [LEDs]) in recent years.
- Revisions to heat pump estimates to reflect updates in market sales data for recent years in Europe, Japan and China.

Industry

The *ETP 2017* industry scenario results are based on the ETP industry model, which has been reviewed and revised since the previous results in 2016. During each modelling cycle, the base year (2014 for this publication) is updated to reflect the most recent IEA energy balance data. Additional revisions include:

- Extension of the modelling horizon to 2060.

5. Further details on the added national and municipal policies, the elasticities that are used to model transport activity, stock and mode share responses to these policies, and the demand generation module can be found in Annex F of *ETP 2016* at www.iea.org/etp/etp2016/annexes.

- Conversion of the chemicals and petrochemicals and pulp and paper sector models to a TIMES-based linear cost optimisation framework, including additional detail on process technologies and technological synergies.
- Updates to overall sectoral activity projections for industry, with more detailed revisions in energy-intensive sectors; significant revisions include:
 - Material efficiency analysis for the iron and steel and aluminium sectors, including additional levers such as manufacturing yield improvement and increased recycling and scrap reuse, affecting overall primary metals demand in the B2DS, as well as additional detail on plastics recycling influencing primary chemicals demand.
 - Lower production of ethylene and propylene and slower growth in aromatics production in the long term, primarily in OECD countries and Latin America.
 - A shift in methanol production away from Europe towards North America, and more detailed representation of the methanol-to-olefins process route in China.
 - Additional product detail for pulp, paper, and paperboard and moderated demand in the long term, especially in developing Asia and Africa.
 - Later peaking of cement production in China.
 - Decreased crude steel production in the Middle East in the long term in favour of production in ASEAN.
- Revision of the potential for innovative low-carbon processes and BAT-level intensity in energy-intensive sectors.
- Reallocation of carbon capture and storage (CCS) on auto-producer co-generation at industrial sites to the industry sector (previously included in power sector results).
- Estimation of CO₂ captured and utilised from ammonia production for urea and methanol production.
- Improved investment cost estimation related to chemicals and petrochemicals, pulp and paper, and cement sector equipment.
- Development of regional sets of crude oil product prices by scenario, based on historical regression of crude oil product prices to crude oil and natural gas prices.

Transport

Besides the extension of the modelling time frame to allow the estimation of results to 2060, key developments in the IEA MoMo occurred primarily in relation to road freight transport and international shipping.

The historical data for medium and heavy freight trucks (MFTs and HFTs) have been re-evaluated and a new baseline set. The main updates were to country- and regional-level fuel economy, mileage and age profile. These were calibrated to approximate road consumption of diesel and gasoline as provided in the IEA energy balance on the one hand, and national and regional statistics (e.g. total activity in vehicle kilometres and tonne kilometres, average mileage and load factor) on the other.

The revision of historical data for MFTs and HFTs also led to the revision of estimates of mileage and age profile for light commercial vehicles (LCVs) and passenger vehicles, including in particular buses and PLDVs. The rationale for these revisions was the need for consistency of the data, primarily based on vehicle registrations, fuel economy estimates and energy use data from the IEA balances.

The costs of alternative powertrains for MFTs and HFTs have been updated based on an assessment of technology and fuel production, transmission and distribution, and fuelling station costs at a regional level. These have been used to update MFT and HFT costs as assessed in the scenarios. LCV powertrain costs were also revised to match PLDVs.

New projections of road freight transport activity have been developed, based on regression analysis of historical panel data. The explanatory variables are GDP per capita, country size

and long-term fuel tax regimes, used to project vehicle kilometres and tonne kilometres for MFTs and HFTs in the period 2015–60.

An assessment of the potential for systemic and logistical measures to improve the efficiency of LCVs, MFTs and HFTs, in urban and non-urban operations, has also been incorporated into the MoMo. The impacts of discrete policies are combined (non-additively) to estimate their impacts: reductions in vehicle kilometres, increases in vehicle utilisation (load factors) and reductions in operational vehicle energy intensity.

The assessment of international shipping energy use and emissions has been upgraded, shifting from a top-down approach to a bottom-up methodology. Energy use is now calculated as a result of the evolution of trade flows, the type and value of goods traded, ship categories, ship sizes/load capacities, capacity utilisation rates, travel distances, and the energy efficiency of the ships operating on international routes.

This update was developed building on monetary trade flows identified by the OECD Economic Directorate, the allocation of these into physical trade flows by mode as developed by the International Transport Forum and the IEA, information on ship specifications by category available from the International Maritime Organization, and statistics on the global stock of vessels by category from the United Nations Conference on Trade and Development. Assumptions on the most uncertain parameters (load capacities and energy intensity by ship type) were calibrated against the benchmark provided by the IEA statistics on fuel use in international marine bunkers.

A stock model was also developed in order to estimate the number of new ships leaving and entering the global fleet every year. This allowed for the development of scenarios using different sets of assumptions on technology deployment.

Framework assumptions

Economic activity (Table A.1) and population (Table A.2) are the two fundamental drivers of demand for energy services in ETP scenarios. These are kept constant across all scenarios as a means of providing a starting point for the analysis and facilitating the interpretation of the results. Under the ETP assumptions, global GDP will more than triple between 2017 and 2060; uncertainty around GDP growth across the scenarios is significant, however. The climate change rate in the Reference Technology Scenario (RTS) is likely to have profound and unpredictable impacts on the potential for economic growth. These impacts are not captured by ETP analysis. Moreover, the structure of the economy is likely to have non-marginal differences across scenarios, suggesting that GDP growth is unlikely to be identical even without considering secondary climate impacts. The redistribution of financial, human and physical capital will affect the growth potential both globally and on a regional scale.

