Energy and the Sustainable Development Goals

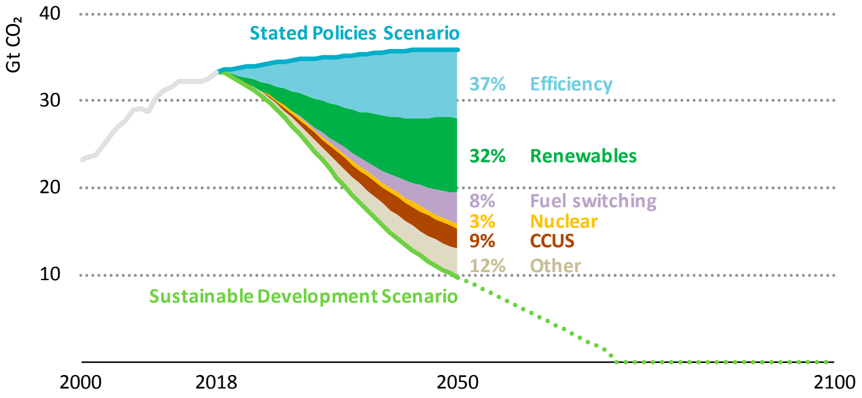
Are we on the path to achieve the SDGs?

SUMMARY

- The Sustainable Development Scenario lays out a pathway to reach the United Nations Sustainable Development Goals (SDGs) most closely related to energy: achieving universal energy access (SDG 7), reducing the impacts of air pollution (SDG 3.9) and tackling climate change (SDG 13). It is designed to assess what is needed to meet these goals, including the Paris Agreement, in a realistic and cost-effective way.

- Recent progress has been mixed, and so are prospects for improvement given proposed policies. The number of people without access to electricity fell from 980 million in 2017 to 860 million in 2018, but the lack of electricity access in sub-Saharan Africa remains acute. Current and planned policies deliver universal electricity access in many parts of the world, but are insufficient to fully electrify Africa by 2030. Annual premature deaths linked to household and outdoor air pollution stand at around 5.5 million globally. This figure is set to rise to around 7 million by 2050.

Figure 2.1 ▷ Energy-related CO_2 emissions and reductions by source in the Sustainable Development Scenario



Efficiency and renewables provide most emissions reductions, but more technologies are needed as emissions become increasingly concentrated in hard-to-abate sectors

Note: CCUS = carbon capture, utilisation and storage.

- Energy-related carbon dioxide (CO_2) emissions grew by 1.9% in 2018. A peak in these emissions is not in sight: they are set to reach nearly 36 gigatonnes (Gt) annually by 2050 in the Stated Policies Scenario. Jurisdictions accounting for nearly 13% of total

current emissions have put forward net-zero emissions targets, an important step in increasing global ambition, but insufficient to significantly alter the trajectory of global energy-related CO_2 emissions.

- In our Sustainable Development Scenario, universal access to electricity and clean cooking facilities is achieved by 2030 with net reductions in greenhouse gas emissions, as increased CO_2 emissions from the power sector and use of liquefied petroleum gas (LPG) for cooking are more than offset by the reduction in methane emissions from reduced biomass burning for cooking. Premature deaths from air pollution are 3 million lower in 2050 than in the Stated Policies Scenario.
- Thanks to efficiency improvements, electrification and fuel switching, energy demand remains broadly stable, despite a growing global economy. However, the fuel mix changes dramatically. Electricity demand grows steadily in the Sustainable Development Scenario, as mobility and heating are electrified. By 2040, wind and solar become the top two sources of power generation and by 2050 the power sector is mostly decarbonised. Electric cars make up three-quarters of all cars sold. Hydrogen and biomethane are used in gas grids. Energy efficiency, material efficiency and carbon capture, utilisation and storage (CCUS) together decarbonise heavy industries. A host of new low-carbon technologies move from low market shares to wide deployment at a speed as fast as anything in the history of the energy sector.
- By 2050, oil use falls to 50 million barrels per day (mb/d), 40% of which is used as a feedstock to produce plastics and asphalt (i.e. non-emitting uses). Demand for natural gas hovers just above 4 000 billion cubic metres (bcm) until the late 2030s, before entering a pronounced decline. Coal demand declines in both absolute and relative terms, and by 2050 accounts for 8% of total energy use. By 2050, low-carbon technologies, most of which are renewables, but also nuclear and CCUS, support well over half of global energy demand, from less than 20% today, a reversal of the stable share of fossil fuels at over 80% for the past three decades.
- Global energy-related CO_2 emissions decline rapidly, in line with the objectives of the Paris Agreement. They reach 25 Gt in 2030, reduce to under 10 Gt in 2050, and are on track for net zero in 2070 (Figure 2.1). This trajectory is consistent with a 66% chance of limiting the temperature rise to 1.8 °C or a 50% chance of a 1.65 °C stabilisation, and does not rely on large-scale negative emissions. If negative emissions technologies were deployed in the second-half of the century at levels similar to those reported in the IPCC's *Special Report on Global Warming of 1.5 °C*, then the Sustainable Development Scenario would provide a 50% chance of limiting the temperature increase to 1.5 °C. For this temperature target to be achieved without negative emissions, global energy-related emissions would need to fall to zero by 2050. The changes required to set such a course are rapid, deep and unprecedented and their implications would be far-reaching and extend well beyond the energy sector.

Introduction

This chapter illustrates our Sustainable Development Scenario, depicting an energy future that simultaneously delivers on the United Nations Sustainable Development Goals (SDGs) most closely related to energy: universal energy access (SDG 7), reducing impacts of air pollution (part of SDG 3) and tackling climate change (SDG 13). The time horizon[1] for this analysis has been extended this year for the first time to 2050 to assess the potential of new technologies (such as hydrogen and renewable gases) in supporting the global energy transition and to reflect the announcements that several countries have made about plans to reach carbon neutrality by 2050.

The first part of this chapter provides an overview which shows that there has been mixed progress on meeting the SDGs most closely related to energy. It then describes the scenario outcomes in terms of achieving the SDGs, before looking at the energy sector transformation and the investment needs implied by the scenario.

The chapter continues with three focus areas that take a long-term perspective towards 2050 (and beyond). They cover:

- **How are we doing?** This section assesses where stated policies will take us in meeting the SDGs. It also looks at current plans to increase ambitions and the impact of those on carbon dioxide (CO_2) emissions.
- **Where do we need to get to?** This section explores in detail the energy sector transformation in the Sustainable Development Scenario, shedding light on critical gaps, including finance and technology innovation. It also explains how the Sustainable Development Scenario has evolved, capturing recent technology progress as well as science and investment trends.
- **How much further can we go?** This section, more exploratory in nature, looks at the scope to do more in the light of proposals for even more ambitious temperature goals. It depicts a future pathway for the energy system compatible with limiting the global temperature increase to 1.5 degrees Celsius (°C) without the use of net-negative emissions, and discusses the standing of the Sustainable Development Scenario in the pursuit of this more ambitious target.

Figures and tables from this chapter may be downloaded from www.iea.org/weo2019/secure/.

---

[1] The *World Energy Outlook* scenarios extend to 2050, with inputs (see Annex B) quoted to 2040 for the analyses, while this chapter looks to 2050 and beyond.

Sustainable Development Scenario

2.1 Scenario overview

There are three pillars to the Sustainable Development Scenario. These are to ensure universal energy access for all by 2030; to bring about sharp reductions in emissions of air pollutants; and to meet global climate goals in line with the Paris Agreement (see section 2.4). The scenario meets them simultaneously while reflecting national priorities and the latest technology and market developments. Taking those changes into account, the scenario outcome has evolved over successive editions of the *World Energy Outlook (WEO)* (see Box 2.1).

In many cases the policies necessary to achieve the multiple SDGs covered in the Sustainable Development Scenario are complementary. For example, energy efficiency and renewable energy significantly reduce local air pollution, particularly in cities, while access to clean cooking facilitated by liquefied petroleum gas (LPG) also reduces overall greenhouse gas (GHG) emissions by reducing methane emissions from incomplete combustion of biomass as well as by reducing deforestation (Masera, Bailis and Drigo, 2015; IEA, 2017a).

Yet there can be trade-offs. For example, while electric vehicles (EVs) reduce local air pollution from traffic, the overall CO_2 footprint of EVs can actually exceed that of combustion engine vehicles if there is not a parallel effort to decarbonise the power sector (Box 2.4). To take another example, retrofitting coal-fired power plants with pollution controls may be the cheapest option in the short term to deal with local pollution, but may lead to long-term emissions not aligned with climate goals (see Chapter 6).

Dichotomies between short- and long-term policy actions can also add to the challenge of accomplishing the Sustainable Development Scenario. Ultimately, the balance of potential synergies or trade-offs depends on the route chosen to achieve the energy transition. The Sustainable Development Scenario portrays an energy future which emphasises the co-benefits of the measures needed to simultaneously deliver energy access, clean air and climate goals.

This chapter shows that, despite positive movement in many countries and sectors, we are not on track to meet the Sustainable Development Goals, and sets out some possible ways to address the shortfall. On the basis of current stated policies, energy-related CO_2 emissions are set to continue to rise, premature deaths linked to air pollution are set to increase, and in 2030 there would still be around 620 million people without access to electricity and around 2.3 billion people cooking with primitive stoves or without access to cleaner fuels. Consequently, the transformation required in the energy sector to deliver the SDG goals is profound (Table 2.1).

Table 2.1 ⊳ Key energy indicators in the Sustainable Development and Stated Policies scenarios

		Sustainable Development		Stated Policies	
	2018	2030	2050	2030	2050
SDG 7: Access (million people)					
Population without access to electricity	862	0	0	623	736
Population without access to clean cooking	2 651	0	0	2 302	1 538
Related premature deaths	2.5	0.6	0.8	2.4	1.8
SDG 13: Energy-related GHG emissions					
CO_2 emitted (Gt)	33.2	25.2	9.75	34.9	35.9
CO_2 captured with CCUS (Mt)	32	763	2 776	71	154
Methane (CH_4) (Mt)	127	51	30	116	108
of which from oil and gas operations	*77*	*20*	*14*	*66*	*63*
SDG 3: Air pollution (million people)					
Premature deaths from energy-related outdoor air pollution	3.0	2.7	3.0	3.6	5.1
Primary energy supply					
Total primary energy supply (Mtoe)	14 314	13 750	13 110	16 311	18 832
Share of low-carbon supply	19%	30%	61%	23%	29%
Energy intensity of GDP (toe/$1 000)	106	67	37	79	53
average annual reduction from 2018		*3.8%*	*3.2%*	*2.4%*	*2.1%*
Power generation					
CO_2 intensity of power (g CO_2/kWh)	476	237	23	370	262
Share of low-carbon generation	36%	61%	94%	46%	57%
of which renewables	*71%*	*80%*	*84%*	*80%*	*86%*
Final consumption					
Total final consumption (Mtoe)	9 954	9 904	9 225	11 607	13 555
of which renewables	*10%*	*21%*	*44%*	*14%*	*21%*
Industry					
Share of electricity	28%	31%	40%	29%	31%
CO_2 intensity (t CO_2/$1 000 VA)	0.26	0.15	0.06	0.20	0.15
Transport					
Electric cars % of new car sales	2%	47%	72%	15%	27%
Carbon intensity of new PLDVs (g CO_2/v-km)	175	62	21	121	90
Carbon intensity of truck fleet (g CO_2/t-km)	82	55	21	65	50
Shipping emissions (Mt CO_2)	878	832	435	1 064	1 276
Aviation emissions (Mt CO_2)	982	925	625	1 217	1 661
Buildings					
Energy intensity: residential (toe/dwelling)	1.04	0.72	0.59	0.94	0.88
Energy intensity: services (toe/$1 000 VA)	0.016	0.012	0.007	0.014	0.010

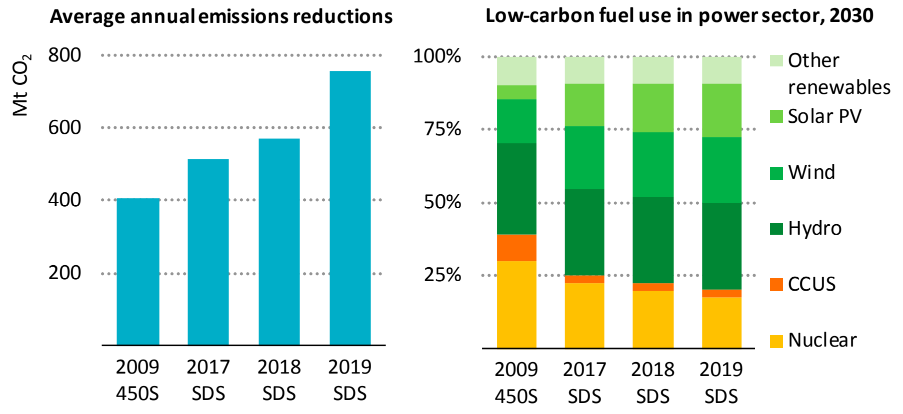
Notes: Mt = million tonnes; CCUS = carbon capture, utilisation and storage; GDP = gross domestic product; $PM_{2.5}$ = particulate matter with a diameter of less than 2.5 micrometres; Mtoe = million tonnes of oil equivalent; toe = tonnes of oil equivalent; t = tonnes; $ = USD (2018); g = grammes; kWh = kilowatt-hour; VA = value added; PLDVs = passenger light-duty vehicles; v-km = vehicle-kilometre; t-km = tonne-kilometre. Buildings: services include public and commercial buildings. See Annex B for details of the scenarios.

Box 2.1 ▷ The future ain't what it used to be – a decade of *WEO* energy transition scenarios

The *World Energy Outlook* introduced a detailed energy transition scenario in 2009. Back then, climate policy discussions focused on the targeted stabilisation level of CO_2 concentration. The scenario got its 450 name from 450 parts per million (ppm), the CO_2 concentration that was seen at that time to be consistent with a 50% likelihood of keeping average global temperature rise below 2 °C. Since then the global goalposts have shifted, technological progress has been uneven, and emissions have continued to grow. How has the *WEO* energy transition scenario changed?

A tougher starting point. Energy-related CO_2 emissions in 2018 reached a record high 33 gigatonnes (Gt), only marginally lower than the figure projected in the Reference Scenario of 2009, but a huge 2.5 Gt above what was set out in the 450 Scenario (which, as with all *WEO* energy transition scenarios, embodies the principle of early action). Higher emissions are associated with a larger carbon-intensive capital stock: the first version of the 450 Scenario in the *WEO-2009* saw no more than 1 700 GW of unabated coal capacity in 2020, but in the years since that publication, the world has continued to build unabated coal-fired power plants and is on track to have over 2 100 GW in operation in 2020. This investment wave completely dwarfed the impact of positive developments from solar panels to EVs. In fact, without the slower than expected recovery after the financial crisis, global CO_2 emissions today would probably be higher than projected in the 2009 Reference Scenario.

Figure 2.2 ▷ Average annual post-peak CO_2 emissions reductions and power sector mix in various *WEO* scenarios



Annual WEO updates of energy transition scenarios have changed to reflect continued emissions growth, uneven technology progress and more ambitious long-term targets

Note: 450S = 450 Scenario in *WEO-2009*; SDS = Sustainable Development Scenario in *WEO* editions 2017-2019; CCUS = carbon capture, utilisation and storage.

Higher ambition. The 450 Scenario was compatible with reaching net-zero CO_2 emissions towards the end of the century. The emission trajectory of the 2019 Sustainable Development Scenario (Figure 2.5) combined with the higher starting point result in 730 million tonnes (Mt) average emissions decline per year (with peaks of yearly reduction of 1 Gt) compared with just 400 Mt reductions per year in the *WEO-2009* (Figure 2.2).

Uneven technological progress. The Sustainable Development Scenario relies much more on solar and wind in the power sector, and less on carbon capture, utilisation and storage (CCUS) and nuclear in the power sector than the 450 Scenario. The 2040 low-carbon system described by the 2014 edition of the 450 Scenario would have been dominated by baseload low-carbon technologies with nuclear at roughly the same level as wind and solar combined. Five years later, the Sustainable Development Scenario continues to rely on nuclear power and CCUS in 2040, but wind and solar contribute 2.5-times their combined generation.

This is a reflection of technology progress, or lack of it, principally determined by policy preferences. In the European Union, for example, the revision of transport-related policies strongly benefited electric cars over biofuels. Korea, which in 2014 had a robustly pro-nuclear policy stance, has since introduced a moratorium on new nuclear construction and an ambitious renewable energy investment drive and – apart from the recent 45Q tax credit reforms in the United States designed to incentivise carbon capture projects – there has been relatively little policy progress on CCUS.

Hydrogen provides another example of how shifting technology developments and preferences are reflected in the *Outlook*. The inclusion of new hydrogen-based technologies is timely, following the IEA's first comprehensive hydrogen study and it reflects unprecedented interest in hydrogen (IEA, 2019a). *WEO-2019* includes the modelling of the full diversity of possible contributions of hydrogen to sustainable development across all sectors, as well as an assessment of the technical potential and costs of biogas and biomethane supply, together with projections for the future.

