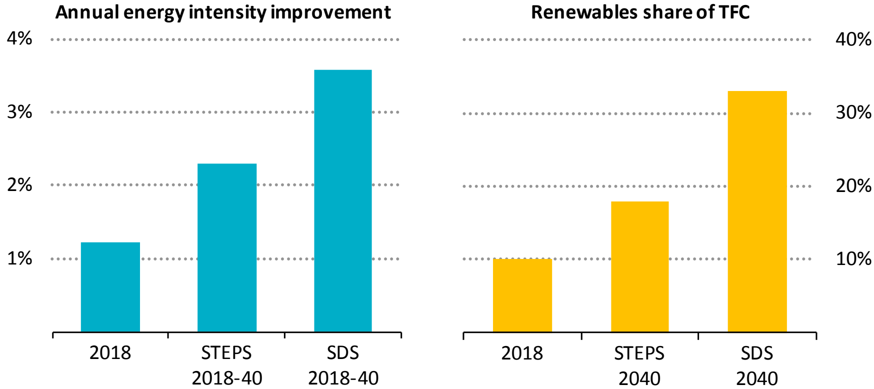
Outlook for energy efficiency and renewables

Untapped potential for sustainable growth?

S U M M A R Y

- Total global final energy consumption was almost 10 000 million tonnes of oil equivalent (Mtoe) in 2018, an increase of 2.2% compared with 2017. In the Stated Policies Scenario, it rises to almost 12 700 Mtoe by 2040, an increase of around 1.1% per year on average, while global energy intensity improves by 2.3% per year. Implementation of the Stated Policies Scenario results in energy intensity improvements and an expansion of renewable energy, but the rate of improvement is not sufficient to achieve the energy-related Sustainable Development Goals.

Figure 7.1 ▷ Energy intensity improvement and renewables share of total final consumption by scenario



A significant step up in effort is required if the world is to achieve the targets set out in the Sustainable Development Goals

Note: TFC = total final consumption; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

- Annual investment in energy efficiency increases in the Stated Policies Scenario from $240 billion in 2018 to around $445 billion a year by 2030 and to $635 billion a year thereafter to reach a cumulative total of $11.7 trillion over the period to 2040. In the Sustainable Development Scenario, there is a much larger increase in energy efficiency investment, with spending rising to a cumulative total of $16.7 trillion by 2040 (around $625 billion a year to 2030 and almost $920 billion thereafter).
- The story for renewables is similar. While investment in the Stated Policies Scenario is expected to increase from around $390 billion in 2018 to an average of almost $440 billion a year until 2030, it falls short of the annual $650 billion that would be required on average to 2030 to meet the Sustainable Development Goals.

- Energy transitions worldwide imply changes in how we supply and consume energy. Demand for materials and industrial products plays a central role in shaping energy consumption and carbon dioxide (CO_2) emissions in industry. In the face of demand growth, the policies so far implemented or announced will not halt a future increase in industry emissions: which grow by 16% in 2040 the Stated Policies Scenario.
- The energy transformation in the Sustainable Development Scenario implies changes in demand for materials, some of them counter-intuitive, including more steel for renewable energy infrastructure and more aluminium for electric vehicles. Greater emphasis on materials efficiency and materials recycling, reuse and substitution succeeds in reversing the historic trend of growing emissions for steel and cement, leading to a stronger decline in industrial CO_2 emissions.
- As the electrification of economies progresses and the share of variable renewables in generation increases, the carbon footprint of electricity use increasingly fluctuates depending on the time of day or night. In India, our analysis indicates that, when the share of variable renewables reaches 50%, average CO_2 emissions from using electricity at midday or 23:00 differ by a factor of seven. In Europe, the difference is a factor of three.
- Targeting efficiency measures on appliances and equipment used when power sector emissions are high could bring major reductions in emissions of CO_2 and other pollutants. In the case of India and the European Union, enhanced energy efficiency sees emissions from electricity generation decrease by around 30% and 20% respectively in the Sustainable Development Scenario relative to the Stated Policies Scenario.
- Facilitated by digitalisation and new business models, demand-side response has a role to play in shifting consumer demand to low CO_2 and energy price periods and selling flexibility services to the grid. In doing so, it can both increase the share of variable renewables used and also cut CO_2 emissions from power generation. IEA analysis shows potential for further power sector emissions reductions of 25% in the United States and 16% in China, relative to the Sustainable Development Scenario.
- While the technologies to produce biogas are not new, there has been a resurgence of interest in their potential in recent years. IEA analysis indicates that over 570 Mtoe per year of biogas could be produced sustainably today, equivalent to almost 20% of global natural gas demand. Emerging economies account for two-thirds of the global biogas potential. However, biogas everywhere requires supportive policies if it is to be fully utilised.
- The benefits of using biogas are many and the economic case improves considerably if these non-economic benefits are fully taken into account. In the Stated Policies Scenario, close to 150 Mtoe of biogas is produced globally by 2040, over 40% of which is in China and India. In the Sustainable Development Scenario, there is a more pronounced increase in biogas production: it reaches around 330 Mtoe in 2040, utilising around 40% of the total sustainable technical potential.