Energy prices, including those of fossil fuels, are a central variable in the ETP analysis (Table A.3). The continuous increase in global energy demand is translated into higher prices for energy and fuels. Unless current demand trends are broken, rising prices are a likely consequence. However, the technologies and policies to reduce CO₂ emissions in the *ETP 2017* scenarios will have a considerable impact on energy demand, particularly for fossil fuels. Declining demand for oil in the 2DS and the B2DS reduces the need to produce oil from costly fields higher up the supply curve, particularly in non-members of the Organization of the Petroleum Exporting Countries (OPEC). As a result, oil prices in the 2DS and B2DS are lower than in the RTS. In the 2DS and B2DS, oil prices even decline. Prices for natural gas will also be affected, directly through downward pressure on demand, and indirectly through the link to oil prices that often exists in long-term gas supply contracts.⁶ Finally, coal prices are also substantially lower owing to the large shift away from coal in the 2DS and B2DS.

6. This link is assumed to become weaker over time in the ETP analysis, as the price indexation business model is gradually phased out in international markets.

Table A.1. Real GDP growth projections in *ETP 2017* (assumed identical across scenarios)

CAAGR (%)	2014–20	2020–30	2030–40	2040–60	2014–60
World	4.2	4.2	3.5	2.2	2.9
OECD	2.4	2.1	1.9	1.6	1.8
Non-OECD	5.5	5.5	4.2	2.4	3.5
ASEAN	5.8	5.1	3.9	2.4	3.4
Brazil	-0.6	3.3	3.5	2.0	2.1
China	7.5	5.7	3.5	1.6	3.3
European Union	2.3	1.8	1.6	1.4	1.5
India	9.1	7.8	6.0	3.0	5.0
Mexico	3.3	3.9	3.2	1.9	2.6
Russia Federation	0.0	2.9	2.8	1.7	1.9
South Africa	2.0	3.1	3.3	2.2	2.4
United States	2.8	2.2	2.2	1.9	2.0

Notes: CAAGR = compounded average annual growth rate. Growth rates based on GDP in United States dollars (USD) in purchasing power parity (PPP) constant 2015 terms.

Sources: IEA (2016d), *World Energy Outlook*; IMF (2016), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2016/01/weodata/index.aspx.

Table A.2. Population projections used in *ETP 2017* (millions)

Country/region	2014	2020	2030	2040	2050	2060
World	7 255	7 747	8 490	9 146	9 714	10 173
OECD	1 258	1 297	1 348	1 381	1 400	1 407
Non-OECD	5 997	6 450	7 143	7 765	8 314	8 766
ASEAN	623	664	721	763	788	799
Brazil	206	216	229	236	238	236
China	1 372	1 405	1 418	1 398	1 351	1 280
European Union	510	513	514	511	505	495
India	1 295	1 389	1 528	1 634	1 705	1 745
Mexico	120	129	142	151	156	159
Russian Federation	144	143	139	133	129	125
South Africa	54	57	60	63	66	67
United States	319	333	355	373	388	403

Source: UNDESA (2015), *World Population Prospects: The 2015 Revision*, <https://esa.un.org/unpd/wpp/>.

Table A.3. Fossil fuel prices by scenario

Oil (2015 USD/bbl)	Scenario	2015	2020	2030	2040	2050	2060
IEA crude oil import price	RTS	51	79	111	124	137	148
	2DS	51	73	85	78	72	67
	B2DS	51	73	66	64	62	60
Coal (2015 USD/t)	Scenario	2015	2020	2030	2040	2050	2060
OECD steam coal import price	RTS	64	72	83	87	90	92
	2DS	64	66	64	57	55	53
	B2DS	64	66	63	54	52	51
Gas (2015 USD/MBtu)	Scenario	2015	2020	2030	2040	2050	2060
United States price	RTS	2.6	4.1	5.4	6.9	8.9	10.7
	2DS	2.6	3.9	4.8	5.4	5.9	6.3
	B2DS	2.6	3.8	4.2	4.1	4.0	3.8
Europe import price	RTS	7.0	7.1	10.3	11.5	12.2	12.6
	2DS	7.0	6.9	9.4	9.9	10.2	10.5
	B2DS	7.0	6.7	8.2	7.7	7.2	6.9
Japan import price	RTS	9.7	9.6	11.9	12.4	12.8	13.2
	2DS	9.7	9.0	10.8	10.9	11.0	11.1
	B2DS	9.7	8.9	9.9	9.2	8.6	8.2

Notes: bbl = barrel; t = tonne; MBtu = million British thermal units.

Technology approach

In *ETP 2017*, the definition of technologies “available and in the innovation pipeline” includes those technologies that are commercially available, or at the stage of development that makes commercial-scale deployment possible within the 2015–60 scenario period.