Today, around 330 million tonnes of oil equivalent (Mtoe) of hydrogen is used globally, mainly in the refining and chemicals sectors, with future interest focused on hydrogen's ability to complement variable renewable electricity and enable deep decarbonisation. In the Sustainable Development Scenario, smart policies combine to support the development of the hydrogen industry and bring down costs as a springboard for subsequent widespread use in a wider variety of sectors. Globally, around 150 Mtoe of biogas is consumed directly in 2050, and this contributes significantly to improving access to clean cooking, with around 240 million people using biogas to move away from the traditional use of biomass. In addition, the uptake of biomethane (or renewable low-carbon gas) rises strongly to 280 Mtoe in 2050, equal to around 10% of natural gas demand in that year.

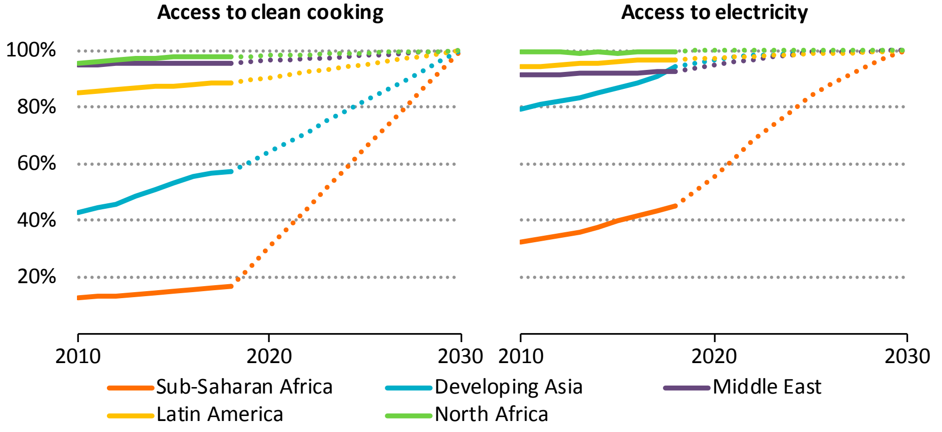
2.2 Scenario outcomes: Universal energy access

In the Sustainable Development Scenario, universal access to both electricity and clean cooking facilities is achieved by 2030, in line with target 7.1 of SDG 7 (Figure 2.3). Given expected strong population growth over that period, particularly in countries where many people still lack access, this means a cumulative total of around 1 billion additional people with access to electricity by 2030, and more than 2.5 billion people moving away from the traditional use of biomass by the same date. This reduces the health impact of air pollution, promotes gender equality and is achieved without increasing GHG emissions (IEA, 2017a).

A cost-effective way to achieve electricity access in many areas is with renewable energy sources, thanks to the declining costs of small-scale solar photovoltaics (PV) for off-grid and mini-grid electricity as well as batteries, and to the increasing use of renewables for grid-connected electricity. This is especially the case in rural areas in sub-Saharan Africa, home to around 60% of the global population still deprived of electricity access (see Chapter 10).

The means of achieving clean cooking depends on cultural and economic factors, as well as on resources available locally and infrastructure. LPG delivers access to clean cooking in about half of all cases – particularly in urban areas - with improved and more energy-efficient biomass cookstoves playing a more significant role in rural communities. Overall, the additional CO_2 emissions resulting from increased electricity consumption and use of LPG are more than offset by the reduction in methane and nitrous oxide emissions from incomplete combustion of biomass as well as by reduced deforestation. Taking into account the higher equivalent warming effect of methane and nitrous oxide relative to CO_2, even a conservative calculation shows a net climate benefit from simultaneously achieving universal access to both electricity and clean cooking solutions.

Figure 2.3 ▷ Pathways to universal access in the Sustainable Development Scenario



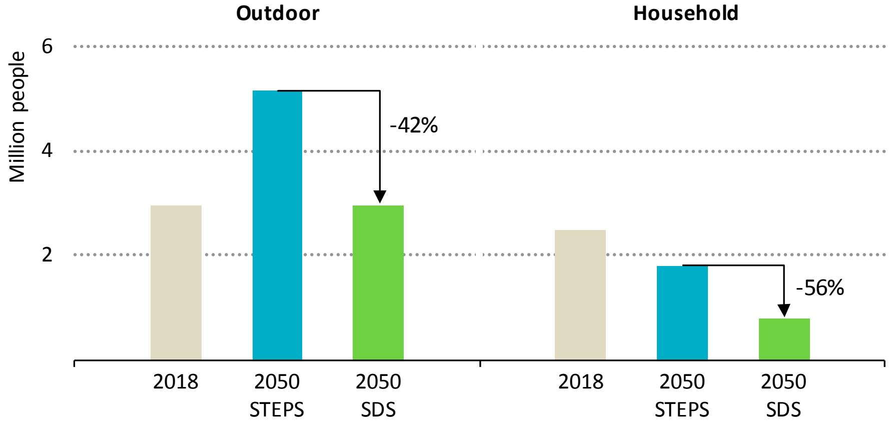
Acceleration in access is particularly needed in sub-Saharan Africa and developing Asia

2.3 Scenario outcomes: Air pollution

Air pollution has major implications for health: nine-out-of-ten people breathe polluted air every day, causing more than 5 million premature deaths each year. Around 3 million people die prematurely each year from diseases linked to breathing polluted air outdoors and around 2.5 million from smoky household air pollution: the biggest burden is on developing economies, where more than 2.6 billion people still do not have access to clean cooking.

While premature deaths due to outdoor air pollution are projected to increase and reach 5 million a year by 2050 in the Stated Policies Scenario, the higher level of ambition on air quality in the Sustainable Development Scenario translates into more than 2 million premature deaths avoided each year by 2050, compared to the Stated Policies Scenario (Figure 2.4). This is driven by reductions in emissions from the three major air pollutants – sulphur dioxide (SO_2), nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$). Improvements in power plant and industrial facilities – especially reduced coal use – cause total energy-related SO_2 emissions to be two-thirds lower in 2050 compared to the Stated Policies Scenario in that year; these measures, together with stricter emissions standards in the transport sector, cause NO_X emissions to drop by more than 70%. Reducing reliance on polluting fuels for cooking by 2030 reduces $PM_{2.5}$ emissions by more than 80% compared to the Stated Policies Scenario: premature deaths due to household air pollution fall to 0.8 million a year[2] in the Sustainable Development Scenario by 2050, compared to 1.8 million a year in the Stated Policies Scenario.

Figure 2.4 ▷ Global premature deaths attributable to air pollution



Lower pollutant emissions from power plants, cars and industries could avoid 2.2 million premature deaths a year, and broader access to clean cooking another 1 million a year

Note: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

Source: International Institute for Applied Systems Analysis (IIASA).

---

[2] While improvements in biomass cookstoves reduce indoor pollution by around 75%, they do not completely eliminate health risks.

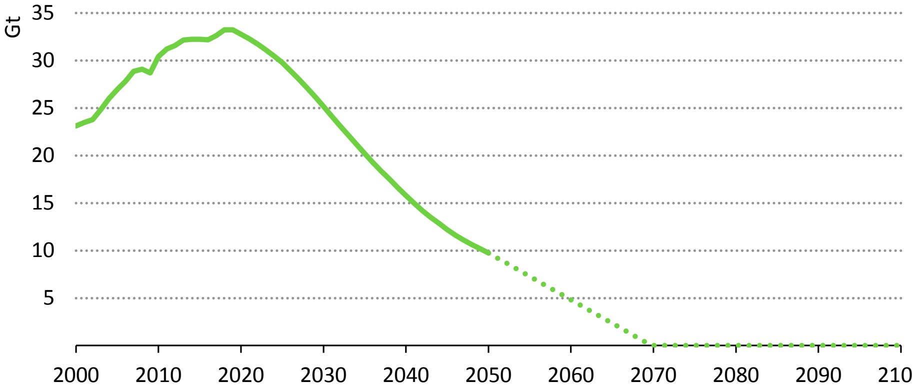
2.4 Scenario outcomes: CO_2 emissions

The Paris Agreement has an objective of "holding the increase in the global average temperature 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". Article 4 of the Agreement sets out related aims on how to achieve this temperature goal including the need to: reach a global peak in GHG emissions as soon as possible (recognising that peaking will take longer for developing economies); undertake rapid reductions thereafter; and achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second-half of this century.

The Sustainable Development Scenario is constructed on the basis of limiting the temperature rise to below 1.8 °C with a 66% probability without the implied reliance on global net-negative CO_2 emissions, or 1.65 °C with a 50% probability. Because emissions do not turn net negative, this means that there is no "overshooting" of the 1.8 °C temperature rise (see section 2.9). However the emissions trajectory of the Sustainable Development Scenario to 2050 leaves open the possibility that – if emissions were to turn net negative during the second-half of the century – the temperature rise could be limited to 1.5 °C with a 50% probability (Figure 2.5). The Sustainable Development Scenario adopts a principle of early action and sees energy sector CO_2 emissions peak immediately at around 33 Gt, and then fall at an average of 3.8% per year to less than 10 Gt by 2050, on course to net zero by 2070.

In the Sustainable Development Scenario, the cumulative level of CO_2 that is emitted between 2018 and 2070 is 880 Gt. After taking into account emissions from land-use change and industrial processes, this gives a remaining energy-related CO_2 budget of around 800 Gt.

Figure 2.5 ▷ Energy-related CO_2 emissions in the Sustainable Development Scenario to 2050 and extended pathway to 2100



Energy-related CO_2 emissions are less than 10 Gt in 2050, on course for net zero by 2070. If emissions remain at zero after 2070, this would provide a 66% chance of limiting the temperature rise to below 1.8 °C.

2.5 Energy sector transformation in the Sustainable Development Scenario

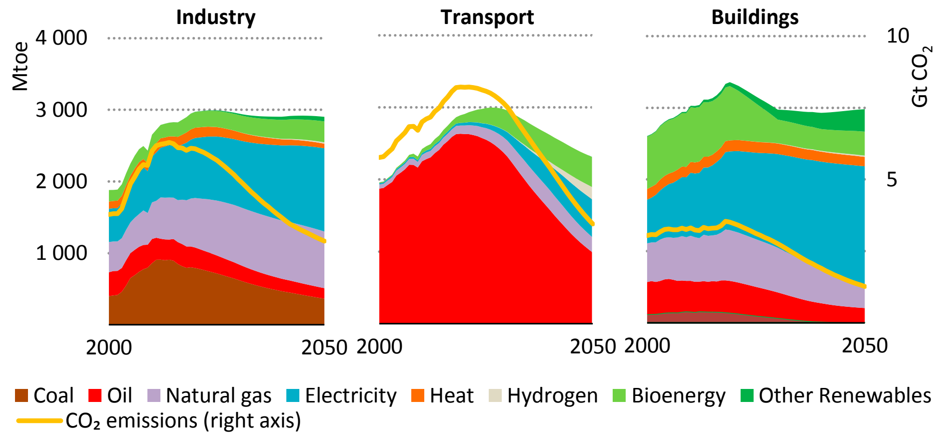
Total final consumption

Households and industries are at the heart of the energy transitions in the Sustainable Development Scenario. Households opt for very efficient appliances, buildings renovations and electric options. Industrial processes become very efficient (including through material efficiency, see Chapter 7), fuel switching, electrification and CCUS. Innovations are made in sectors such as cement, and ammonia (with 50 Mtoe produced via electrolytic hydrogen in 2050) is utilised widely (Figure 2.6).

Efficiency, including through electrification, has a major role to play and is a common denominator across sectors: efficiency gains mean that final energy use stays flat, despite a near tripling of the economy and an additional 2 billion people. Conventional cars sold in 2050, for example, consume around 50% of the fuel consumed by the average car sold today. This is accompanied by strong electrification: in 2050, three-quarters of cars sold globally are electric, as are all scooters, all urban buses, and 50% of trucks.

In the Sustainable Development Scenario, both oil and coal use peak imminently. Oil use declines steeply for passenger cars and for other uses. The use of oil for non-energy and non-emitting uses (for example in plastic feedstock and asphalt) rises to 40% of the final consumption of oil. Coal use declines steeply, but it continues to be used in industry, mainly for the production of cement, iron and steel, with a third of these emissions captured via CCUS. Natural gas use increases through to the late 2020s, as it replaces more polluting fuels, but consumption declines after this as deep retrofits, biomethane, hydrogen and electrification provide less polluting alternatives. Hydrogen starts to be used in gas grids and shipping. Inefficient use of biomass is phased out in buildings.

Figure 2.6 ▷ Total final consumption by sector and fuel in the Sustainable Development Scenario

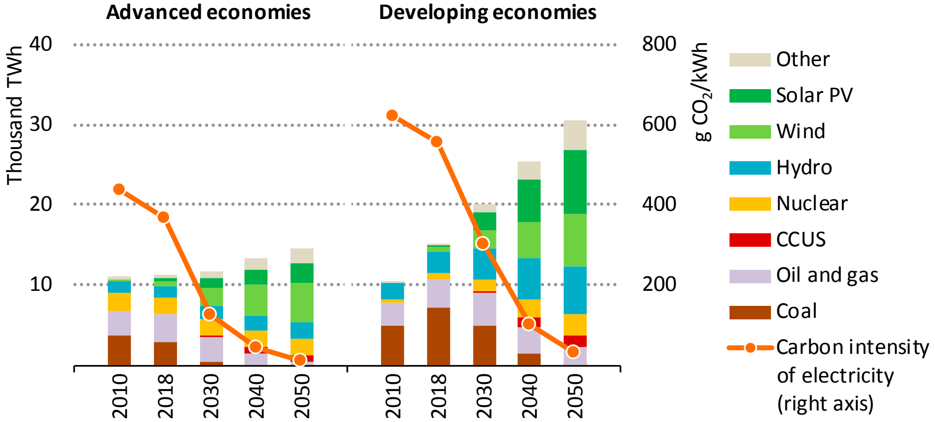


A shift to low emitting energy sources cuts end-use emissions by 57%, but the drop in total final consumption in buildings flattens out due to expanding electricity access

Power generation

In the Sustainable Development Scenario, the entire global population gains access to electricity by 2030 and a number of sectors – including transport – see a shift from other fuels to electricity. Electricity increases its share in the fuel mix across all sectors, doubling its current share of 19% by 2050. By 2050 the electricity system grows to more than 45 000 terawatt-hours (TWh), some 70% larger than today (Figure 2.7). Global electricity supply in the Sustainable Development Scenario moves rapidly from unabated fossil fuels towards low-carbon sources. By 2030, 60% of global electricity production comes from low-carbon sources, increasing to 94% in 2050 (up from 36% today). The global carbon intensity of electricity supply falls to just 23 grammes of CO_2 per kilowatt-hour kWh (g CO_2/kWh) on average in 2050, from 475 g CO_2/kWh in 2018.

Figure 2.7 ▻ Electricity generation by source and carbon intensity of electricity in the Sustainable Development Scenario



Both advanced and developing economies move towards full decarbonisation of electricity supply by 2050

Note: CCUS = carbon capture, utilisation and storage.

Wind and solar become the two main sources of generation by 2040, and supply half of global electricity generation by 2050. Hydro keeps its current share of around 17% of generation, and bioenergy grows to supply 7% of generation. Nuclear supplies about 10% of total generation, and coal and natural gas with CCUS an additional 5%. Coal-fired generation declines sharply, although CCUS mitigates the drop (see IEA, 2017b for uncertainties related to CCUS). Starting with the least efficient coal-fired power plants, virtually all generation from coal-fired power plants without carbon capture is phased out by 2030 in advanced economies and by 2045 in developing economies. Natural gas-fired power generation increases through to the late 2020s, providing important flexibility (in some regions), but then declines as renewables become cheaper and as flexibility needs are increasingly met by battery storage.

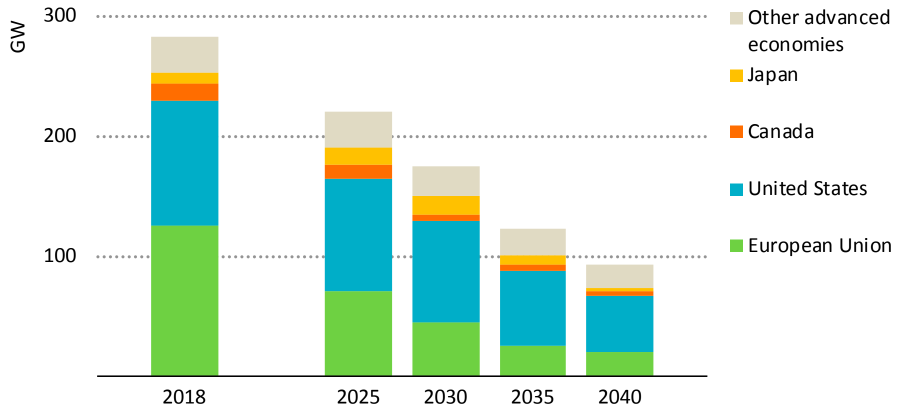
Box 2.2 ▹ The risk of nuclear power fading away in advanced economies

Nuclear power can play an important role in clean energy transitions. Today, it provides 18% of electricity supply in advanced economies, where it is the largest low-carbon source of electricity. Alongside renewable energy and CCUS technologies, nuclear power will be needed for clean energy transitions around the world. Nuclear power also contributes to electricity security as a dispatchable source.

Policy and regulatory decisions remain critical to the fate of reactors, particularly in advanced economies, where the average age of reactors is 35 years. Lifetime extensions offer a low-cost source of clean baseload energy, at $40-60 per megawatt-hour (MWh), competitive in most cases with the falling costs of renewables. At the same time, hurdles to investment in new nuclear projects are daunting, as cost overruns and delays raise doubts of future development, although advanced nuclear technologies, such as small modular reactors, could offer new opportunities.