Introduction

This chapter examines current trends in energy efficiency and renewable energy. The past decade has been characterised by continuous growth in the deployment of renewable energy technologies. The power sector has been leading the way but the uptake of renewables has been slower in other sectors such as industry and buildings[1]. Energy efficiency has also seen significant investment in recent years, although growth stalled in 2018 owing to lacklustre progress in implementing new efficiency policies and increasing the stringency of existing ones. Efficiency gains and increased use of renewables remain among the most cost-effective ways to enhance security of energy supply, reduce carbon dioxide (CO_2) emissions and improve local air quality. The first part of this chapter presents the key findings on energy efficiency and renewable energy from the Stated Policies and Sustainable Development scenarios. It explores three important topics in detail:

- The production of steel, cement and aluminium accounts for 10% of global energy consumption, and is generally carbon intensive. This means that curbing material demand has an important role in achieving the goals of the Sustainable Development Scenario, in which improved material efficiency contributes over 20% of the savings in CO_2 emissions from steel, cement and aluminium production by 2040. Material efficiency improvements can be realised along the entire product lifecycle, covering design, fabrication, use and recycling.
- Smarter electricity use can significantly reduce the environmental footprint of electricity consumption. As the share of electricity generation from variable renewables increases, so does the hourly variability of power sector emissions: in other words, the level of emissions from electricity consumption will vary depending on whether power is used at a time of day when most electricity comes from renewable sources or not. Targeted energy efficiency measures and demand-side response measures can reduce electricity demand in periods of high CO_2 intensity of electricity supply, and thus reduce emissions. Additional benefits include lower bills, improved power system operation and a reduction in air pollutant emissions.
- Biogas is emerging as having significant potential to reduce greenhouse gas (GHG) emissions, improve waste management, enhance security of supply and improve access to clean cooking in rural areas. We provide a complete overview of the key technology and production pathways for biogas, exploring the potential volumes and production costs, and discussing various biogas applications. While there is significant global potential for biogas, most of this requires supportive policies if it is to be exploited.

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

[1] Industry is defined in this chapter as including transformation in blast furnaces and coke ovens and petrochemical feedstock, unless where reference is made to final consumption of industry.

Scenarios

7.1 Energy efficiency overview

Table 7.1 ▷ Key indicators by scenario

		Stated Policies		Sustainable Development		Current Policies	
	2018	**2030**	**2040**	**2030**	**2040**	**2030**	**2040**
TPED (Mtoe)	14 314	16 311	17 723	13 750	13 279	16 960	19 177
Share of fossil fuels (%)	81%	77%	74%	72%	58%	79%	78%
TFC (Mtoe)	9 954	11 607	12 672	9 904	9 500	11 996	13 540
Energy intensity of GDP (2018=100)	100	75	60	63	45	78	65

Notes: TPED = total primary energy demand; Mtoe = million tonnes of oil equivalent; TFC = total final consumption of energy; TPED indicators exclude fossil fuel statistical differences.

Global primary energy demand grew by almost 2.3% in 2018, its largest annual increase since 2010, with China, United States and India accounting for over two-thirds of total energy demand growth. Global energy intensity reached 106 tonnes of oil equivalent (toe) per $1 million of gross domestic product (GDP), a 1.2% improvement compared to 2017, but around half the rate of improvement in the 2010-17 period.[2] This third consecutive year of slowdown was the result of weaker energy efficiency policy implementation and strong demand growth in energy-intensive economies.

As always, worldwide trends conceal considerable regional variations. In India, energy intensity improved by around 3%. Energy intensity in China improved by 2.8% while energy demand reached an all-time high. In the European Union, energy intensity improved by 2.3% as efforts to meet the 2020 energy efficiency targets continued. The United States, in contrast, saw energy intensity deteriorate, by close to 1%, driven by heating demand in winter and cooling demand in summer as well as growing demand in the transport sector.