This includes:

- Existing commercial BATs, for example, solar thermal and heat pumping technologies for space and water heating, LEDs for lighting, high-performance windows (e.g. low-emissivity, double- or triple-glaze), high-performance insulation, green or cool roofs, thermal energy storage, enhanced catalytic and biomass-based processes for chemical production, onshore wind, offshore wind, solar PV, STE, hydropower, geothermal (direct, flash), nuclear power, large-scale electric heat pumps, and conventional biodiesel and bioethanol.
- Technologies in demonstration phase (technologies that have been proven, and have sufficient techno-economic data available to be assumed to be commercially available within the time horizon of the model), for example, high-performance heat pumping technologies, high-efficacy (e.g. greater than 150 lumens/Watt) LED lighting, aerosol-based whole building envelope air sealing, advanced building insulation (aerogel, vacuum insulated panel, phase change materials), whole-building renovation solutions, zero-emission fuels for transport, upgraded smelt reduction and direct reduced iron, coal-fired integrated gasification combined cycle (IGCC), coal-fired IGCC with CO₂ capture, coal-fired power plant with post-combustion CO₂ capture, conventional bioethanol with CO₂ capture, advanced biodiesel, large-scale hydrogen electrolysis, and hydrogen from natural gas with CO₂ capture.
- Technologies in pilot testing, for example, “smart” building technologies and intelligent controls, dynamic solar control, hybrid heat pumps, fuel cells and hydrogen-ready equipment, inert anodes for aluminium smelting, oxy-fuelled coal power plants with CO₂ capture, gas-fired power plants with CO₂ capture, biomass integrated gasification

combined cycle (BIGCC), wave energy, tidal stream, tidal lagoon, enhanced geothermal energy systems, advanced biodiesel with CO₂ capture, hydrogen from biomass gasification, and biofuels from algae.

- Technologies under development, for example, solar cooling solutions, vacuum insulated panels for refrigeration and building envelopes, thermoelectric cooling using heat pumps, full oxy-fuelling kilns for clinker production, BIGCC with CO₂ capture, and hydrogen from coal and biomass with CO₂ capture.
- Technologies with incremental improvements of performances compared with today's BATs (may not be available yet but can be envisaged to be available within the time frame of scenarios), for example, high-performance appliances in buildings, improved controls of cooling and heating (smart thermostats), advanced district energy networks, low rolling resistance tyres, vehicle design improvements that reduce energy needs, and energy intensity improvements towards BAT in industrial process technologies.
- Supporting infrastructure to facilitate the uptake of improved and newly demonstrated technologies, for example, low-temperature distribution, high-performance district energy networks, smart grids with intelligent demand-side response, transport and storage infrastructure to support CCS, and EV charging infrastructure.

Some technology options are not available within the model until later time periods, depending on their current level of readiness, and some have constraints to account for process-specific limitations to deployment. See the sectoral chapters for more detailed discussion of technologies included in the *ETP 2017* analysis.

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Abbreviations and acronyms

	2DS	2°C Scenario
A	ABS	acrylonitrile butadiene styrene
	AC	alternating current
	ACES	autonomous and connected vehicles, electrification and sharing
	ACO	advanced catalytic olefins
	ACTL	Alberta Carbon Trunk Line
	ADNOC	Abu Dhabi National Oil Company
	AMI	advanced metering infrastructure
	ASEAN	Association of Southeast Asian Nations
	ASU	air separation unit
	ATAG	Air Transport Action Group
	AV	automated vehicle
B	B2DS	Beyond 2°C Scenario
	BAT	best available technology
	BECCS	bioenergy with carbon capture and storage
	BECCU	bioenergy with carbon capture and utilisation
	BEEP	Buildings Energy Efficiency Policy
	BEV	battery electric vehicle
	BF	blast furnace
	BFG	blast furnace gas
	BF-TGR	blast furnace top gas recovery
	BICS	Bloomberg Industry Classification System
	BIGCC	biomass integrated gasification combined cycle
	BOF	basic oxygen furnace
	BOS	balance-of-system
	BTL	biomass-to-liquids
	BTX	benzene, toluene and xylene
C	CAAGR	compounded average annual growth rate
	CAPEX	capital expenditure
	CAT-ERS	catenary-based electric road systems
	CCGT	combined-cycle gas turbine
	CCS	carbon capture and storage
	CCU	carbon capture and utilisation
	CEM	Clean Energy Ministerial
	CEPI	Confederation of European Paper Industries
	CFB	circulating fluidised bed
	CFE	Comisión Federal de Electricidad
	CFL	compact fluorescent lamp
	CHP	combined heat and power
	CNG	compressed natural gas
	CNRC	Canadian National Research Council

CNY	yuan renminbi
CO	carbon monoxide
CO ₂	carbon dioxide
CO ₂ -EOR	carbon dioxide-enhanced oil recovery
CO-BF-BOF	coke oven-blast furnace-basic oxygen furnace
COG	coke oven gas
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	concentrated solar power

D

DC	direct current
DER	distributed energy resources
DG	distributed generation
DRI	direct reduced iron

E

EAF	electric arc furnace
EBC	Energy in Buildings and Communities
ECBM	enhanced coalbed methane recovery
EEDI	Energy Efficiency Design Index
EEG	German Renewable Energy Act
EMS	energy management systems
EOR	enhanced oil recovery
ERS	electric road system
<i>ETP</i>	<i>Energy Technology Perspectives</i>
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EV	electric vehicle
EVI	Electric Vehicles Initiative
E4	Energy Efficiency in Emerging Economies

F

FACTS	flexible alternating current transmission systems
FAO	Food and Agriculture Organization
FCV	fuel cell vehicle
FID	final investment decision
FIDE	Fideicomiso para el Ahorro de Energía Eléctrica
FiT	feed-in tariff
FLH	full load hours
FYP	Five-Year Plan