Without investment in lifetime extensions or new projects, operational nuclear capacity in advanced economies would decline by two-thirds from 2018 to 2040 (Figure 2.8), with important implications for sustainability and affordability. Achieving the clean energy transition with less nuclear power is possible but would require more to be done to reduce emissions in other ways, adding to the difficulty of delivering ambitious emissions goals. It would also be very likely to cost more: offsetting less nuclear power with more renewables would raise overall power investment needs by some $1.6 trillion over the period to 2040, resulting in 5% higher electricity bills for consumers in advanced economies (IEA, 2019b).

Figure 2.8 ▹ **Operational nuclear power capacity in advanced economies absent further investment**



Without investment in lifetime extensions or new projects, nuclear power capacity in advanced economies would decline by two-thirds by 2040

Primary energy demand

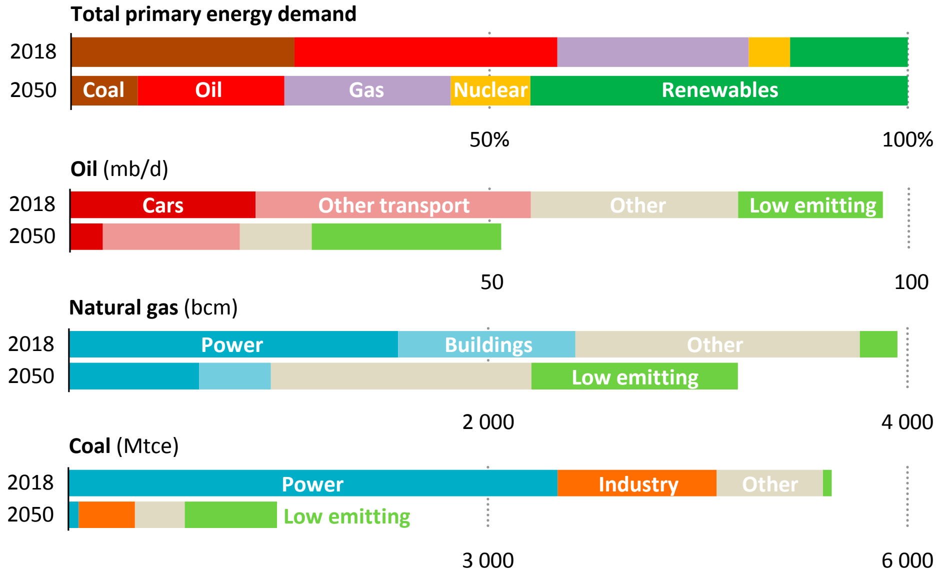
Thanks to efficiency improvements, electrification and fuel switching, energy demand remains broadly stable, despite a growing economy. However the fuel mix changes dramatically. Low-carbon technologies (including CCUS) grow to supply 60% of primary energy by 2050 from less than 20% today, a reversal of a stable share of fossil fuels at over 80% for the past three decades (Figure 2.9).

Coal demand declines in both absolute and relative terms, and by 2050 accounts for just 8% of total energy uses, with industrial processes (iron, steel and cement production) and transformations accounting for the largest component. Around half of the remaining energy-related coal emissions (for industry and power) are captured via CCUS.

By 2050 natural gas and oil account for 18% and 20% of primary energy demand respectively. The share of natural gas rises to 26% in 2030 and then slowly falls back. Across the energy system, half of the decline in the use of natural gas is compensated for by strong growth in the use of biomethane and hydrogen (see Chapter 13).

Although oil demand for non-combustion uses, such as petrochemical feedstock, increases until 2050, oil is still used in 2050 to fuel 17% of the car fleet and 40% of the truck fleet. It is also used in aviation and shipping, where substitutes are more difficult to find.

Figure 2.9 ▷ Primary energy mix and fuel use by sector in the Sustainable Development Scenario, 2018 and 2050



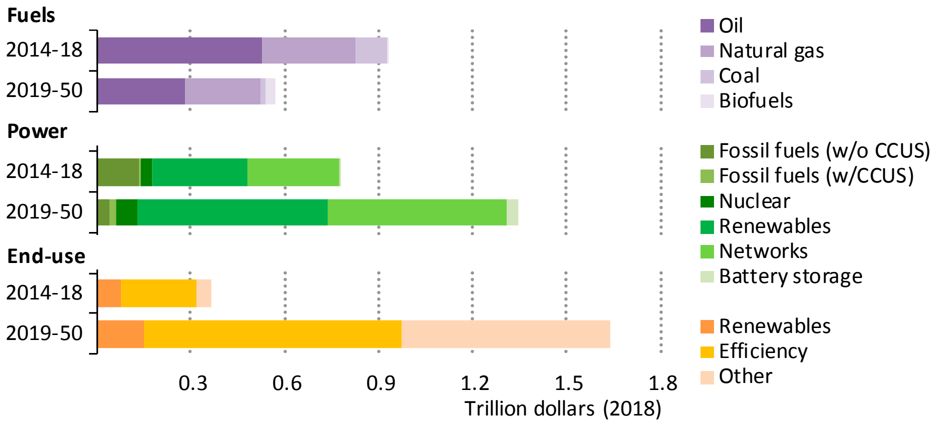
While growth in renewables and nuclear power contribute most to decarbonising the energy mix, the carbon footprint of fossil fuels also improves

Notes: mb/d = million barrels per day; bcm = billion cubic metres; Mtce = million tonnes of coal equivalent. Low emitting includes feedstocks and fuel use equipped with CCUS.

2.6 Investment in the Sustainable Development Scenario

The Sustainable Development Scenario sees an increase in overall investment compared to the Stated Policies Scenario of around 25% over the period 2019-50. This additional investment cost is partially counterbalanced by reduced fuel costs. The Sustainable Development Scenario brings considerable benefits in terms of energy access, health/air quality and mitigating the impacts of climate change. It also requires a different approach to financing. Average annual supply-side investment in power increases by three-quarters through to 2050, whereas investment in fuels decreases by about 40% from today's level. This marks a significant shift away from fossil fuels to renewables and other low-carbon sources as well as to electricity (Figure 2.10).

Figure 2.10 ▹ Average annual energy investment in the Sustainable Development Scenario, 2014-2018 and 2019-2050



Investment in fuels and power is marked by a major reallocation of capital towards renewables and electricity networks; demand-side investment increases substantially

Notes: Other end-use includes CCUS in industry, spending to meet the incremental cost of EVs and investment in EV charging infrastructure. w/o CCUS = without CCUS, w/CCUS = with CCUS.

Despite this shift, some investment in oil supply – in both currently producing fields and new fields – is still required to meet demand (Box 2.3). While investment in natural gas supply is lower in 2050 than it is today, it rises over the next decade to meet increasing demand, as natural gas increasingly substitutes for coal, and to maintain and develop the gas infrastructure that helps support the use of low-carbon gases.

The largest increase in supply investment comes from renewables-based power, which doubles from today's levels to nearly $610 billion a year on average. This ramp-up is supported by additional spending on electricity grids and battery storage. While there continues to be investment in fossil fuel power generation, about half of this spending is associated with plants equipped or retrofitted with CCUS technology after the late 2020s.

Spending on more efficient buildings, industrial processes and transport accounts for half of demand-side investment needs. In buildings, this includes spending on more efficient appliances as well as on efficiency measures such as thermal insulation and efficient lighting. In transport, it includes spending that supports the shift towards EVs and associated charging infrastructure, as well as the costs of more efficient internal combustion engines.

The investment needed to achieve universal energy access amounts to some $45 billion per year between 2019 and 2030, the lion's share of it for electricity access. While this is more than double the amount in the Stated Policies Scenario, it is less than 2% of the total annual energy sector investment in the Sustainable Development Scenario.

Box 2.3 ⊳ Oil and gas investment in the Sustainable Development Scenario

Fossil fuel producers are used to making long-term investment decisions despite the range of uncertainties faced in markets. But the lower demand trajectory of the Sustainable Development Scenario, coupled with a prolonged period of low prices would represent a new set of pervasive risks for the oil and gas industry.

For oil, demand in the Sustainable Development Scenario peaks within the next few years and then falls to just over 50 million barrels per day (mb/d) in 2050 from close to 97 mb/d today. This is an average drop of around 1.4 mb/d every year, but this decline is not spread equally across all sectors. Consumption in sectors where the oil is not combusted and does not produce CO_2 emissions see continued growth in oil use. For example:

- There is a significant increase in plastic recycling rates in the Sustainable Development Scenario (from a global average of 15% today to over 40% in 2050), but oil use as a petrochemical feedstock still grows to almost 15 mb/d in 2050.
- A further 5 mb/d is used in 2050 for non-energy products such as lubricants, bitumen, asphalt and paraffin waxes.

Because of the rise in the relative share of non-emitting[3] uses, the average emissions from using a barrel of oil fall globally by nearly 30% between 2018 and 2050 (these figures exclude emissions from the production, processing and transport of the oil).

Despite these increases, overall oil demand drops on average by 2% every year between 2018 and 2050. This is well short, however, of the decline in production that would occur if all capital investment in currently producing fields were to cease immediately, which would lead to a loss of over 8% of supply each year. If investment were to continue in currently producing fields but no new fields were developed, then

---

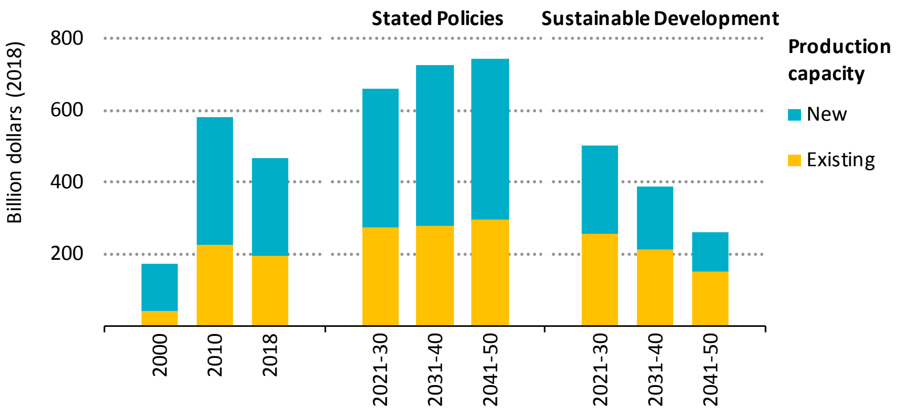
[3] The IPCC 2006 Guidelines for National Greenhouse Gas Inventories as well as the IEA statistics on *CO_2 Emissions from Fuel Combustion 2018* exclude all non-energy use of fuel from energy sector emissions calculations and thus apply a zero emissions factor to oil use as a feedstock (IPCC, 2006; IEA, 2018d).

the average annual loss of supply would be around 4.5%. Continued investment in both new and existing oil fields, even as overall production declines in line with climate goals, is therefore a necessary part of the energy transition envisaged in the Sustainable Development Scenario.

Demand for natural gas grows by around 10% between 2018 and the late 2020s. The rise stems mainly from the need to offset the major drop in coal consumption. Huge increases in generation from variable renewable electricity technologies plug most of the gap left by the decline in coal generation, but increased natural gas use also plays a role. During the 2030s, natural gas consumption falls slowly as it becomes too emissions intensive to be consistent with the emissions reductions required. Decline rates from existing gas fields are similar to those for oil, and investment in new gas assets continues to be necessary even as the use of gas declines (Figure 2.11). Investment in maintaining gas infrastructure is also important as the gas grid helps to support the uptake of low-carbon gases such as biomethane and hydrogen (see Chapter 13).

The need for continuing investment in oil and gas fields in the Sustainable Development Scenario is an important point. However, it is just as important that global decarbonisation plans are fully and clearly integrated into resource development strategies, so that future investment takes account of them and that resources are not developed in the expectation of much higher trajectories for oil and natural gas demand and prices. It is also important that the oil and natural gas industries should minimise the emissions impacts of these fuels to the fullest extent possible. In particular, reducing methane emissions from oil and natural gas operations is an essential component of action to address climate change.

Figure 2.11 ▷ Average annual upstream oil and gas investment in the Stated Policies and Sustainable Development scenarios



Less upstream spending is needed in the Sustainable Development Scenario, but continued investment is still required in new and producing fields

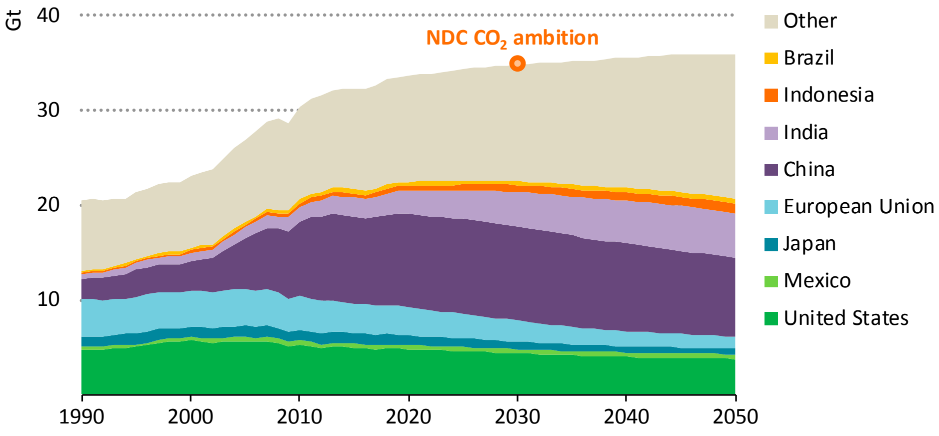
Key themes

2.7 How are we doing?

Status of emissions trajectories

Current country commitments, the Nationally Determined Contributions (NDCs), made under the Paris Agreement and domestic energy policy plans fail to bring about the rapid, far-reaching changes required to avert dangerous and irreversible changes in the global climate system. These are assessed in our Stated Policies Scenario and lead to total global energy-related CO_2 emissions growing steadily from today's levels before plateauing around 36 Gt after the mid-2040s. This trajectory is consistent with limiting the temperature increase to below 2.7 °C above pre-industrial averages with a 50% probability (or below 3.2 °C with 66% probability).

Figure 2.12 ▷ Energy-related CO_2 emissions by region in the Stated Policies Scenario



Emissions are expected to grow slightly and plateau around 2045

Note: NDC = Nationally Determined Contribution.

In the Stated Policies Scenario, trends in emissions see significant regional variations (Figure 2.12). In advanced economies in aggregate they are set to decline by 3.6 Gt to 2050, albeit with rates of reduction varying significantly depending on domestic circumstances. In the European Union they are in steady decline and are on course to be cut by more than half by 2050 under stated policies, reaching 1.3 Gt in 2050 (2.2 Gt in 2030) from 3.1 Gt in 2018. Some countries, such as the United Kingdom, Sweden and France have set very ambitious targets of net carbon neutrality by 2050 or earlier, and a qualified, sector-by-sector interpretation of these targets, which takes into consideration likely barriers to their full realisation, has been incorporated in the Stated Policies Scenario. The European Union's power sector leads the emissions reductions, with generation 90% decarbonised by

2050. Coal phase-out plans, carbon pricing and increasingly competitive renewables all play a role. As the power sector decarbonises it is overtaken by transport as the largest emitter in the next five years. By 2050 it is one of the least emitting sectors. Drops in emissions are also seen in road passenger segments. Emissions also decline in Japan, where they are on course almost to halve compared with today. In the United States, emissions are on a gently declining trend through to 2050 when they reach 3.8 Gt, compared with 4.9 Gt today. Cheaper natural gas and renewables push out coal from the power sector, with its share of generation set to decline from 28% today to 12% in 2050.

Given its stated policies, China's emissions are expected to increase slightly to the late 2020s, reaching a peak of 10 Gt, and then decline to around 8 Gt in 2050. Strong policy support for low-carbon technologies in the power sector, a switch from coal towards electricity and gas for heating in buildings, and a strong push for electrification of vehicles explain this trend. Demographics also play a large role: population is expected to peak and decline on a similar timescale.

In contrast to China, other Asian developing countries in aggregate are expected to increase emissions by more than 4 Gt. Under its stated policies, India would see national CO_2 emissions more than double from 2.3 Gt today to 4.8 Gt in 2050, 3.3 Gt of which would come from coal. Increases are also seen in the Middle East and Africa.

These overall CO_2 trends mask significant differences between particular sectors and technologies. The cost decline in solar and wind and the expected cost decline in offshore wind are transforming the power sector at an unprecedented rate. Power sector emissions remain broadly stable to 2050, while electricity generation almost doubles, as 85% of new additions are low carbon or natural gas. Emissions are also set to decline in the buildings sector by 0.3 Gt as rising electrification offsets oil and coal use, which today account for 15% of energy use in the sector. The road passenger segments see a similar trend with EVs accounting for more than 40% of all sales by 2040 and continued efficiency improvements bringing about a deep decoupling between activity and emissions. However emissions rise in industry (+1 Gt in 2040 compared to today), trucks (+0.6 Gt), aviation and shipping (+0.8 Gt), all contributing to significant emissions growth.

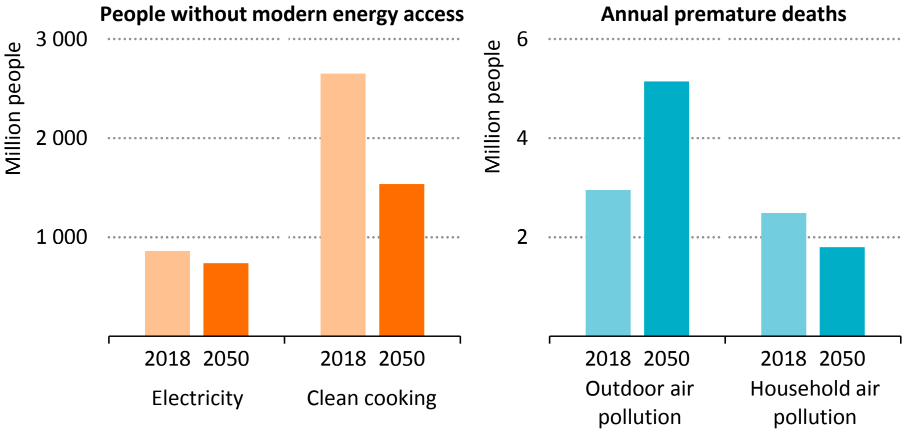
Status of energy access and air pollution

Our latest country-by-country assessment shows that in 2018, the number of people without access to electricity had dropped to 860 million, a record in recent years (Figure 2.13). India continues to make remarkable progress towards its target of universal electrification, with almost 100 million people gaining access in 2018 alone. In March 2019, the government announced that it had provided access to all willing households after connecting 26 million households between October 2017 and March 2019 through the Saubhagya scheme, with 99% of them through the grid. Access to electricity in sub-Saharan Africa remains low, and around 600 million people – more than half of the population – are still without access to electricity. These numbers improve only slightly under current and announced policies: the total number of people without access to electricity reaches

620 million by 2030 and then increases to 740 million by 2050 as progress in expanding electricity access fails to keep pace with population growth.

Progress on access to clean cooking facilities has been gradual and limited compared to progress on electricity access. More than 2.6 billion people continue to rely on the traditional use of biomass, coal or kerosene as their primary cooking fuel. This has damaging consequences for health and productivity, especially for women. The challenge remains particularly acute in sub-Saharan Africa, where less than one-person-in-five has access to clean cooking fuels and technologies. Even though a number of countries, mostly located in developing Asia, have shown signs of improvement in recent years through dedicated policies supporting LPG, there are still 1.5 billion people without access to clean cooking in the Stated Policies Scenario in 2050.

Figure 2.13 ▷ Population without modern energy access and premature deaths due to air pollution in the Stated Policies Scenario, 2018 and 2050



More effort is needed to achieve universal access to modern energy and to bring about major reductions in air pollution

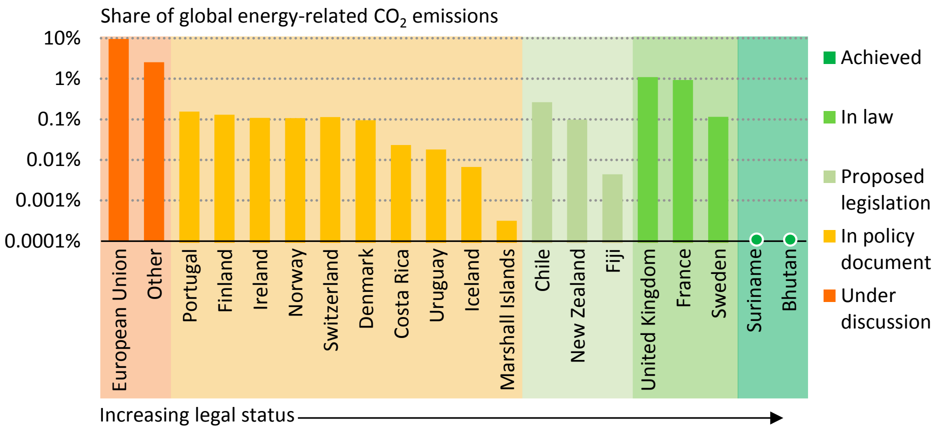
Sources: IIASA and IEA analyses.

The lack of access to clean cooking facilities is directly linked to household air pollution and high numbers of premature deaths. In the Stated Policies Scenario, 1.8 million premature deaths are still linked to pollutant emissions from cooking in 2050. The Stated Policies Scenario leads to some reductions in outdoor air pollution, but these remain insufficient to prevent major threats to human health. Due to the complex relationship between emission levels, atmospheric conditions, exposure levels and timing, the number of premature deaths from outdoor air pollution is actually set to rise to 5 million in 2050.

Recent policy developments

Some governments have recently announced new, more ambitious targets. For example, by the end of September 2019, at least 65 countries, together with the European Union, had set or were actively considering long-term net-zero carbon targets.[4] The economies of these countries together accounted for 21% of global GDP and nearly 13% of emissions in 2018.

Figure 2.14 ▷ Net-zero carbon or GHG emissions reduction announcements



More than 65 jurisdictions accounting for 13% of global CO_2 emissions have announced net-zero CO_2 or GHG emissions commitments for 2050

Notes: The other category includes countries not shown that have recently signalled their intent to put forward net-zero targets (UNFCCC, 2019a). The 13% total share of emissions covers all jurisdictions in the figure, without double counting. Under discussion category means that consultations to develop a net-zero target are ongoing. The policy document category means that a net-zero target has been put forward, however, without legally binding status. The proposed legislation category means that the target has been proposed to parliament to be voted into law. The In law category means that a net-zero target has been approved by parliament and is legally binding. The achieved category means that the jurisdiction absorbs more CO_2 than it emits, e.g. through afforestation. Not included in the figure are the efforts of some state and local entities, such as California, though they would increase the share of emissions covered to over 16%.

Net-zero targets serve an important role in shifting the centre ground of global ambition. By stimulating and testing innovations, regulations and markets that can be replicated elsewhere, they play a role in accelerating progress towards climate targets around the world. This is likely to be particularly the case in hard-to-abate sectors, to which net-zero targets give a clear signal about the need to plan for technological change. As the necessary technologies and business models will take time to develop, first-mover regions - especially those as large as the European Union – will generate vital knowledge. Overall, this

---

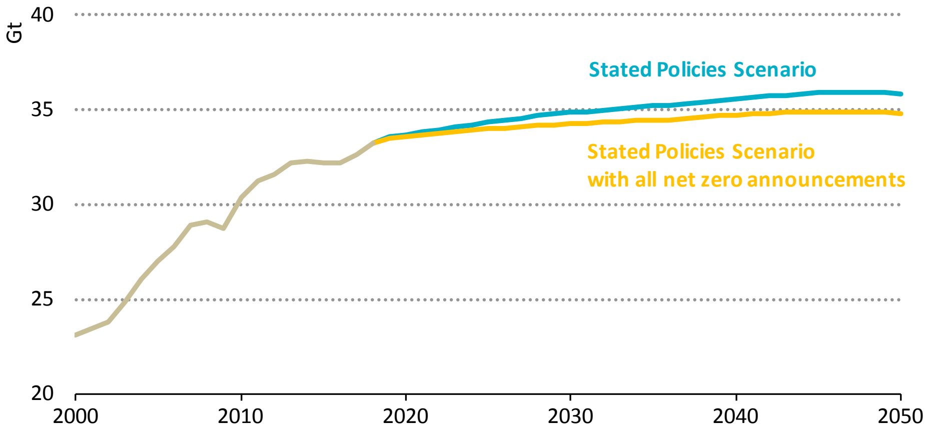
[4] The United Kingdom, Ireland, Fiji, Bhutan and the Marshall Islands have put forward net-zero GHG targets for 2050. It is likely that net-zero CO_2 emissions will be achieved several years before then.

contribution may be as large as the absolute CO_2 reductions that would result from the announcements in Figure 2.14 if all proposals are fully implemented (Figure 2.15).

Non-state actors are also increasingly bringing forward pledges of action. City networks, such as C40[5], account for 2.4 Gt of emissions and are required to have plans to deliver their contribution towards the Paris Agreement. If target setting and actions were to become widespread, these could potentially reduce emissions further given that cities account for 70% of global emissions. Several companies have also announced pledges to make their business compatible with the Paris Agreement. Such pledges can be important because companies can drive innovation and learning. Global shipping giant Maersk has, for example, committed to go carbon neutral by 2050, while the International Maritime Organization reached an agreement in April 2018 calling for a 50% reduction in shipping emissions by 2050, relative to levels in 2008.

Recent years have seen an increased focus on the risks to investment from energy transitions and climate change impacts. The 2019, G20 endorsed, report of the Task Force on Climate Related Financial Disclosure encouraged investors and major asset owners to be more transparent about the risks of: climate change impacts; transition to a low-carbon world; and of litigation. Some jurisdictions have moved to set expectations of greater disclosure of risks. For example, France's recently updated 2017 Value for Climate Action Law required disclosure of transition risks, and the Bank of England in its guidance has encouraged company boards to understand the full range of risks they face.

Figure 2.15 ▷ Effects of including announced net-zero carbon pledges on CO_2 emissions in the Stated Policies Scenario



If all the announced net-zero pledges were implemented by 2050, the direct impact on CO_2 trends would be limited, but the indirect impacts could be significant

---

[5] The C40 Cities Climate Leadership group focuses on reducing GHG emissions from cities as well as reducing risks to the urban environment from climate change.

SPOTLIGHT

Chile's Decarbonisation Plan

Chile will host the United Nations Framework Convention on Climate Change (UNFCCC) climate talks (COP 25) in December 2019, where countries will meet to discuss, among other things, increasing their climate ambition. In advance of COP 25, the president of Chile announced that the country aims to achieve carbon neutrality by 2050. The draft bill has been presented to congress and is expected to receive approval during the climate summit in December. This is a significant increase in ambition compared to the NDC in which Chile committed to reducing the intensity of its emissions relative to its GDP by 30% by 2030 from 2007 levels.

Chile is responsible for less than 1% of global GHG emissions. However, the country is highly vulnerable to changes in climate conditions and ranks among the 16 countries most affected by climate variability (GCRI, 2019). It is home to 82% of Andean glaciers, most of which are in retreat. Highly unusual tornadoes, heatwaves and forest fires are among the other impacts already being felt by Chile (UNFCCC, 2019b).

Among the key actions announced, Chile is planning to phase out coal by 2040 and to generate 70% of electricity from renewables by 2030. Chile's decarbonisation plan focuses on a phase-out of coal in two stages: by 2024, it will close eight of the oldest coal units, which account for 20% of its current coal electricity capacity, and the second stage will phase out the remaining 20 coal units by 2040.

Chile's power generation mix is led by coal, which accounted for 35% of generation in 2018. Hydropower was the second-largest source of electricity, natural gas accounted for 16%, bioenergy for 7%, solar PV for 6% and wind for 5%. Chile has excellent solar and wind resources, and recent competitive tenders brought record low offers for solar PV (at $29 per megawatt-hour). In the Sustainable Development Scenario, the share of renewables generation in Chile expands to almost 80% in 2030 and 94% in 2050, with coal-fired generation phased out by 2040. Chile's strategy is not confined to the power sector; it aims to electrify 40% of the private vehicle fleet and 100% of public urban transport by 2050.

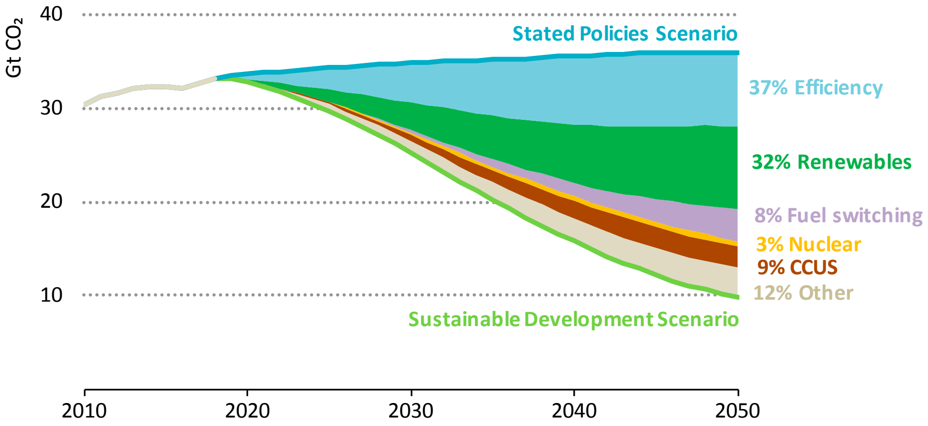
While decarbonising power generation in Chile is within reach, given its large renewable resources and the phase-out plan for coal, additional policies and technologies also will be needed to set end-use sectors, such as industry, on course to meet its stated carbon neutrality goal.

In the Sustainable Development Scenario, policies targeted at the electrification of end-use sectors, the expansion of bioenergy and hydrogen as well as enhanced energy efficiency standards put total emissions from transport and buildings on a declining trend.

2.8 Where do we need to get to?

An energy sector transformation of the scale and pace required to achieve the Sustainable Development Scenario depends upon fundamental changes to the way energy is produced and consumed. This would compel all sectors of the economy to significantly accelerate the uptake of low-carbon technologies, including energy efficiency and renewables as well as nuclear and CCUS (Figure 2.16).

Figure 2.16 ▷ CO_2 emissions reductions by measure in the Sustainable Development Scenario relative to the Stated Policies Scenario



All clean energy technologies are needed in the Sustainable Development Scenario; energy efficiency is the main contributor to emissions savings to 2050

Notes: CCUS = carbon capture, utilisation and storage. Reduced thermal losses in power generation account for 15% of efficiency improvements.

In the Sustainable Development Scenario, the relative contributions of clean energy technologies differ for a variety of reasons, but generally consider least-cost opportunities as well as national circumstances such as the age of the existing capital stock. Energy efficiency is the primary "fuel" of choice in most regions, because of its cost-effectiveness. Energy efficiency measures generally offer an attractive payback, and the barriers to their deployment such as access to finance or lack of information are successfully addressed through policy measures in the Sustainable Development Scenario. No decarbonisation pathway is achievable without rapid and significant deployment of energy efficiency measures. But energy efficiency alone cannot deliver the emissions reductions required for achieving the SDGs. Absent further breakthroughs in energy-efficient technologies beyond what is considered in the Sustainable Development Scenario, energy efficiency alone approximately stabilises global energy-related CO_2 emissions at slightly below 30 Gt by around 2040 and beyond.

The second key option for reducing CO_2 emissions is the deployment of renewables. The cost of solar PV and wind in particular have fallen significantly in recent years and are set to decline further (see Chapter 1). Their deployment in the Sustainable Development Scenario is supported by a host of measures that further strengthens their competitiveness *vis-à-vis* fossil fuel power plants (such as carbon prices) and allows for their successful integration into the power generation mix. The uptake of renewable energy technologies in sectors such as industry and buildings (for heating purposes) and transport (advanced biofuels) has been limited to date, given high costs and lack of sufficiently widespread policy support. Targeted policy measures such as fuel blending mandates and renewable energy quotas are assumed in the Sustainable Development Scenario to overcome these hurdles. In tandem with renewables, the Sustainable Development Scenario sees nuclear energy play an important role in decarbonising the power sector in countries that seek to support its future deployment, especially given the cost-effectiveness of lifetime extensions (Box 2.2).

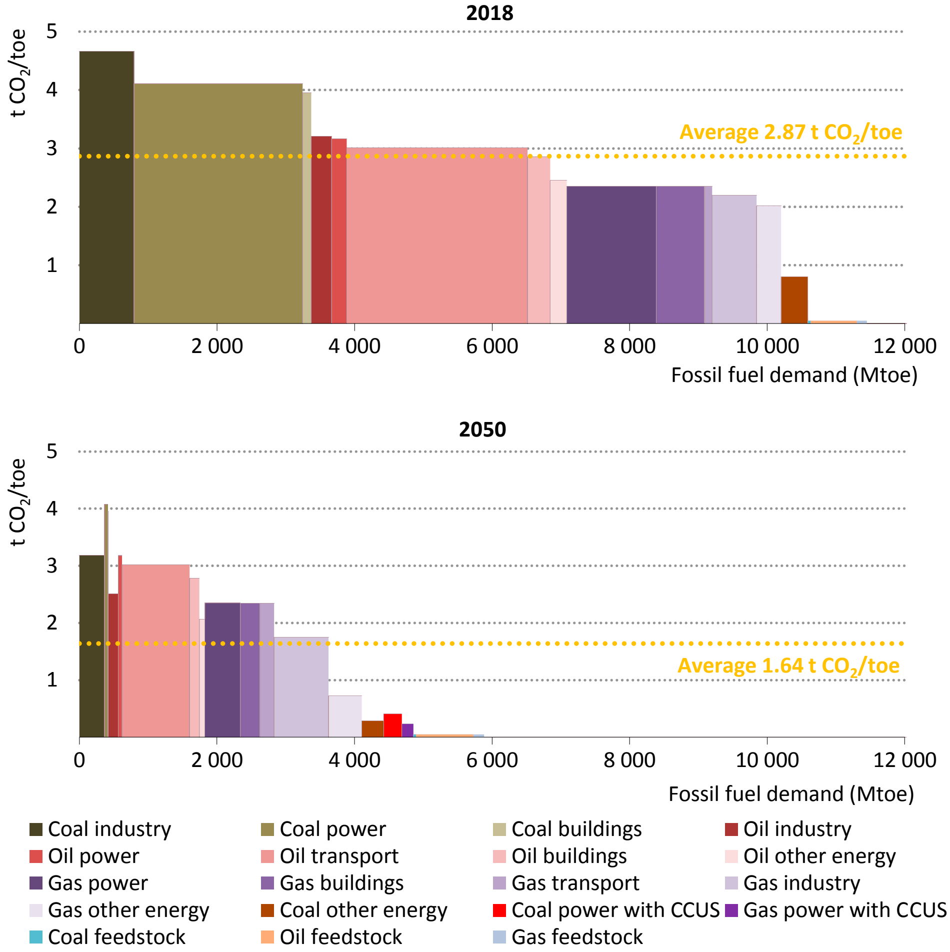
CCUS needs to be more widely deployed in order to capture an annual average of 1.5 Gt CO_2 between 2019-50 to put the world on track to meet the objectives of the Paris Agreement. As the decarbonisation of hard–to-abate sectors becomes more pressing over time, the volume of carbon captured increases to 2.8 Gt in 2050, or 28% of total CO_2 emissions in that year. Governments would have to take steps to enable a framework to foster the uptake of CCUS in order to achieve such levels of captured and stored emissions (IEA, 2017b).