G

GABC	Global Alliance for Buildings and Construction
GBEP	Global Bioenergy Partnership
GBP	British pounds
GCC	Gulf Cooperation Council
GCCSI	Global Carbon Capture and Storage Institute
GDP	gross domestic product
GFEI	Global Fuel Economy Initiative
GHG	greenhouse gas
GIS	geographic information system
GMS	grid management system

GNI	gross national income
GVW	gross vehicle weight

H

H ₂	hydrogen
HCV	high-capacity vehicle
HDPE	high-density polyethylene
HDV	heavy-duty vehicle
HEMS	home energy management system
HEV	hybrid electric vehicle
HFO	heavy fuel oil
HFT	heavy freight truck
HPT	heat pumping technologies
HSR	high-speed rail
HTR	high-temperature gas-cooled reactor
HVAC	high-voltage alternating current
HVC	high-value chemicals
HVDC	high-voltage direct current
HVO	hydrotreated vegetable oil

I

IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICE	internal combustion engine
ICT	information and communication technology
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IEH	industrial excess heat
IGCC	integrated gasification combined cycle
ILUC	indirect land use change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
ISIC	International Standard Industrial Classification
ISO	International Organization for Standardization
ITF	International Transport Forum
IATA	International Air Transport Association
INDCs	Intended Nationally Determined Contributions
Istat	Italy National Institute for Statistics
ISI	Institut für System- und Innovation- forschung (Institute for Systems and Innovation Research)
IT	information technology

K

KAPSARC	King Abdullah Petroleum Studies and Research Center
KPIs	Key Performance Indicators

L

LCOE	levelised cost of electricity
LBNL	Lawrence Berkeley National Laboratory
LCV	light commercial vehicle
LDPE	low-density polyethylene
LDV	light-duty vehicle

LEAP	Lighting and Energy Access Partnership
LED	light-emitting diode
LFL	linear fluorescent lamp
LMDI	Logarithm Mean Decomposition Index
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LRR	low rolling resistance tyres
LULUCF	land use, land-use change and forestry

M

MACC	marginal abatement cost curve
MEPS	minimum energy performance standard
MFT	medium freight truck
MI	Mission Innovation
MIT	Massachusetts Institute of Technology
MoMo	Mobility Model
MSW	municipal solid waste
MTO	methanol-to-olefins

N

NDC	nationally determined contribution
NMA	nickel-manganese-aluminium
NMC	nickel-manganese-cobalt
NO _x	oxides of nitrogen
NPPs	nuclear power plants
NPS	New Policies Scenario
NREL	National Renewable Energy Laboratory
nZEB	near-zero emissions building

O

OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OGCI	Oil and Gas Climate Initiative
OPEC	Organization of the Petroleum Exporting Countries
ORC	organic rankine cycle

P

PAN	polyacrylonitrile
PC	polycarbonate
PEM	polymer electrolyte membrane
PET	polyethylene terephthalate
PEV	plug-in electric vehicle
PHEV	plug-in hybrid electric vehicle
PLDV	passenger light-duty vehicle
PMMA	polymethyl methacrylate
PNNL	Pacific Northwest National Laboratory
PP	polypropylene
PPP	purchasing power parity
PS	polystyrene
PSH	pumped storage hydro
PtX	power-to-X
PVA	polyvinyl acetate
PV	photovoltaics

PVC	polyvinyl chloride
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R

RAC	room air conditioner
RED	Renewable Energy Directive
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RSB	Roundtable on Sustainable Biomaterials
RTS	Reference Technology Scenario

S

SAN	styrene acrylonitrile
SARTRE	Safe Road Trains for the Environment
SBP	Sustainable Bioenergy Partnership
SEC	specific final energy consumption
SEER	seasonal energy efficiency ratio
SHC	solar heating and cooling
SOFC	solid oxide fuel cell
SOFC-GT	solid oxide fuel cell gas turbine
SR	smelt reduction
SSL	solid-state lighting
STE	solar thermal electricity
S&L	standards and labelling
SBIR	Small Business Innovation Research
SETIS	Strategic Energy Technologies Information System
SIRD	Survey of Industrial R&D
SMR	small modular reactor
SO	sulphur oxide

T

T&D	transmission and distribution
<i>TCEP</i>	<i>Tracking Clean Energy Progress 2017</i>
TCO	total cost of ownership
TCP	Technology Collaboration Programme
TDM	travel demand management
TFEC	total final energy consumption
TfL	Transport for London
TGR	top gas recovery
TIMES	The Integrated MARKAL-EFOM System
TOD	time-of-delivery
TPED	total primary energy demand
TPS	tyre pressure system
TRI	Thermochem Recovery International

U

UCC	urban consolidation centre
UHV	ultra high-voltage
ULCOS	Ultra-Low Carbon Dioxide Steelmaking
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

USD	United States dollar
US DOE	US Department of Energy
UKIIF	United Kingdom Innovation Investment Fund
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
USPTO	US Patent and Trademark Office

V	VAT	value-added tax
	VC	venture capital
	VRE	variable renewable energy
	VSC	voltage source converter

W	WAMS	wide area management system
	WGS	water-gas shift
	<i>WEO</i>	<i>World Energy Outlook</i>
	WLTP	Worldwide Harmonised Light Vehicles Test Procedure
	WTW	well-to-wheel