In the Sustainable Development Scenario, CCUS is almost equally split in 2050 between the power and industry sectors (including cement, iron and steel, upstream oil and gas, and refineries). In the power sector, CCUS is concentrated in a handful of countries, most notably China and the United States. Around 215 GW of coal plants are equipped with CCUS by 2050, predominantly in China where the fleet is very young and the potential for CCUS deployment is high. A similar amount of natural gas power plants are equipped with CCUS, led by deployment in the United States where natural gas prices remain low and a young fleet of natural gas plants fitted with CCUS provide cheap and flexible power generation. The use of CCUS in industrial applications is widespread, as emissions from energy-intensive sectors are typically hard-to-abate, and CCUS constitutes one of the few currently available technology options to achieve deep levels of decarbonisation. For example, today the iron and steel sector emits around 2 Gt of emissions each year. Currently, 92% of primary steel is produced in blast furnaces (primarily fuelled by coal) while 7% is produced via the direct reduced iron route (mainly fuelled by natural gas), or in some cases coal (e.g. India). For existing blast furnaces, CCUS is the main decarbonisation option. Similarly, CCUS is the main option under consideration in the cement sector, where process emissions account for two-thirds of the 2.5 Gt CO_2 the sub-sector emits today (IEA, 2018a).

The net result of these changes is a shift in the way energy is produced and consumed (Figure 2.17). Emissions of CO_2 from coal drop by 90% in 2050 in the Sustainable Development Scenario compared to today, and those that remain mostly stem from the iron and steel and cement sub-sectors. Oil is the main source of remaining CO_2 emissions in the transport sector, despite strong inroads made by electrified cars (including electric and hydrogen fuel cell cars) which make up three-quarters of the global car fleet by 2050, about

1.3 billion cars. Among the main contributors to transport-related emissions in 2050 in the Sustainable Development Scenario are trucks, airplanes and ships: modes for which key alternatives to oil such as clean hydrogen or advanced biodiesel and bio-kerosene are not yet available at commercial scale. Demand for natural gas hovers just over 4 000 bcm throughout much of the 2030s as significant near-term reductions of methane emissions from natural gas production further enhance its ability to contribute to bringing down CO_2 emissions by switching away from coal (see Chapter 4). However, from the late 2030s, natural gas demand falls away, and its use is increasingly concentrated in industrial sub-sectors (e.g. petrochemicals) as well as non-energy intensive sectors.

Figure 2.17 ▷ Global fossil fuel demand by CO_2 content in the Sustainable Development Scenario, 2018 and 2050

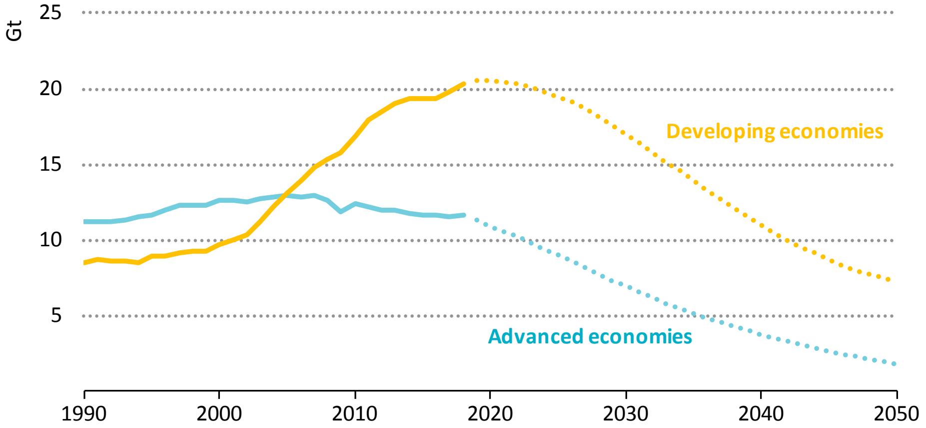


Overall fossil fuel use shrinks by half, with higher emitting fuels being most affected

Notes: t CO_2/toe = tonnes of carbon dioxide per tonne of oil equivalent; CCUS = carbon capture, utilisation and storage. Fossil fuel demand does not include demand from agriculture.

The Sustainable Development Scenario assumes that all countries immediately significantly scale up their clean energy ambitions. That does not mean that emissions in all countries peak at the same time. Aggregate CO_2 emissions from advanced economies have already peaked; emissions in advanced economies have fallen by 0.8% per year on average since 2010 (Figure 2.18). In the Sustainable Development Scenario, the pace of decline accelerates to 5.6% per year through to 2050. In developing economies, emissions have increased on average by 2.3% per year since 2010. In the Sustainable Development Scenario, they peak in aggregate by around 2020 even if some regions (such as India and Southeast Asia) would not be expected to reach peak emissions until later; emissions in developing economies fall by 3.2% on average per year through to 2050.

Figure 2.18 ▷ CO_2 emissions in advanced and developing economies in the Sustainable Development Scenario



All countries accelerate their clean energy transitions, with the timing of the peak in their emissions depending on each individual country's particular circumstances

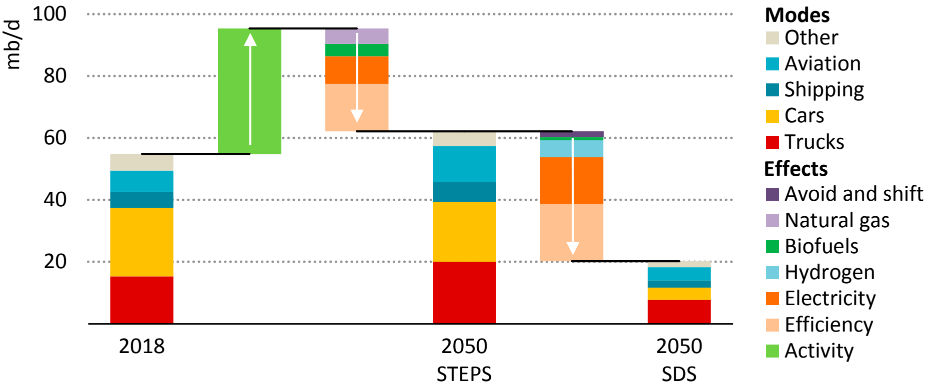
A closer look at the transformation by sector

The pace at which energy sectors decarbonise in the Sustainable Development Scenario differs widely, reflecting the availability, scale and cost-competitiveness of low-carbon technology options by sector. The **power sector** far and away shows the steepest decline in emissions in the Sustainable Development Scenario; CO_2 emissions fall by around 90% until 2050, relative to today, reflecting the scale up in the use of renewables and nuclear, which are commercially available today. The clean energy transition in the end-use sectors is more complex given its diversity and the number of actors involved. In this section, we describe the main transformational changes involved in the pathway described by the Sustainable Development Scenario.

The **transport sector** sees significant growth in activity to 2050, particularly for trucks (120% increased activity) and aviation (200%). Even with the rise in activity, CO_2 emissions in the transport sector decline by around 60% to 3.5 Gt by 2050 in the Sustainable

Development Scenario, relative to today (Figure 2.19). The transport sector is the second-largest contributor to overall emissions reductions, but given the fast pace of decline in the power sector, transport becomes the largest source of CO_2 emissions by the early 2030s. By 2050, transport constitutes 35% of global energy-related CO_2 emissions, compared with 25% today. Around 60% of the emissions reductions are from passenger cars alone due to the combined effects of incentivising the use of public transport, significantly enhancing the efficiency of conventional road vehicles and increasing electrification. Electrifying the global car fleet leads to its decarbonisation given that 94% of electricity is generated from low-carbon sources in the Sustainable Development Scenario by the middle of the century (Box 2.4).

Figure 2.19 ⊳ Oil demand in transport by mode (left) **and change in transport energy use by scenario in 2050 relative to today**



Oil demand in transport falls to 20 mb/d by 2050 in the Sustainable Development Scenario and increasingly concentrates in transport modes where low-carbon options are limited

By 2050, there are around 10% fewer cars on the road than in the Stated Policies Scenario, due to a modal shift from private vehicles to public transport. Three-out-of-four cars still on the road are electrified (including electric cars, plug-in hybrids and fuel cell cars). The remaining conventional vehicles are around 50% more efficient than today, broadly representing what is technically achievable including through hybridisation. Oil demand from passenger cars is already set to decline under stated policies (see Chapter 3). Yet the decline required to meet the objectives of the Sustainable Development Scenario is much steeper: oil demand from passenger cars is around 15 mb/d lower by 2050 than in the Stated Policies Scenario.

Emissions reductions across other transport modes are more modest, owing partly to the more limited suite of commercially available low-carbon options today (especially for trucks, ships and airplanes), but also to the limited amount of CO_2 emissions related to the use of other transport modes. For example, two/three-wheelers are nearly entirely electrified by 2050 in the Sustainable Development Scenario, and so are around 40% of buses. Today their aggregate contribution to transport emissions is around 10% and so the impact of these transitions, although important, is much smaller than for other modes of transport.

The slower pace of emissions decline in trucks, ships and airplanes does not mean that a clean energy transition is absent in these areas in the Sustainable Development Scenario. By 2050, trucks are close to 50% more efficient on average; ships use about 60% less fuel to transport a tonne of goods a kilometre, and airplanes use about 60% less fuel per revenue passenger-kilometre. Alternative fuels make inroads as well, in particular advanced biofuels. In aviation, around 60% of global fuel use in 2050 is bio-kerosene; in shipping, more than one-third of fuel use is advanced biodiesel by 2050, and around 20% is natural gas, hydrogen and hydrogen-based fuels. In aggregate, emissions in these three transport modes fall by 43% to 2050, relative to today, with the largest contribution from trucks (55%), with shipping (25%) and aviation (20%) making significant contributions as well. The emissions reductions in shipping are in line with the targets of the International Maritime Organization.

Box 2.4 ⊳ How clean is your car?

The fuel economy of new cars improved in all regions during the last decade, and while their stringency varies, fuel economy standards today cover around 85% of global car sales. While cars within each segment are becoming more efficient, a slowdown in the rate of global average improvement has been recorded over the last three years, caused in part by the boom in sports utility vehicle (SUV) ownership (see Chapter 3, section 3.9).

In the Sustainable Development Scenario, a conventional car sold in 2050 consumes around half the energy of one sold today, as the technical potential for fuel efficiency improvements in internal combustion engines (ICEs) is maximised. Gains in fuel efficiency make an even larger contribution to curbing oil demand than the expansion of EVs.

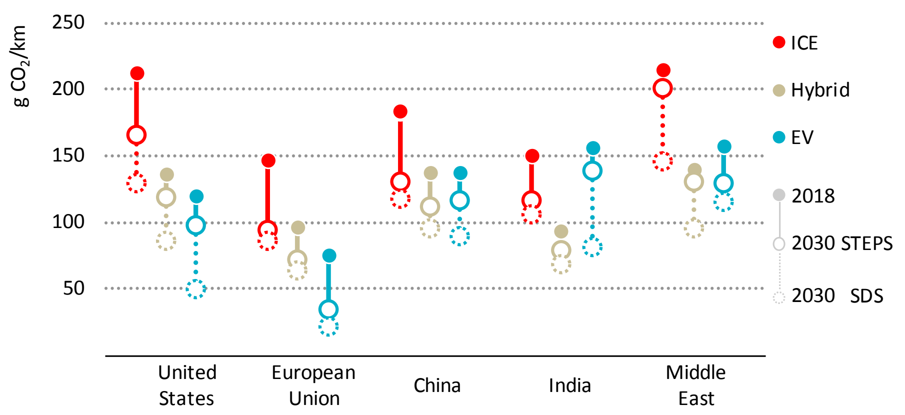
Efficient hybrid petrol cars available on the market today emit nearly 110 g CO_2/km, while EVs running on electricity with carbon intensity[6] close to 600 g CO_2/kWh emit around 130 g CO_2/km (Figure 2.20). The difference in terms of emissions is marginal in regions where coal- or oil-fired plants are the dominant sources of electricity generation. In the Stated Policies Scenario, nearly half of car sales take place in markets in which the gains are less than 10 g CO_2/km by 2030.

Strategies that tap both the remaining potential for improvements in ICEs and the deployment of EVs while decarbonising power will be key to meet the Paris Agreement goals. EV deployment requires strong inter-sectoral co-ordination to maximise emissions abatement such as smart-charging (see Chapter 7, section 7.6).

---

[6] For comparison, today's global average intensity of the power sector is 475 g CO_2/kWh.

Figure 2.20 ▷ **Carbon emissions of different car powertrains by region**



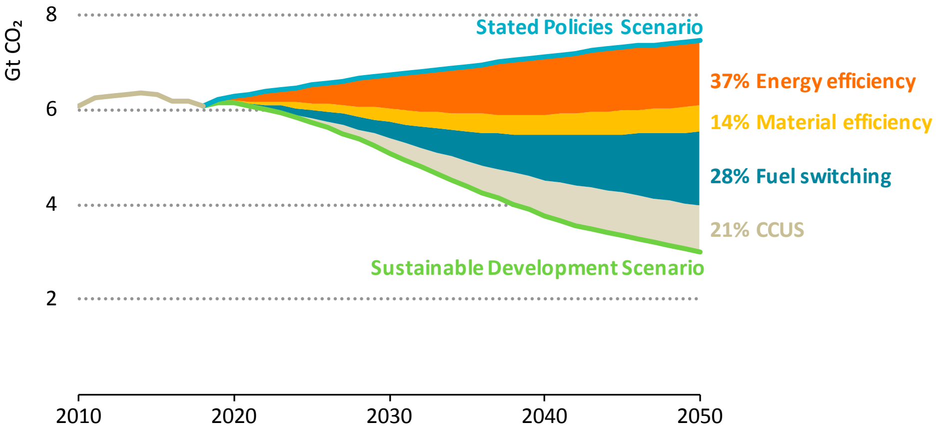
The relative carbon footprint of ICE versus electric cars strongly depends on the power sector mix

Note: EV = electric vehicle; ICE = internal combustion engine; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

In the **industry sector**, emissions from the combustion of fossil fuels decline by around 50% to 3.0 Gt in 2050, relative to today (Figure 2.21). Emissions related to industrial processes (mostly cement production) decline by nearly 40% to around 1.4 Gt in 2050. The majority of the overall emissions savings (i.e. process and energy-related) are from the production of cement, iron and steel and petrochemicals; energy-intensive industries that together account for around two-thirds of total industry sector CO_2 emissions today. Because the transport sector electrifies more quickly than the industry sector, the relative contribution of the industry sector to global energy- and process-related CO_2 emissions rises from 25% today to nearly 40% by 2050 due to the rapid decarbonisation of power.

A variety of technology opportunities are being deployed to achieve the projected emissions reductions. The largest near-term options are in energy efficiency, material efficiency and fuel switching. Energy efficiency and fuel switching account for 37% and 28% of emissions reductions in industry. They reduce oil and coal consumption by almost a third in 2050, with electricity, natural gas and bioenergy stepping in as substitutes and some use of hydrogen in the iron and steel industries, where pilot projects start around the mid-2020s. In light industry sub-sectors and chemicals, process heat requirements in the low-temperature segment allow for high shares of electrification and fuel switching at reasonable cost, for instance through the use of heat pumps. In China, for example, a marked shift to electricity in light industries helps cut coal use in industry by almost 80% in 2050, relative to today. In 2050, electricity accounts for half of industrial end-use energy demand in China, almost double the share of today.

Figure 2.21 ▻ Savings in energy-related CO_2 emissions in industry by measure and scenario



The industry sector is slow to decarbonise given the long lifetime of its capital stock; energy efficiency, material efficiency and fuel switching make the most difference in the near term

Notes: CCUS = carbon capture, utilisation and storage. Excludes all fuel transformation and industrial process emissions.

Material efficiency in the industry sector contributes around 14% of cumulative emissions reductions in the Sustainable Development Scenario, relative to the Stated Policies Scenario (see Chapter 7). Material efficiency stems from a variety of sources; it comprises direct strategies such as reducing yield losses and other process improvements in the aluminium and iron and steel sub-sectors. Yet, the majority of savings come from systemic strategies across the energy sector (IEA, 2019c). For example, in the Sustainable Development Scenario, iron and steel demand in 2050 is 15% less than in the Stated Policies Scenario as a result of lightweighting strategies for reducing the fuel consumption of cars and trucks and of lifetime extension for capital stock in the buildings and power sectors; in the chemicals sector, recycling reduces the need to produce plastics.

As discussed, a clean energy transition in the industry sector at the pace and scale depicted in the Sustainable Development Scenario is very difficult to envisage without the use of CCUS given the long lifespans of much of the capital stock and related lock-in effects, as well as the general absence of commercially available alternatives. In the Sustainable Development Scenario, about 1 Gt CO_2 from the combustion of fossil fuels is captured in the industry sector in 2050, and a further 0.7 Gt from process-related emissions, on the assumption that price uncertainties are effectively addressed by governments (IEA, 2017b). The majority of total CO_2 capture in the industry sector is in cement production with much of the remainder in iron and steel production. Additional CO_2 capture occurs in the refining sub-sector, and in oil and gas extraction.

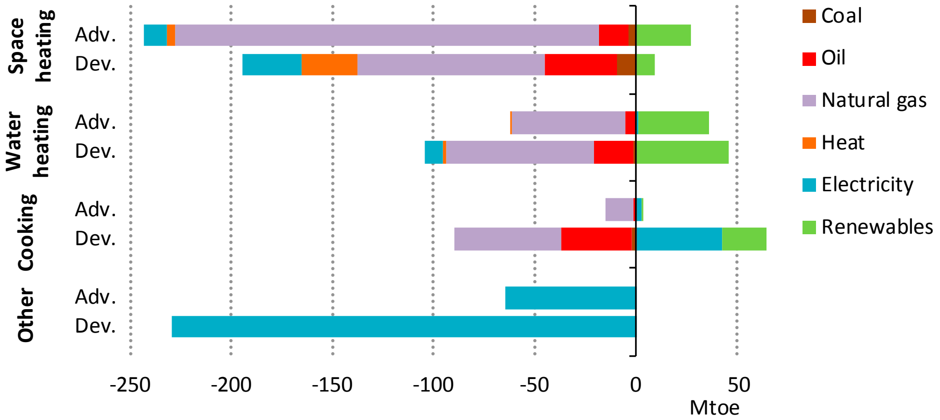
Direct CO_2 emissions from the **buildings sector** fall from 3.1 Gt today to 1.1 Gt in 2050 in the Sustainable Development Scenario, two-thirds of which are in the residential sector. Emissions from the production of electricity and heat used in buildings, the largest source of buildings-related CO_2 emissions today, fall by 5.7 Gt (around 85%) due to the fast pace of power sector decarbonisation. In aggregate, this means that by 2050 direct and indirect emissions from the buildings sector account for just one-fifth of global energy-related CO_2 emissions, compared to a third today.

The rapid decline in CO_2 emissions from the buildings sector in the Sustainable Development Scenario should not hide the significance of the challenge. Unlike in some other sectors, there is no lack of viable technological and economic options that are generally available to the market today. The complexity of the transition to low-emissions in the buildings sector relates to the large variety of actors involved, the split incentives they face and the complexity of considerations involved. In the Sustainable Development Scenario, a host of policies are introduced to facilitate the transition to clean energy use in buildings, with energy efficiency being the most prominent. The rate of renovations of buildings rises to about 4% per year through to 2050, compared with less than 1% today (and around 2% in the Stated Policies Scenario), helping to curb demand for space heating and cooling.

As a result of these renovations and stringent minimum energy performance standards (MEPS), electricity demand for cooling – a major driver of electricity demand growth in the buildings sector today – is over 30% lower by 2050 than in the Stated Policies Scenario. This decline is achieved despite the increased need for cooling associated with rising global temperatures. Overall energy demand for space and water heating is lowered by a similar rate. More efficient refrigerators, cleaning appliances, TVs and computers, light bulbs and appliances further help to curb energy demand in buildings. Overall, energy demand from the buildings sector falls steadily through efficiency improvements, and is around 10% lower by 2050 than today, despite supporting a projected total floor space that is a two-thirds larger than today and a level of GDP per capita that is twice as large.

The decrease in energy demand in buildings in the Sustainable Development Scenario comes with a change in the way energy demand is satisfied (Figure 2.22). Worldwide, the use of coal in buildings, most of which is linked to space heating in China today, all but disappears by 2050, further accelerating a trend that is already reflected in the Stated Policies Scenario. Demand for oil in the buildings sector also declines rapidly in the Sustainable Development Scenario as its use for space and water heating (the source of 70% of oil demand in buildings today) declines by three-quarters to 2050. Oil demand for cooking (much of the remaining use of oil in buildings today) roughly stabilises at today's level. Oil use for cooking is nearly phased out by 2050 in advanced economies in the Sustainable Development Scenario, but remains an important means of providing access to clean cooking in developing countries. Around 2.3 mb/d of oil are still used for cooking purposes in 2050 in the Sustainable Development Scenario, mostly in the form of LPG, and mostly in Africa, India, Southeast Asia and Latin America.

Figure 2.22 ▷ **Change in energy demand by end-use in the buildings sector in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2050**



Sustainable Development Scenario sees significant improvements in buildings efficiency as well as fuel switching; gas is the hardest hit, with demand cut by two-thirds

Note: Adv = advanced economies; Dev = developing economies.

The use of natural gas in buildings in 2050 is cut by 60% in the Sustainable Development Scenario, relative to today. Demand for space and water heating – at more than 80% the primary source of gas demand in buildings today – contracts by 75% to 2050 as a result of both reduced overall demand (through improved buildings insulation) and a shift to electric heat pumps. The use of gas for cooking purposes also falls by around 25%. As with oil for cooking, the use of gas for cooking is increasingly concentrated in developing countries. The use of gas for desalination provides access to clean water in the Sustainable Development Scenario and is the only growth area for natural gas in the services portion of the buildings sector; three-times more gas is used for desalination in 2050 than today.

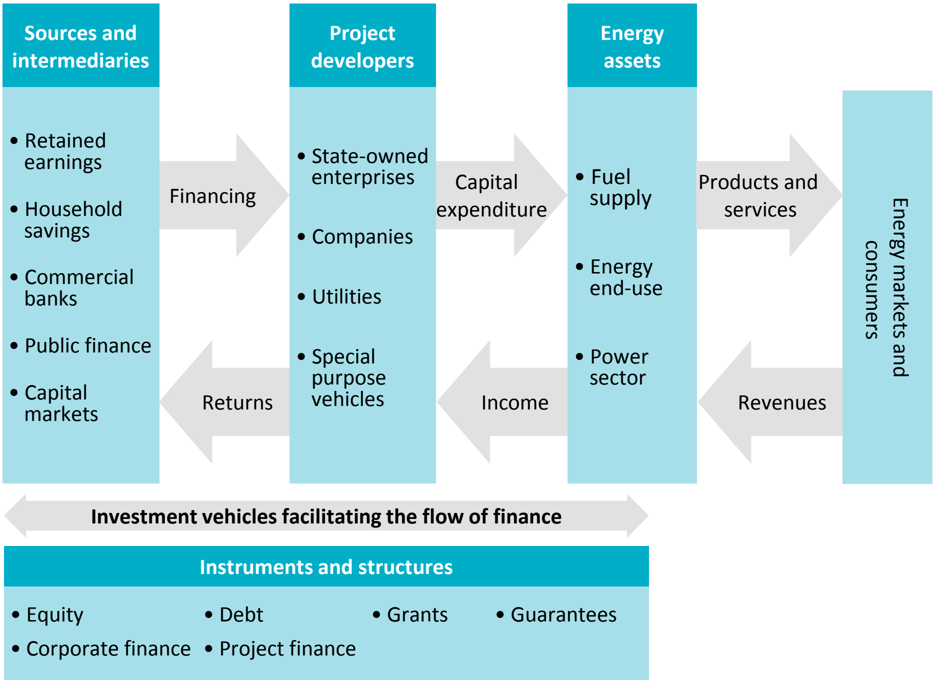
Electricity is the primary means for decarbonising the buildings sector. At 19 000 TWh, electricity demand from buildings in 2050 in the Sustainable Development Scenario is around 3 000 TWh lower than in the Stated Policies Scenario thanks to stringent MEPS for appliances and cooling equipment. But its use is much more widespread: in 2050, electricity demand accounts for nearly 60% of all energy use in buildings, more than ten percentage points above the level of the Stated Policies Scenario. Electricity becomes the primary source for space and water heating as well as cooking, breaking into the long-held domain of oil and natural gas. In developing countries, the achievement of full electricity access by 2030 further boosts electricity demand.

How to finance the Sustainable Development Scenario?

Investment in clean energy assets would need to rise substantially to meet the goals of the Sustainable Development Scenario, which require nearly $115 trillion of investments over the next three decades. This is around 25% more than in the Stated Policies Scenario. While energy investment as a share of GDP rises initially in the Sustainable Development Scenario, it falls to close to 1.3% by 2050, comparable to today's level, and there are additional operational savings in terms of reduced fuel spending. With greater emphasis on capital-intensive low-carbon assets, the Sustainable Development Scenario is more sensitive to the cost of capital than the Stated Policies Scenario, so factors affecting financing play a more important role in the pace and affordability of the transition.

In the Sustainable Development Scenario, governments play an increasingly important role in influencing the overall institutional, regulatory and market environment, and this influences the willingness and ability of the financial community and industry to mobilise clean energy investment at scale. Some jurisdictions, notably in Europe, are starting to address these challenges in a more holistic way, with policy linkages between the energy and finance sectors. There are particular challenges in developing economies, where investment can be affected by the structure and maturity of local financial sectors and by perceived risks.

Figure 2.23 ▻ Financial flows in energy investment



Financial pathways to a more sustainable energy system are multifaceted, involving a range of actors and vehicles at different stages of the investment value chain

How a particular investment is financed depends on the business model of the developer, the source of funds, the available financial instruments and the risk-return profile of the asset, among other factors, all of which impact the cost of capital. The framework in Figure 2.23 shows project developers as the primary actors investing in energy assets, but their success depends on a having robust inter-connected system of secondary financial sources and intermediaries, diverse investment vehicles to facilitate flows and clear signals for action, based on profit expectations and risk profile.

There is substantial investor appetite for more sustainable investments. As the financial community increasingly seeks strategies for allocating capital in way that is consistent with the SDGs, green bond issuance has surged to $650 billion cumulatively since 2007. Actors are paying more attention to climate-related risks and institutions responsible for trillions of dollars in investment funds have announced divestments from fossil fuel holdings.

These trends and ambitions raise fundamental questions about potential trade-offs between increased financing for sustainable energy and long-term returns, and about potential new risks and financing models investors will need to navigate along the way. Another key uncertainty is the extent to which current investors have the necessary skills, incentives and products to fund the clean energy transition adequately. While low-carbon projects vary considerably in terms of risk profile, lead times, useful life and level of complexity, they tend to raise several common key issues (Table 2.2).

Table 2.2 ▷ Key financing issues in the Sustainable Development Scenario

	Potential challenges	Potential options
Managing risks for low-carbon power and infrastructure	Risk-return profiles for renewables and flexible assets with changing government support.	Financial strategies (e.g. insurance, contracts, hedging instruments), beyond subsidies, to manage potential exposure to short-term market pricing (in competitive markets).
Attracting capital to developing economies	Underdeveloped financial systems, investment risks and high cost of capital.	Provision of low-cost debt and guarantees from public sources coupled with reforms that reduce risks and crowd-in private capital (in regulated markets).
Financing efficiency and distributed resources	Small transaction sizes, limited consumer balance sheets and complex cash flow evaluation based on energy savings.	Repayment through energy bills or property taxes, pay-for-performance markets and third-party finance from energy service companies, plus better measurement and verification.
Broader participation of capital markets	Limited routes and higher transaction costs for direct investment in projects by institutional investors.	Aggregation of projects from the balance sheets of developers into portfolios that can be securitised and issued as debt or equity.

First, the risk and return profiles of low-carbon investment mostly differ considerably from fossil fuels, raising questions over the willingness of traditional developers to shift capital allocations based on pure profit motives. Over time, the top oil and gas companies have earned, on average, higher returns on invested capital than the power companies who have led investment in solar PV and wind (IEA, 2019d). Lower risk – due to policy frameworks that have supported revenue certainty for renewables and grids – has partly compensated for lower returns in the power sector. There are however questions over how these policies will evolve and what this might mean for risk allocation between public and private actors. A balance of continued government support and increased use of more market-based solutions to manage risk will probably be required for there to be enough capital for the renewable energy and flexibility investments foreseen in the Sustainable Development Scenario.

Second, power investment depends on risk perceptions and the capacity and willingness of banks to make available long-term, low-cost debt. In Europe, a combination of supportive long-term policies, improved technology, participation of public finance institutions to reassure private investors and low interest rates has helped to halve debt costs for offshore wind (see Chapter 14). In India, similar dynamics have improved the confidence of banks to lend at lower rates for renewables (Box 2.5). However, new challenges are emerging to securing bank debt, which is less able to absorb uncertainty and market volatility than equity finance. Large project sizes and persistent risks make financing nuclear increasingly difficult without state-backed capital or guarantees (IEA, 2019b). Battery storage costs have fallen considerably, but few banks are willing to lend without a long-term capacity contract due to the complexity of the revenue model. As newer technologies (e.g. CCUS, hydrogen) enter the mix, financiers will need to continually navigate new risks and revenue models.

Third, in emerging economies, domestic banking constraints make the facilitation of domestic capital markets and the attraction of international capital particularly important. Domestic public finance institutions in China have made ample low-cost financing available for a range of technologies, but few countries have such balance sheets. Moreover, the provision of attractively priced public finance is often most effective when coupled with reforms that simultaneously crowd-in private sources. In South Africa, the implementation of a transparent framework for competitive procurement for renewables has been successful in attracting considerable finance from private international lenders, but there has been less activity in other sub-Saharan Africa markets without the involvement of debt or guarantees from development banks or governments (see Chapter 10).

Box 2.5 ▷ Improved risk perceptions and financing for renewables in India[7]

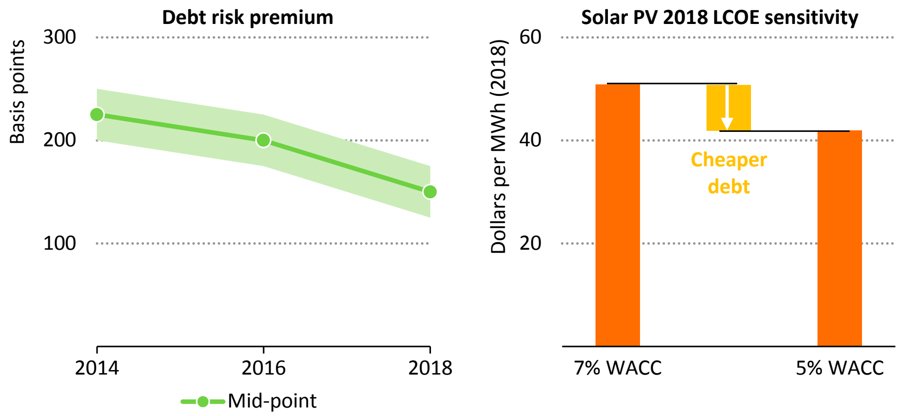
India’s renewable power investment has doubled over the past five years, reaching nearly $20 billion in 2018, and now exceeds that for coal power. Ambitious targets, supportive policies with competitive bidding and falling costs have lowered risks for investors and led to reductions in power purchasing tariffs for utility-scale solar PV and wind. Better financing terms also played a key role. Domestic banking rules force renewables, coal and gas power to compete for the same pool of debt finance (all categorised as power sector lending, with exposures capped by the central bank), which makes risk perceptions central to determining the share of capital flowing to renewables.

---

[7] This analysis has been developed in collaboration with the Council on Energy, Environment and Water (CEEW), Centre for Energy Finance in New Delhi. For further information, see CEEW and IEA (2019f).

An analysis of final investment decisions on solar PV and wind projects between 2014 and 2018 shows improvements in key risk parameters. Banks have been willing to fund projects with more debt-heavy capital structures, and have offered longer duration loans. The debt risk premium to benchmark bank lending rates has come down by around 75 basis points (Figure 2.24). Combined with lower economy-wide interest rates, improved debt financing makes over a 15% difference to the levelised cost of electricity (LCOE) for solar PV. Future financing cost pathways continue to have an impact on electricity prices and the affordability of the transition in the power sector (see Chapter 6).

Figure 2.24 ▷ **Evolution of debt risk premiums for solar PV and wind in India and sensitivity of solar PV LCOE 2018 to debt financing**



Risk perceptions and debt financing terms have improved for solar PV and wind in India, enabling investment in energy transition at lower costs

Notes: LCOE = levelised cost of electricity; WACC = weighted average cost of capital. The debt risk premium is the excess interest charged by banks over benchmark rates, reflecting the risks to a specific project or company. The LCOE is expressed in real terms and the sensitivity analysis assumes constant capital cost levels at $796 per kilowatt (average of commissioned plants in 2018) and capacity factor of 19%, with only the cost of debt and capital structure varying, which results in a 4.7% WACC compared with 7.0% under base assumptions.

Sources: Debt risk premiums are based on CEEW and IEA (2019f); LCOEs are based on IEA analysis.

Financing the clean energy transition also requires more focus on investments made at the consumer level, which tend to be much smaller and depend on the creditworthiness of households and small and medium-size enterprises. Traditional financing approaches can make an impact here – for example, the size of outstanding auto loans in the United States would support the purchase of 20 million EVs. However, additional measures may be needed to encourage the turnover of the capital stock in line with sustainability goals, while also balancing potential economic risks from consumers potentially taking on too much debt.