Y	y-o-y	Year-on-year
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Z	ZEP	European Technology Platform for Zero Emission Fossil Fuel Power Plants (European Zero Emissions Platform)
	ZEV	zero-emission vehicle

Definitions, regional and country groupings and units

Definitions

	2-, 3- and 4-wheelers	This vehicle category includes motorised vehicles having two, three or four wheels. 4-wheelers are not homologated to drive on motorways, such as all-terrain vehicles. Most often, 2- and 3-wheelers are reported as an aggregated class.
A	Advanced biofuels	Advanced biofuels comprise different emerging and novel conversion technologies that are currently in the research and development, pilot or demonstration phase. This definition differs from the one used for “advanced biofuels” in the US legislation, which is based on a minimum 50% life-cycle greenhouse gas (GHG) reduction and which, therefore, includes sugar cane ethanol.
	Aquifer	A porous, water-saturated body of rock or unconsolidated sediments, the permeability of which allows water to be produced (or fluids injected). If the water contains a high concentration of salts, it is a saline aquifer.
B	Biodiesel	Biodiesel is a diesel-equivalent, processed fuel made from the transesterification (a chemical process which, in this case, refers to the removal of glycerine from the oil) of both vegetable oils and animal fats.
	Bioenergy	Bioenergy is material which is directly or indirectly produced by photosynthesis and which is utilised as a feedstock in the manufacture of fuels and substitutes for petrochemical and other energy intensive products.
	Biofuels	Biofuels are fuels derived from biomass or waste feedstocks and include ethanol and biodiesel. They can be classified as conventional and advanced biofuels according to the technologies used to produce them and their respective maturity.
	Biogas	Biogas is a mixture of methane and CO ₂ produced by bacterial degradation of organic matter and used as a fuel.
	Biomass	Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood, plant and animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

C

Biomass and waste	Biomass and waste includes solid biomass, gas and liquids derived from biomass, industrial waste and the renewable part of municipal waste. Includes both traditional and modern biomass.
Biomass-to-liquids	Biomass-to-liquids (BTL) refers to a process that gasifies biomass to produce syngas (a mixture of hydrogen and carbon monoxide), followed by synthesis of liquid products (such as diesel, naphtha or gasoline) from the syngas using Fischer-Tropsch catalytic synthesis or a methanol-to-gasoline reaction path. The process is similar to those used in coal-to-liquids or gas-to-liquids.
Bio-SNG	Bio-synthetic natural gas (Bio-SNG) is biomethane derived from biomass via thermal processes
Black liquor	A by-product from chemical pulping processes, which consists of lignin residue combined with water and the chemicals used for the extraction of the lignin.
Bond market/bonds	Bond is a formal contract to repay borrowed money with interest at fixed intervals.
Benzene, toluene and xylene	Benzene, toluene and xylene (BTX), also referred to as aromatics, are a major group of products from the petrochemicals sector.
Buses and minibuses	Passenger motorised vehicles with more than nine seats.
Capacity credit	Capacity credit refers to the proportion of capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.
Capacity (electricity)	Measured in megawatts (MW), capacity (electricity) is the amount of power produced, transmitted, distributed or used at a given moment.
Carbon capture and storage	A process in which CO ₂ is separated from a mixture of gases (e.g. the flue gases from a power station or a stream of CO ₂ -rich natural gas) and compressed to a liquid state; transported to a suitable storage site; and injected into a geologic formation where it is retained by natural trapping mechanisms and monitored as necessary.
Clinker	Clinker is a core component of cement made by heating ground limestone and clay at a temperature of about 1 400°C to 1 500°C.
CO₂ emissions	CO ₂ emissions in the ETP analysis include, if not noted otherwise, emissions from energy use and process emissions (industry, gas processing). If a fossil fuel is used as a raw material (or feedstock) for manufacture of products such as plastics or in a non-energy use (e.g. bitumen for road construction), only some of the carbon in the fossil fuel is oxidised to CO ₂ .
Coal	Coal includes both primary coal (including hard coal and brown coal) and derived fuels (including patent fuel,

		brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast-furnace gas and oxygen steel furnace gas). Peat is also included.
	Coal-to-liquids	Coal-to-liquids (CTL) refers to the transformation of coal into liquid hydrocarbons. It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined with Fischer-Tropsch or methanol-to-gasoline synthesis to produce liquid fuels, or through the less developed direct-coal liquefaction technologies in which coal is directly reacted with hydrogen.
	Coefficient of performance	Coefficient of performance is the ratio of heat output to work supplied, generally applied to heat pumps as a measure of their efficiency.
	Co-generation	Co-generation refers to the combined production of heat and power.
	Coking coal	Coking coal, also known as metallurgical coal, is used to create coke, an essential ingredient for the production of steel. Coking coal exhibits qualities that allow the coal to soften, liquefy and then re-solidify into hard but porous lumps when heated in the absence of air. Coking coal must also have low sulphur and phosphorous contents.
	Conventional biofuels	Conventional biofuels include well-established technologies that are producing biofuels on a commercial scale today. These biofuels are commonly referred to as first-generation and include sugar cane ethanol, starch-based ethanol, biodiesel, Fatty Acid Methyl Ester (FAME) and Straight Vegetable Oil (SVO). Typical feedstocks used in these mature processes include sugar cane and sugar beet, starch-bearing grains like corn and wheat, oil crops like canola and palm, and in some cases animal fats.
D	Demand response	Demand response is a mechanism by which electricity demand is shifted over given time periods in response to price changes or other incentives, but does not necessarily reduce overall electrical energy consumption. This can be used to reduce peak demand and provide electricity system flexibility.
	Direct equity investment	Direct equity investments refer to the acquisition of equity (or shares) in a company.
	Distribution	Electricity distribution systems transport electricity from the transmission system to end users.
E	Electric arc furnace (EAF)	Electric arc furnaces are used as a less energy-intensive alternative to the traditional blast furnace-basic oxygen furnace steelmaking process route, when the necessary material inputs are available. Steel is formed by creating an electric arc to melt scrap metal or direct reduced iron.
	Electrical energy	Measured in megawatt-hours (MWh) or kilowatt-hours (kWh), indicates the net amount of electricity generated, transmitted, distributed or used over a given time period.

Electricity generation	Electricity generation is defined as the total amount of electricity generated by power only or co-generation (combined heat and power) plants including generation required for own use. This is also referred to as gross generation.
Energy intensity	A measure where energy is divided by a physical or economic denominator, e.g. energy use per unit of GDP or energy use per tonne of cement.
Enhanced oil recovery (EOR)	Enhanced oil recovery (EOR) is a tertiary recovery process that modifies the properties of oil in a reservoir to increase recovery of oil, examples of which include: surfactant injection, steam injection, hydrocarbon injection, and CO ₂ flooding. EOR is typically used following primary recovery (oil produced by the natural pressure in the reservoir) and secondary recovery (using water injection).
Ethanol	Although ethanol can be produced from a variety of fuels, in this book ethanol refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Today, ethanol is usually made from starches and sugars, but second-generation technologies allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.
F	Fischer-Tropsch (FT) synthesis Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.
Flexibility	Power system flexibility expresses the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system of maintaining reliable supply in the face of rapid and large imbalances, whatever the cause. It is measured in terms of the MW available for ramping up and down, over time (\pm MW/time).
Fuel cell	A device that can be used to convert hydrogen or natural gas into electricity. Various types exist that can be operated at temperatures ranging from 80°C to 1 000°C. Their efficiency ranges from 40% to 60%. For the time being, their application is limited to niche markets and demonstration projects due to their high cost and the immature status of the technology, but their use is growing fast.
G	Gas Gas includes natural gas, both associated and non-associated with petroleum deposits, but excludes natural gas liquids.
Gas-to-liquids	Gas-to-liquids (GTL) refers to a process featuring reaction of methane with oxygen or steam to produce syngas (a mixture of hydrogen and carbon monoxide) followed by synthesis of liquid products (such as diesel and naphtha) from the syngas using Fischer-Tropsch

		catalytic synthesis. The process is similar to those used in coal-to-liquids or biomass-to-liquids.
H	Heat	Heat is obtained from the combustion of fuels, nuclear reactors, geothermal reservoirs, capture of sunlight, exothermic chemical processes and heat pumps which can extract it from ambient air and liquids. It may be used for domestic hot water, space heating or cooling, or industrial process heat. In IEA statistics, heat refers to heat produced for sale only. Most heat included in this category comes from the combustion of fuels in co-generation installations, although some small amounts are produced from geothermal sources, electrically powered heat pumps and boilers. Heat produced for own use, for example in buildings and industry processes, is not included in IEA statistics, although frequently discussed in this book.
	Hydropower	Hydropower refers to the energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.
I	Industrial excess heat (IEH)	IEH can be defined as the heat content of all streams leaving an industrial process at a given moment in time. The extent to which heat can be technically and economically recovered depends on the characteristics of the heat sources and the availability of a compatible end use.
	Integrated gasification combined-cycle (IGCC)	Integrated gasification combined-cycle (IGCC) is a technology in which a solid or liquid fuel (coal, heavy oil or biomass) is gasified, followed by use for electricity generation in a combined-cycle power plant.
L	Liquidity	Liquidity is the ability to sell assets without significant movement in the price and with minimum loss of value.
	Low-carbon energy technologies	Energy technologies emit less CO ₂ (in comparison with conventional sources) from all sectors (buildings, industry, power and transport) that are being pursued in an effort to mitigate climate change.
M	Markets	Markets are structures which allow buyers and sellers to exchange any type of goods, services and information.
	Middle distillates	Middle distillates include jet fuel, diesel and heating oil.
	Modern biomass	Modern biomass includes all biomass with the exception of traditional biomass.
	Non-energy use	Non-energy use refers to fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, coal tars and oils as timber preservatives.
N	Nuclear	Nuclear refers to the primary heat equivalent of the electricity produced by a nuclear plant with an average thermal efficiency of 33%.