Obtaining finance for efficiency measures in the buildings and industry sectors is a bigger difficulty, given the challenge for banks to evaluate financial models based on energy savings. Measures that improve capital recovery, help improve the risk profile of investments. In 20 US states it is now possible to make repayments on upgrades through electricity bills or property taxes. Commercial arrangements with developers, such as energy service companies, provide an additional channel, which is strongest when backed by energy savings and performance guarantees. Pay-for-performance markets are emerging in California and other US states, where programme administrators (e.g. utilities) offer incentives (that help reduce cash flow risks) to customers or project developers in exchange for energy savings measured during pre-agreed periods, though the attractiveness of this practice depends on the ability of the project implementer to manage and insure against potential performance risks.

In terms of financing energy access, pay-as-you-go models for solar home systems – supported by digital finance – have facilitated access for electricity in East Africa by addressing creditworthiness concerns for a class of consumers with severe balance sheet constraints (see Chapter 10).

Newer financial solutions will need to be scaled up to crowd-in larger pools of capital. The aggregation of small-scale projects from the balance sheets of developers into portfolios that can be securitised, i.e. issued as debt or equity in the capital markets, can spread the risks among more investors and reduce financing costs However, structuring and evaluating the credit profiles of diverse small-scale assets remains challenging, and requires further co-operation between developers, banks and ratings agencies.

Investors such as pension funds and insurance companies can provide long-term capital at lower cost than developers and banks. Their demand for vehicles such as green bonds continues to rise as investors and companies pay more attention to climate-related risks in their companies. Some of these investors have also been particularly active in announcing financial restrictions on investment in fossil fuel assets, particularly coal (see Chapter 5).

Governments will play a fundamental role in setting the policies and regulations that influence who invests and the risks and returns that shape the allocation of energy capital: around 40% of energy capital is in any case owned by state-owned enterprises (IEA, 2018b). Policy makers also set the broader financial rules, and some countries are trying to facilitate financial decision making that supports the sustainable energy transition. For example, the United Kingdom issued a Green Finance Strategy in 2019 that seeks to align investment decision making with sustainability through a combination of long-term policy frameworks, new financial standards and products, and better industry analytics. The European Union has meanwhile proposed legislation seeking to channel private sector investment into sustainable development through better classification of aligned economic activities, enhanced corporate disclosure and development of benchmarks for investors. However the appropriate balance between private investment and state-directed capital mobilisation remains an area of debate, with calls in some quarters for states to play a more direct role in financial pump-priming and directing energy capital in order to achieve deeper levels of decarbonisation.

Which technology portfolio for the Sustainable Development Scenario?

The energy sector is technology-intensive, and it has passed through several innovation-led transformations in the last two centuries. We are now entering a new phase of technology-driven transformation propelled by advances in digital technologies, mass manufacturing and environmental awareness. Meeting the goals of the Sustainable Development Scenario will require the deployment of a range of technologies, some of which may evolve rapidly in this new phase. The markets for these technologies will be largely shaped by policy goals, which means that governments have a central role to play.

History tells us that the adoption of new technologies takes time. Experience shows that it can take two to three decades to move from first commercialisation of energy technologies to 2.5-3% market share, and more decades to reach maximum deployment (Bento, Wilson and Anadon, 2018; Gross et al., 2015). It took almost 25 years from the introduction of the first market-based feed-in tariff for renewable electricity to reach the point where solar PV made up 1% of global electricity output. Fortunately, most of the clean energy technologies deployed in the Sustainable Development Scenario are already well established. Many of the technologies that play a major role over the outlook period can be directly traced back to the 1950s. In that decade, gas turbines, hydraulic fracturing, liquefied natural gas (LNG), nuclear, solar PV and three-bladed alternating current wind turbines all made their debuts on the energy scene. The primary focus therefore is on how to accelerate their market uptake and improve performance and costs in the most efficient manner.

Table 2.3 ▷ Examples of technologies that scale from low levels today to over 3% market share in the Sustainable Development Scenario

	By 2030	After 2030
Liquids supply	Bio-liquids (jet fuel, diesel and gasoline)	CCUS on refinery hydrogen supply.
Natural gas supply	Remote, continuous methane leak detection	Biomass gasification. Clean hydrogen in gas supply to buildings.
Power generation and supply	Solar PV Smart meters	Small modular nuclear reactors. Battery storage. Biomass-fired power generation.
Buildings	Heat pumps Near-zero emissions buildings Home biogas digesters for clean cooking	Hydrogen fuel cells and boilers.
Transport	Electric cars and trucks	Alternative drivetrains for ships. Hydrogen-powered heavy trucks.
Industry	CCUS for iron and steel and cement	Electrolytic hydrogen feedstock for industrial processes. Heat pumps for industrial heat.

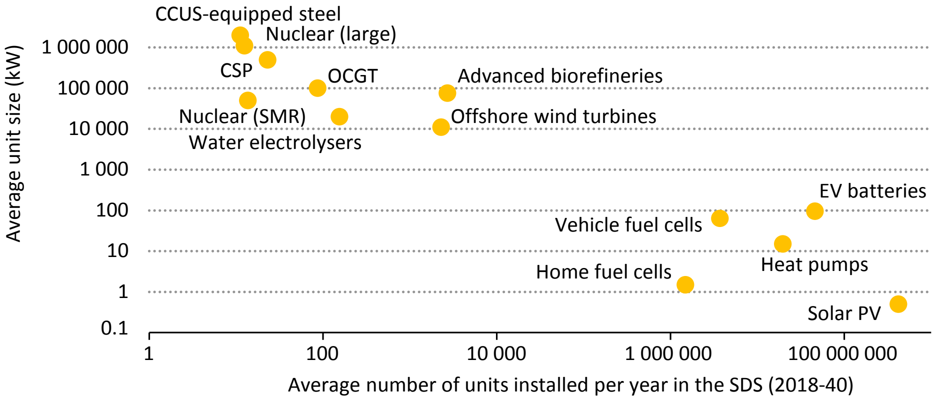
Notes: Market share defined as share of global sales or additions of equipment for the provision of equivalent energy services. For CCUS and hydrogen supply, shares refer to the emissions captured and gas delivered.

Of the critical clean energy technologies required to meet the Sustainable Development Scenario, only 7 of 45 are “on track” in terms of deployment, indicating the need for performance and cost improvements (IEA, 2019e). The next 30 years will witness dramatic improvements in a wide variety of energy technologies, many of which have components still in the laboratory today. Most will result in incremental changes to existing ways of doing things, but some could lead to radical and barely foreseeable new approaches. In the Sustainable Development Scenario, a number of key technologies move from very low levels of market penetration today to widespread commercialisation in the next decade, and in subsequent years (Table 2.3). As they do so, their costs decline in line with learning rates. A few of the technologies deployed in the Sustainable Development Scenario have not yet been commercialised, for example steel smelting with integrated CCUS and low-carbon cement production. However, the Sustainable Development Scenario does not assume any breakthroughs that would lead to deployment of technologies that have not yet been demonstrated.

The technologies that need to be improved and costs reduced throughout the Sustainable Development Scenario period have very diverse characteristics. They range from the physical sizes of individual units and the types of owners or operators to the types of materials and engineering involved. New nuclear designs, CCUS and low-carbon industrial processes are similar in many ways to the types of technologies that have dominated energy supply over the past century: each unit is designed for 50 megawatts (MW) to 2 GW of energy throughput; deployment is up to around 50 units per year; and much of the innovation is in materials and chemical engineering. In contrast, fuel cell, battery and solar PV units are designed for energy throughput of up to 0.1 kW to 100 kW, are deployed at rates of 100 000 to more than 400 million units per year worldwide in the Sustainable Development Scenario, and benefit from innovations in mass production, electronics and standardised installation. Other technologies, such as wind turbines, electrolysers and new ship drivetrains can be mass produced, but their unit size is larger and fewer units are expected to be deployed (Figure 2.25).

The policy and market dynamics that drive performance improvements and cost reductions in these types of technologies are very different. Mass produced consumer energy products are much more responsive to changes in prices, policies and social preferences than traditional energy technologies. More factories are needed to meet global demand for these items and industrial competition leads to faster turnover of products. New products with improved features hit the market every few years, and sometimes mismatched investment and consumption cycles can lead to oversupply and intensive competition for market share. These dynamics were at play in the case of solar PV over the last decade. This was the first time that mass produced, small unit size energy products and technologies became a significant feature of the energy supply landscape. Furthermore, because capital costs dominate for solar PV, costs reductions from manufacturing scale up had a disproportionate impact on electricity supply costs compared to cost reductions in traditional energy technologies requiring fuel inputs.

Figure 2.25 ▷ Low-carbon technologies by unit size and average annual installations in the Sustainable Development Scenario



Products with large unit sizes are installed in double-digits per year, while small products are installed at annual rates over 400 million enabling faster innovation

Notes: CCUS = carbon capture, utilisation and storage; CSP = concentrating solar power; SMR = small modular reactor; EV = electric vehicles; OCGT = open-cycle gas turbine; PV = photovoltaics; SDS = Sustainable Development Scenario. Capacities refer to rated maximum energy output. For technologies that do not have output rated in energy terms, energy throughput for the relevant technology component is used.

The link between policy, learning and cost reductions is particularly instructive in the case of solar PV. As described in prior editions of the *World Energy Outlook*, the capital costs of this technology have been decreasing with a learning rate[8] of around 20% for over a decade. In practice, this means that each time the cumulative amount of added PV capacity doubles, the costs fall by 20% as a result of economies of scale and innovations, especially by manufacturers. As in previous *WEOs*, the Stated Policies and Sustainable Development scenarios both follow this trend over the outlook period, but with different outcomes (Figure 2.26). In the Sustainable Development Scenario, policies and markets drive a higher level of installation overall, resulting in more progress along the learning curve: total capital costs fall towards $600/kW by 2030, which is around 10% lower than in the Stated Policies Scenario. However, the absolute level of cost decline per year in the outlook is much less pronounced than in the period from 2010 to 2018 for two reasons: it takes longer to double the cumulative production of PV panels from 1 terawatt (TW) to 2 TW than from 0.25 TW to 0.5 TW; and a 20% reduction translates to fewer dollars per kilowatt when applied to a cost that is getting smaller over time.

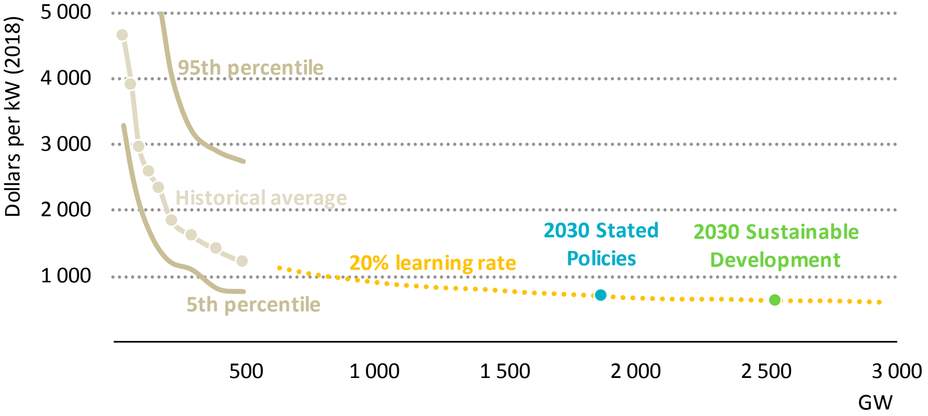
There is however no guarantee that this learning rate will be maintained in the future. If total capital costs are falling towards $600/kW by 2030, they will be similar to the current costs of the basic hardware alone in the cheapest locations in the world. As a minimum, incremental innovations in technology, manufacturing and installation will be required, yet

---

[8] The capital cost reduction for a doubling of cumulative installed capacity.

there are indications that patenting and venture capital activity in these areas are slowing (Cárdenas Rodríguez, Haščič and Johnstone, 2019; IEA, 2019d). This is in part related to the success of mass manufacturing in establishing a dominant type of PV with low prices, which makes it harder for innovative approaches with significant future potential to enter the market. There are two main ways to counter this with the aim of facilitating faster cost declines. The first is to put more effort into researching new approaches that could potentially yield a step-change in cost reduction, especially if they enable much lower local installation costs. Thin, flexible, printed PV cells would fall into this category. The second is to ensure that advances in techniques are shared as quickly and widely as possible. Some elements of the solar PV learning rate are global, and some are local. International collaboration and trade can raise the global component of learning, and therefore bend the curve towards lower costs.

Figure 2.26 ▷ Evolution of capital costs of solar PV in the Stated Policies and Sustainable Development scenarios



Policies drive more unit additions in the Sustainable Development Scenario, leading to lower costs that approach the expected limits of current technology

Sources: IEA analysis; IRENA (2019).

In the Sustainable Development Scenario, some of the biggest changes in the energy system relate to the diffusion of technologies that have small unit size and are for energy end-uses. These include electric heat pumps, EVs, electrolysers and fuel cells that are modular even in large installations. Governments have an important role to play in establishing a market framework that helps to make these technologies attractive to end-users, thus promoting uptake and innovation and enabling manufacturers and installers to raise finance at low cost. As the size and turnover of the market rises, the private incentives for improving the technologies increase. This is especially the case where developments can piggyback on progress in other fast-evolving sectors, such as communications and smart technology, as is the case for batteries and sensors for energy efficiency and demand response. Private investment is also likely to flow more readily where consumer energy products can be differentiated for various users, as with cars, or where end-user data can be commercialised.

The Sustainable Development Scenario, however, cannot be achieved without a range of complex, large unit size technologies that require associated infrastructure and generally involve a high degree of investment risk. These technologies require more capital to be put at risk in an early stage of the innovation chain and often face regulatory uncertainties. CCUS, nuclear, hydrogen and integrated smart city solutions fall into this category because of their costs and complexity. In the case of CCUS, for example, the first commercial projects can cost around $1 billion, take five or more years to move from engineering designs to results, and generally produce products – such as lower emissions cement, gasoline or power – with market values below their levelised and marginal costs today. If these technologies are to thrive, governments around the world will have to take on a significant proportion of the costs and risks of early commercial projects, sometimes for well over a decade, and provide strong signals that they will be supported in the future. Given the reduced appetite for governments to become involved in long-term, large-scale projects in some countries, reducing unit size and diversifying potential applications could be helpful: small modular nuclear reactors, CCUS for hydrogen production and even direct air capture all offer potential in this perspective.

The technologies that move from low market shares to wide deployment in the Sustainable Development Scenario mostly do so at a speed that is as fast as anything in the history of the energy sector.[9] Regardless of the technology type, the Sustainable Development Scenario requires an integrated approach to technology support which seeks to identify gaps in innovation, promote research that advances key technologies, establish market frameworks that support new clean energy technologies, penalise polluting technologies and encourage entrepreneurship. In this context, governments may wish to consider the scope for redirecting revenues from pollution charges to clean energy research grants, loans and other instruments, which would tackle two market failures at the same time.

2.9 How much further can we go?

The Paris Agreement goal to "pursue efforts towards 1.5 °C", together with the Intergovernmental Panel on Climate Change (IPCC) *Special Report on Global Warming of 1.5 °C* (*IPCC SR1.5*) released in 2018, has prompted a robust debate in some quarters about what a trajectory compatible with 1.5 °C might look like (IPCC, 2018). A salient point in this debate is that many of the physical impacts of climate change scale in a non-linear fashion with temperature rise: the impacts of 2.0 °C of warming are far worse than those of 1.5 °C of warming. This section looks at the Sustainable Development Scenario in the context of this debate and explores the implications for the energy system of limiting the temperature rise to 1.5 °C.

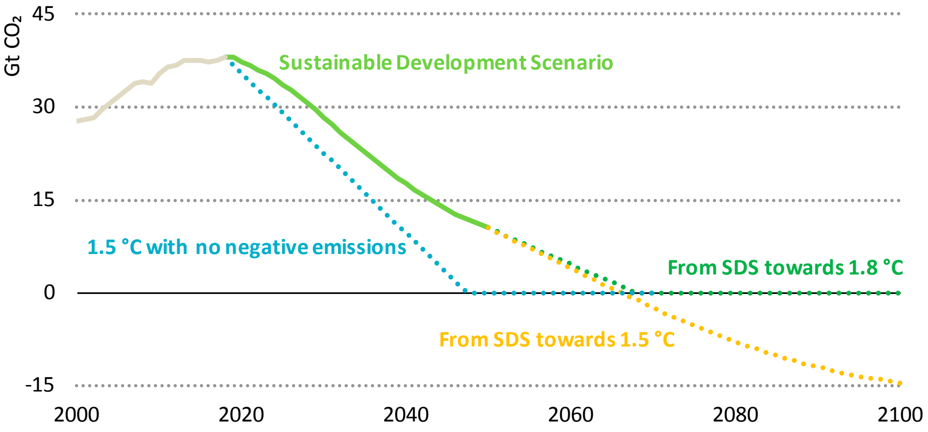
---

[9] Among transport options, the government-directed penetration of compressed natural gas into the vehicle fleets of Pakistan and Iran, and the adoption of LPG in Turkey, are the fastest to date, gaining around 5% fleet share per year.