O	Oil	Oil includes crude oil, condensates, natural gas liquids, refinery feedstocks and additives, other hydrocarbons (including emulsified oils, synthetic crude oil, mineral oils extracted from bituminous minerals such as oil shale, bituminous sand and oils from coal liquefaction) and petroleum products (refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes and petroleum coke).
	Options	Options are instruments that convey the rights, but not the obligation, to engage in a future transaction on an underlying security or in a future contract.
P	Passenger light-duty vehicles	This vehicle category includes all four-wheel road vehicles aimed at the mobility of persons on all types of roads, up to nine persons per vehicle and 3.5 t of gross vehicle weight.
	Private equity	Private equity is money invested in companies that are not publicly traded on a stock exchange or invested as part of buyouts of publicly traded companies in order to make them private companies.
	Process CO2 emissions	Process emissions refer to the portion of CO2 emissions that are inherently generated by the reactions taking place in an industrial process, such as CO2 released during calcination of limestone in cement kilns.
	Project finance	Project finance is the financing of long-term infrastructure, industrial projects and public services, based upon a non-recourse or limited recourse financial structure where project debt and equity used to finance the project are paid back from the cash flow generated by the project.
	Purchasing power parity (PPP)	Purchasing power parity (PPP) is the rate of currency conversion that equalises the purchasing power of different currencies. It makes allowance for the differences in price levels and spending patterns between different countries.
R	Renewables	Renewable energy sources (renewables) include biomass and waste, geothermal, hydropower, solar photovoltaic, concentrating solar power, wind and marine (tide and wave) energy for electricity and heat generation.
S	Steam coal	All other hard coal that is not classified as coking coal. Also included are recovered slurries, middlings and other low-grade coal products not further classified by type. Coal of this quality is also commonly known as thermal coal.
	Synthetic fuels	Synthetic fuel or synfuel is any liquid fuel obtained from coal, natural gas or biomass. The best known process is the Fischer-Tropsch synthesis. An intermediate step in the production of synthetic fuel is often syngas, a mixture of carbon monoxide and hydrogen produced from coal which is sometimes directly used as an industrial fuel.

T

Total final consumption (TFC) TFC is the sum of consumption by the different end-use sectors, it excludes conversion losses from the transformation sector (power plants, oil refineries, etc.), energy industry own energy use and other losses. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). In the ETP scenarios, the final consumption of the transport sector on a regional or national level includes international marine and aviation bunkers, but not pipeline transport, which is included under energy-industry own energy use. Energy use from blast furnaces and coke ovens is included in the final consumption of the industry sector.

Total primary energy demand Total primary energy demand (TPED) represents domestic demand only and is broken down into power generation, other energy sector and total final consumption. Deviating from this IEA definition, ETP results at regional or national level also include primary energy demand from international aviation and shipping. In addition, if not stated otherwise, total primary energy demand includes bioenergy conversion losses for liquid and gaseous biofuel production for future years, while these losses are not included in primary energy numbers from the IEA World Energy Statistics and Balances for historic years. The ETP online result tables (www.iea.org/etp2017) show both primary bioenergy demand indicators, including and excluding biofuel conversion losses, for future years.

Total primary energy supply Total primary energy supply (TPES) is equivalent to total primary energy demand. TPES represents inland demand only and, except for world energy demand, excludes international marine and aviation bunkers. Deviating from this IEA definition, ETP results at regional or national level also include primary energy use for international aviation and shipping. In addition, if not stated otherwise, total primary energy supply includes bioenergy conversion losses for liquid and gaseous biofuel production for future years, while these losses are not included in primary energy numbers from the IEA World Energy Statistics and Balances for historic years. The ETP online result tables (www.iea.org/etp2017) show both primary bioenergy demand indicators, including and excluding biofuel conversion losses, for future years.

Traditional use of biomass Traditional use of biomass refers to the use of fuel wood, charcoal, animal dung and agricultural residues for cooking and heating in the residential sector. It tends to have very low conversion efficiency (10% to 20%) and often unsustainable biomass supply.

Transmission Electricity transmission systems transfer electricity from generation (from all types, such as variable and large-scale centralised generation, and large-scale hydro with storage) to distribution systems (including small and large consumers) or to other electricity systems.

V

Venture capital Venture capital is a form of private capital typically provided for early stage, high potential growth companies.

Sector definitions

Buildings	The buildings sector (buildings) includes energy used in residential, commercial and public buildings. Buildings energy use includes space heating and cooling, water heating, lighting, appliances, cooking and miscellaneous equipment (such as office equipment and other small plug loads in the residential and service sectors).
Energy industry own use	Energy industry own use covers energy used in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences as well as pipeline transport are also included in this category.
Fuel transformation	Fuel transformation covers the use of energy by transformation sectors and the energy losses in converting primary energy into a form that can be used in final consuming sectors. It includes losses by gas works, petroleum refineries, coal and gas transformation and liquefaction as well as biofuel and hydrogen production. Energy use in blast furnaces, coke ovens and petrochemical plants is not included, but accounted for in the industry sector.
Industry	Industry includes International Standard Industrial Classification (ISIC) divisions 7, 8, 10–18, 20–32, and 41–43 and Group 099, covering mining and quarrying (excluding fuel mining and extraction), construction and manufacturing. Petrochemical feedstock energy use and blast furnace and coke oven energy use are also included.
Other end uses	Other end uses refer to final energy used in agriculture, forestry and fishing as well as other non-specified consumption.
Power generation	Power generation refers to fuel use in electricity plants, heat plants and co-generation plants. Both main activity producer plants and so-called autoproducer plants that produce electricity or heat for their own use are included.
Transport	The transport sector comprises all major motorised modes, including domestic marine and aviation activity and international marine and aviation bunkers, the latter being allocated among countries based on available statistics. Tank-to-wheel emissions cover all the energy used once transformed, while well-to-tank emissions are based on attributional life-cycle assessment studies of fossil-derived fuels (e.g. gasoline, diesel, compressed and liquefied natural gas), biofuels and electricity (based on time- and scenario-specific estimated average grid carbon intensity). Energy use and emissions resulting from pipeline transport are accounted for under “Energy industry own use”.

Regional and country groupings

Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other African countries and territories. ¹
ASEAN (Association of Southeast Asian Nations)	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.
Asia	Bangladesh, Brunei Darussalam, Cambodia, People's Republic of China, India, Indonesia, Japan, Korea, the Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Chinese Taipei, Thailand, Viet Nam and other Asian countries and territories. ²
China	Refers to the People's Republic of China, including Hong Kong.
European Union	Austria, Belgium, Bulgaria, Croatia, Cyprus, ³ Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.
Latin America	Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and other Latin American countries and territories. ⁴
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.
OECD	Includes OECD Europe, OECD Americas and OECD Asia Oceania regional groupings.
OECD Americas	Canada, Chile, Mexico and United States.
OECD Asia Oceania	Includes OECD Asia, comprising Japan, Korea and Israel, ⁵ and OECD Oceania, comprising Australia and New Zealand.
OECD Europe	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.
Other developing Asia	Non-OECD Asia regional grouping excluding People's Republic of China and India.

1. Individual data are not available for: Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Reunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland, Uganda and Western Sahara (territory). Data are estimated in aggregate for these regions.

2. Individual data are not available for: Afghanistan, Bhutan, Cook Islands, East Timor, Fiji, French Polynesia, Kiribati, Lao PDR, Macau, Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Data are estimated in aggregate for these regions.

3. Footnote by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

Footnote by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

4. Individual data are not available for: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guyana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, St. Kitts and Nevis, Saint Lucia, Saint Pierre et Miquelon, St. Vincent and the Grenadines, Suriname and Turks and Caicos Islands. Data are estimated in aggregate for these regions.

5. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Units of measure

Unit prefix	E	exa (10^{18} , quintillion)
	P	peta (10^{15} , quadrillion)
	T	tera (10^{12} , trillion)
	G	giga (10^9 , billion)
	M	mega (10^6 , million)
	k	kilo (10^3 , thousand)
	c	centi (10^{-2} , hundredth)
	m	milli (10^{-3} , thousandth)
	μ	micro (10^{-6} , millionth)
Area	m^2	square metre
Distance	km	kilometre
	m	metre
	pkm	passenger kilometre
	tkm	tonne kilometre
	vkm	vehicle kilometre
Emissions	tCO ₂	tonne of carbon dioxide equivalent
	GtCO ₂	GtCO ₂ -eq gigatonnes of carbon dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	MtCO ₂	million tonnes of carbon dioxide equivalent
	gCO ₂ /kWh	grammes of carbon dioxide per kilowatt hour
Energy	MBtu	million British thermal units
	MJ	megajoule ($1 \text{ joule} \times 10^6$)
	GJ	gigajoule ($1 \text{ joule} \times 10^9$)
	TJ	terajoule ($1 \text{ joule} \times 10^{12}$)
	PJ	petajoule ($1 \text{ joule} \times 10^{15}$)
	EJ	exajoule ($1 \text{ joule} \times 10^{18}$)
	GJ/t	gigajoules per tonne
	kWh	kilowatt hour
	MWh	megawatt hour
	GWh	gigawatt hour
	TWh	terawatt hour
	PWh	petawatt hour
	MWh/t	megawatt hour per tonne

	kWh/m ²	kilowatt hour per square metre
	kWh/vkm	kilowatt hour per vehicle kilometre
	kW	kilowatt
	MW	megawatt
	GW	gigawatt
	kV	kilovolt
Mass	t	tonne
	kt	kilotonne
	Mt	million tonnes
	Gt	gigatonne
Temperature	°C	degrees Celsius
Others	bbl	barrel
	Lge	litre of gasoline equivalent
	lm/W	lumens per watt
	mD	millidarcy
	RPK	revenue per passenger kilometre
	Wh/L	watt hours per litre

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Energy Technology Perspectives 2017

Catalysing Energy Technology Transformations

The global energy system is moving closer to a historic transformation. This year's edition of the International Energy Agency (IEA)'s comprehensive publication on energy technology focuses on the opportunities and challenges of scaling and accelerating the deployment of clean energy technologies. This includes looking at more ambitious scenarios than the IEA has produced before.

Improvements in technology continue to modify the outlook for the energy sector, driving changes in business models, energy demand and supply patterns as well as regulatory approaches. Energy security, air quality, climate change and economic competitiveness are increasingly being factored in by decision makers. *Energy Technology Perspectives 2017 (ETP 2017)* details these trends as well as the technological advances that will shape energy security and environmental sustainability for decades to come.

For the first time, *ETP 2017* looks at how far clean energy technologies could move the energy sector towards higher climate change ambitions if technological innovations were pushed to their maximum practical limits. The analysis shows that, while policy support would be needed beyond anything seen to date, such a push could result in greenhouse gas emission levels that are consistent with the mid-point of the target temperature range of the global Paris Agreement on climate change. The analysis also indicates that regardless of the pathway chosen for the energy sector transformation, policy action is needed to ensure that multiple economic, security and other benefits to the accelerated deployment of clean energy technologies are realised through a systematic and co-ordinated approach.

ETP 2017 also features the annual IEA *Tracking Clean Energy Progress* report, which shows that the current progress in clean energy technology development and deployment remains sub-optimal. It highlights that progress has been substantial where policies have provided clear signals on the value of technology innovation. But many technology areas still suffer from a lack of financial and policy support.

ETP 2017 purchase includes extensive downloadable data, figures and visualisations. For more information, please visit www.iea.org/etp2017



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