Emissions trajectories consistent with 1.5 °C

A useful starting point to frame the energy-related consequences of limiting the temperature rise to 1.5 °C is the remaining CO_2 budget commensurate with this target. For a 50% chance of limiting the temperature rise to 1.5 °C, the *IPCC SR1.5* report provides remaining CO_2 budgets of 580 Gt and 770 Gt.[10] These different budgets reflect different views about the extent to which warming has already taken place, but both assume accompanying wholesale reductions in non-CO_2 emissions from methane and other gases, which have a strong, short-term effect on the temperature rise. Without such reductions the remaining CO_2 budgets would be lower.

Figure 2.27 ▻ Emissions trajectories for total CO_2 emissions in the Sustainable Development Scenario and to limit warming to 1.5 °C



Without negative emissions, global CO_2 emissions would need to fall to zero by around 2050 to achieve a 50% chance of 1.5 °C

Note: SDS = Sustainable Development Scenario.

In the Sustainable Development Scenario, energy-related emissions fall to 10 Gt in 2050 and are on course to reach net zero in 2070. If emissions were to remain at exactly zero after 2070, then cumulative emissions between 2018 and 2100 would be 880 Gt and this would provide a 66% chance of keeping the temperature rise below 1.8 °C, and a 50%

---

[10] These budgets are from the start of 2018. The different budgets included in the *IPCC SR1.5* are associated with differences over the temperature increase today relative to pre-industrial times. The 770 Gt budget is associated with a lower current temperature rise today (0.87 °C above pre-industrial times) and the 580 Gt budget with a higher current temperature rise (0.97 °C above pre-industrial times). There are a number of additional uncertainties, such as the assumed future level of non-CO_2 GHG emissions and their impact on the temperature rise, that could also have a substantial impact on the remaining budget (although these are not included in the choice of 580 Gt or 770 Gt as a remaining budget).

chance of staying below 1.65 °C.[11] If emissions were to turn net negative, and around 300 Gt of CO_2 were to be absorbed from the air cumulatively by 2100, this would lead to a 50% chance of limiting the temperature rise to below 1.5 °C (using the smaller of the two IPCC budgets).

There are uncertainties about the scale of negative emissions that may be possible, and about their impacts and costs. However, 88 of the 90 scenarios in the *IPCC SR1.5* report which have at least a 50% chance staying below 1.5 °C warming in 2100 rely on net negative emissions, and the median level of cumulative net-negative emissions in these scenarios is around 420 Gt. In other words, an assumption about net-negative emissions which is well below the median in terms of the scenarios in the *IPCC SR1.5* report would make the Sustainable Development Scenario compatible with at least a 50% chance of keeping the temperature rise below 1.5 °C in 2100 (Figure 2.27).

SPOTLIGHT

What is the role of negative emissions in 1.5 °C scenarios?

One of the key characteristics of nearly all scenarios that aim to limit the temperature rise to 1.5 °C is their reliance on net negative CO_2 emissions in the second-half of the century.

There are four main options that could provide large-scale negative CO_2 emissions: afforestation and reforestation, sequestration of biochar[12], bioenergy used in conjunction with carbon capture and storage (often called "BECCS"), and direct air capture.

While it is technically conceivable that the world will reach a point where large quantities of CO_2 are absorbed from the atmosphere, there are uncertainties about what may be possible and about the likely impacts. Many of the technologies or methods involved are unproven at scale, and could have negative consequences outside the energy system related to land use, biodiversity and food security (IPCC, 2019; Anderson and Peters, 2016).

Negative emissions could help in particular to offset emissions from hard-to-abate sectors, such as aviation or the manufacturing of iron, steel and cement. Without future technological solutions to decarbonise these sectors or else negative emissions at sufficient scale, it would be necessary to curtail activity in order to reduce emissions from these sectors.

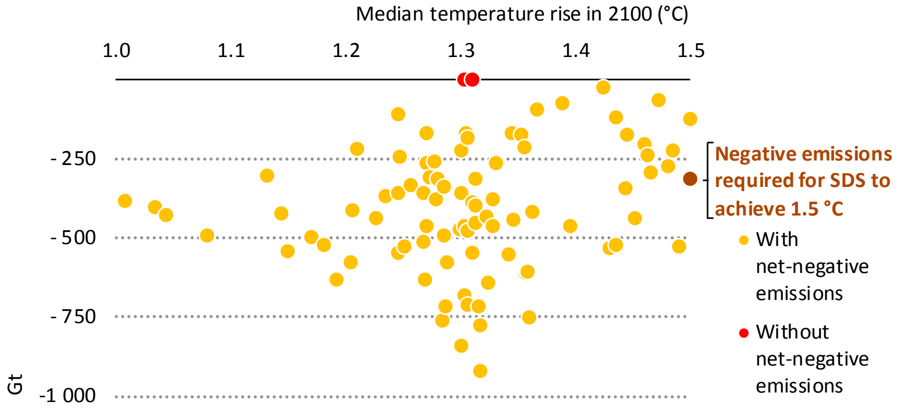
---

[11] A 66% chance of a less than 1.8 °C temperature rise is broadly equivalent to a 50% chance of a less than 1.65 °C temperature rise (IPCC, 2018).

[12] Biochar is a carbon-rich soil amendment made from biomass by pyrolysis (burning with limited oxygen), which could be used to sequester carbon in soil.

The range of sustainable bioenergy potential globally is estimated to be 130-240 exajoules (EJ) (3 100-5 700 Mtoe) per year (IEA, 2017c), similar to the level of current oil demand globally (4 450 Mtoe). The Sustainable Development Scenario uses around 80 EJ (1 900 Mtoe) of bioenergy in total in 2050, and around 0.25 Gt CO_2 is absorbed from the atmosphere in that year through the use of BECCS, compared to a median of 4.7 Gt from scenarios in the *IPCC SR1.5* database of scenarios (IPCC, 2018).

Figure 2.28 ▷ Cumulative net-negative CO_2 emissions between 2018 and 2100 in 1.5 °C scenarios assessed by the IPCC



Only two of the 90 scenarios assessed by the IPCC with at least a 50% chance of 1.5 °C warming in 2100 achieve this without recourse to negative emissions

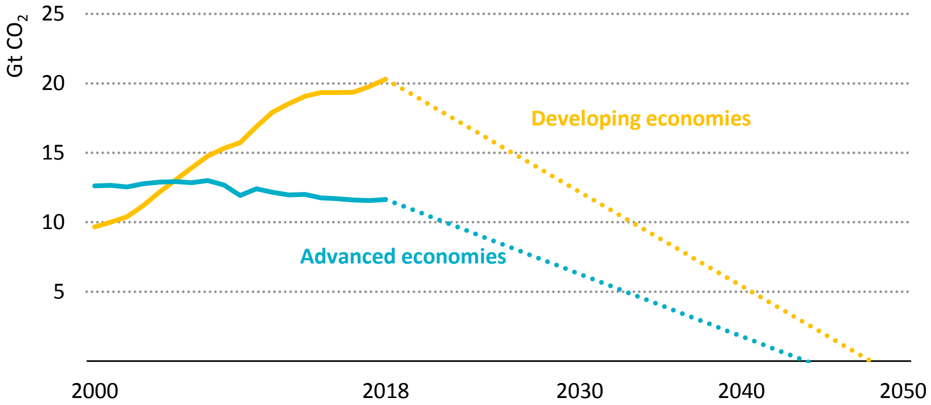
Notes: SDS = Sustainable Development Scenario. Cumulative from the point at which energy sector emissions reach net zero until 2100.

Implications for the energy sector of achieving zero CO_2 emissions in 2050

A 1.5 °C scenario which does not rely on negative emissions implies achieving zero CO_2 emissions around 2050 (Figure 2.27). This in turn implies a reduction in emissions of around 1.3 Gt CO_2 every year from 2018 onwards. The 1.3 Gt CO_2 is roughly equivalent to the emissions that would be avoided by shutting down around 290 GW of coal-fired power capacity (14% of the global installed coal capacity) or by replacing 490 million ICE passenger cars (around 40% of the global passenger car fleet) with electric cars running on zero carbon electricity.

We have not modelled this scenario in detail, but on the assumption of a regional pathway similar to that used in the Sustainable Development Scenario, a 1.5 °C scenario would imply that advanced economies reach net-zero energy sector CO_2 emissions around 2045, and developing economies around 2050 (Figure 2.29). The year in which net-zero emissions are achieved may vary depending on domestic circumstances, stage of development and energy sector characteristics.

Figure 2.29 ▷ Illustrative trajectory of energy-related CO_2 emissions to achieve a 50% chance of 1.5 °C in advanced and developing economies



Achieving a 1.5 °C stabilisation would imply that advanced economies reach net-zero energy-related CO_2 emissions around 2045 and developing economies around 2050

Power sector

There are technologies available today to move towards full decarbonisation of electricity generation, but the challenges and costs of achieving this by 2050 would be considerable.

- A zero carbon power system would need to pre-date an economy-wide decarbonisation goal by at least a few years. This implies moving to a zero emissions electricity system in the 2030s for advanced economies and around 2040 for developing economies.
- Adding only zero carbon generation would not be sufficient: existing assets would have to be repurposed, retrofitted with CCUS or retired. In Chapter 6, we examine the practicalities and costs of this for coal-fired power plants. The costs of the possible strategy for coal outlined in Chapter 6 are significant; bringing this forward would inevitably increase these costs considerably.
- Building sufficient flexibility into a zero emissions power system would be challenging given that the practical constraints – such as planning and permitting a major expansion of the transmission grid – would need to be overcome on a shorter timeline than in the Sustainable Development Scenario.

End-use sectors

In end-use sectors, the starting point today is that 5% of kilometres driven are low carbon (that is, they involve the use of biofuels or EVs that use low-carbon electricity), 11% of energy used for heating buildings comes from low-carbon sources, and 17% of industry energy demand is low carbon. In some sectors technical solutions for decarbonisation are yet to be developed, for instance there are no commercially viable low-carbon planes.

There are some end-use sectors where technologies are now available that would allow decarbonisation. One example is electric cars, if coupled with zero carbon electricity. As the lifetime of cars is also relatively short[13], at least compared with other assets and infrastructure in the energy sector, to achieve zero CO_2 emissions in 2050 the sale of internal combustion engine cars would probably need to fall to zero in advanced economies in 2030 or soon after and in developing economies a few years later. This implies that sales of EVs would need to reach around 100 million in 2030 (from around 2 million a year today). This would increase electricity demand and the need for the deployment of low-carbon technologies in the power sector.

The focus for any economy-wide 100% decarbonisation target eventually narrows to the hard-to-abate sectors other than power generation and personal mobility. This includes decarbonisation of buildings, energy-intensive industries, aviation and freight transport. The Sustainable Development Scenario sees about 1.2 Gt CO_2 emissions from these sectors in advanced economies in 2045 and in developing economies around 3.4 Gt in 2050. Nearly all of the technical potential for energy efficiency measures is exploited in the Sustainable Development Scenario. Some of the key difficulties relate to:

- **Infrastructure constraints**: Most of the existing buildings stock would need to be retrofitted to become net-zero energy and be heated using zero carbon means. For example, in the United Kingdom, the Climate Change Committee has calculated that meeting a net-zero GHG target in 2050 implies that new homes would not be connected to the natural gas grid from 2025, that almost all heating systems for existing homes would be low carbon or ready for hydrogen by 2035, and that the share of low-carbon heating would need to increase from 4.5% today to 90% in 2050 (CCC, 2019). These types of changes would need to apply to many of the 2 billion houses existing today, as well as the additional one billion houses built to 2050 in order to reach net-zero emissions globally.
- **Social acceptance and behavioural changes**: Some of the changes that would be necessary would have wide-ranging effects, implying the need for a broad measure of public acceptance. For example, it would be hard to renovate and retrofit all buildings by 2050 without a high degree of support from the public. Another example is air travel, where it is uncertain that low-carbon aviation will be widely available before 2050. Currently, aviation emits around 1 Gt CO_2 per year and passenger activity is expected to at least double over the next 20 years. In the Sustainable Development Scenario, we assume significant efficiency improvements in aircraft and widespread use of advanced biofuels, but aviation still emits over 600 Mt CO_2 in 2050. Eliminating these emissions entirely could entail measures to limit air travel either via behavioural changes, administrative constraints or higher prices. However, there are areas where behavioural changes not associated with any absolute reductions in demand for goods and services could also help achieve deep decarbonisation. For example, dietary shifts towards less meat are often stipulated in 1.5 °C compatible scenarios. These go

---

[13] Assumes an average of 16 years in advanced economies and 18 years in developing economies.

beyond the energy sector but become equally essential as the share of emissions from agricultural and land use increases in importance. Digitalisation could help to enable behavioural changes, and make it easier to accept changes to the way that energy services are accessed, for example with the use of EV smart-charging as part of demand-side response (see Chapter 7, section 7.6).

- **Capital stock replacement**: Getting to zero emissions by 2045 for the hard-to-abate sectors in advanced economies would require the development and deployment of new technologies for all production – and in many cases the replacement of all capital stock – within the next 25 years. This process would need to take place in parallel in all developing economies within an additional five years, in a setting where the extent of the capital stock involved is much larger and, in most cases, the capital available to effect such a transformation is much more limited.

In terms of the fuel mix, all zero carbon energy sources would need to ramp up even faster than envisaged in the Sustainable Development Scenario. Three-quarters of energy demand for steel production today is met using coal. This would mean that in 20 years the majority of primary steel plants (around 80% of global production) in the world would need to be refurbished or retired and replaced.

Natural gas use may need to increase in the short term in countries that already have a well-established natural gas grid to help replace unabated coal and to allow for the extra flexibility needed by the very steep ramp-up of variable renewables. For unabated natural gas, stringent year-on-year emissions reductions mean that this increase would be temporary, but low carbon gases could make use of existing infrastructure and moderate the decline.

Assuming that oil could continue to be used for long-haul air travel (around 3 mb/d in 2050, with marked efficiency gains and use of alternative fuels), and for non-energy and non-emitting purposes, such as the manufacture of asphalt or chemicals (20 mb/d in 2050), then oil demand would fall sharply through to 2050, following a trajectory closer to the decline in supply from fields already producing today, assuming continued investment in these fields. However, given both the geographical locations and differing characteristics of fields around the world, not all the fields that are producing today would be well placed to reliably satisfy the ongoing demand for oil, meaning that some new field developments would still find a place even in a world of rapidly falling demand.

Summary and implications

More than ten years ago, the 2008 edition of the *World Energy Outlook* introduced an ambitious new climate scenario, warning that the "the consequences for the global climate of policy inaction are shocking" and underlining that "strong co-ordinated action is needed urgently to curb the growth in greenhouse gas emissions and the resulting rise in global temperatures".[14] Today, emissions continue to grow, and the emissions cuts required to avoid the worst effects of climate change get steeper every year.

---

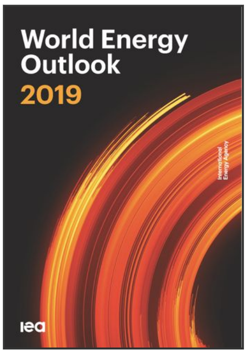
[14] Executive Summary of *World Energy Outlook-2008* (IEA, 2008).

The Sustainable Development Scenario shows a pathway that would keep the temperature rise below 1.8 °C with a 66% probability without any implied reliance on global net-negative emissions. It is fully consistent with the Paris Agreement, and it sees energy sector CO_2 emissions fall to around 10 Gt by 2050, on course for net-zero emissions by 2070. If an assumption were to be made that emissions would turn net negative in the second-half of the century, it would take 300 Gt of negative emissions for the scenario to be consistent with at least a 50% chance of limiting warming to 1.5 °C – less than the median amount in the 90 scenarios included in the *IPCC SR1.5 report*.

There is a significant gap between the outcomes of the Stated Policies Scenario, which reflects the policies that governments have put in place or announced, and the Sustainable Development Scenario, which takes its starting point as the achievement of the energy-related SDGs and then shows what would be necessary to deliver this. This gap is set to grow in the future – an indication of the scale and pace of the transformation set out in the Sustainable Development Scenario.

There are uncertainties associated with net-negative emissions, and it would be possible in the light of concern about these to construct a scenario that goes further than the Sustainable Development Scenario and delivers a 50% chance of limiting warming to 1.5 °C without any reliance on net-negative emissions on the basis of a zero carbon world by 2050. This analysis does not reflect detailed modelling, but it nevertheless shows that eliminating the 10 Gt CO_2 emissions remaining under the Sustainable Development Scenario in 2050 would not amount to a simple extension of the changes to the energy system described in the Sustainable Development Scenario. The additional changes involved would pose challenges that would be very difficult and very expensive to surmount.

This is not something that is within the power of the energy sector alone to deliver. It would be a task for society as a whole, and likely involve widespread behavioural changes. It bears repeating that there is no single or simple solution to turn emissions around. The "moon shot" analogy – a concentrated dedication of resources, leadership and effort in favour of a single, visible outcome – is flawed. Change on a massive scale would be necessary across a very broad front, and would impinge directly on the lives of almost everyone.



From:
World Energy Outlook 2019

Access the complete publication at:
https://doi.org/10.1787/caf32f3b-en

Please cite this chapter as:

International Energy Agency (2019), “Energy and the Sustainable Development Goals”, in *World Energy Outlook 2019*, OECD Publishing, Paris.

DOI: https://doi.org/10.1787/0efa47e9-en