In the **Stated Policies Scenario**, primary energy demand expands by around a quarter between 2018 and 2040 at an average annual growth rate of 1%. This rate is slower than in the past (it was 1.4% between 2010 and 2018, and 2.7% in the preceding decade) as energy consumption and economic growth continue to decouple. In the Current Policies Scenario, energy demand rises at an average annual rate of 1.3% to reach over 19 000 million tonnes of oil equivalent (Mtoe) by 2040.

In the **Sustainable Development Scenario**, energy demand in 2040 is 25% lower than in the Stated Policies Scenario. Further improvements in energy efficiency in final energy consumption in the Sustainable Development Scenario save over 1 900 Mtoe of energy

[2] In the *WEO-2019*, energy intensity is calculated using GDP in purchasing power parity (PPP) terms to enable differences in price levels among countries to be taken into account. In our scenarios, PPP factors are adjusted as developing countries become richer.

demand in end-use sectors by 2040 relative to the Stated Policies Scenario. Energy efficiency is the single biggest contributor to reducing final energy consumption in end-use sectors in the Sustainable Development Scenario relative to the Stated Policies Scenario, responsible for 60% of the savings. Almost half of the energy efficiency savings come from industry, with major contributions also from transport and buildings.

Table 7.2 ▷ Energy intensity of GDP by scenario (toe/$1 000 PPP)

		Stated Policies		Sustainable Development		Current Policies	
	2018	2030	2040	2030	2040	2030	2040
North America	0.11	0.09	0.07	0.08	0.05	0.09	0.07
United States	0.11	0.09	0.07	0.08	0.05	0.09	0.07
Central and South America	0.09	0.07	0.06	0.06	0.05	0.08	0.07
Brazil	0.08	0.08	0.06	0.07	0.05	0.08	0.07
Europe	0.08	0.06	0.05	0.05	0.04	0.06	0.05
European Union	0.07	0.05	0.04	0.05	0.04	0.06	0.05
Africa	0.12	0.10	0.08	0.06	0.05	0.10	0.08
South Africa	0.17	0.13	0.10	0.11	0.08	0.14	0.12
Middle East	0.12	0.11	0.10	0.09	0.07	0.11	0.10
Eurasia	0.17	0.14	0.12	0.12	0.09	0.14	0.12
Russia	0.18	0.15	0.12	0.13	0.10	0.15	0.13
Asia Pacific	0.10	0.07	0.05	0.06	0.04	0.07	0.06
China	0.12	0.08	0.06	0.07	0.04	0.08	0.07
India	0.09	0.06	0.05	0.05	0.03	0.06	0.05
Japan	0.08	0.06	0.05	0.06	0.05	0.07	0.06
Southeast Asia	0.08	0.06	0.05	0.05	0.04	0.06	0.05
World	**0.11**	**0.08**	**0.06**	**0.07**	**0.05**	**0.08**	**0.07**

Note: toe = tonne of oil equivalent; PPP = purchasing power parity.

Energy intensity improves in the Stated Policies Scenario by 2.3% annually to 2040. This is a slightly higher rate than in the period since 2010 and about twice the rate in 2000-10. The link between GDP growth and energy demand growth continues to weaken by 2040. The largest improvements are projected in China, India and European Union, with the implementation of more stringent policies such as the 13th Five-Year Plan for National Energy Conservation Action in China, the Perform, Achieve, Trade scheme in India, and emission performance standards and directives on the energy performance of buildings and Ecodesign in the European Union. Energy intensity in the Sustainable Development Scenario, in contrast, improves much faster at a rate of 3.6% a year on average as all economically viable energy efficiency opportunities are pursued. The biggest improvements are in China, India and Africa.

7.2 Renewables overview

Table 7.3 ▷ World renewable energy demand by scenario

		Stated Policies		Sustainable Development		Current Policies	
	2018	2030	2040	2030	2040	2030	2040
Primary demand (Mtoe)	**1 391**	**2 287**	**3 127**	**2 776**	**4 381**	**2 138**	**2 741**
Solid biomass (Mtoe)	**620**	**613**	**546**	**140**	**75**	**613**	**546**
Share of total bioenergy	*46%*	*37%*	*30%*	*11%*	*5%*	*38%*	*31%*
Electricity generation (TWh)	**6 799**	**12 479**	**18 049**	**15 434**	**26 065**	**11 627**	**15 485**
Bioenergy	636	1 085	1 459	1 335	2 196	1 022	1 256
Hydro	4 203	5 255	6 098	5 685	6 934	5 171	5 923
Wind	1 265	3 317	5 226	4 453	8 295	2 955	4 258
Of which offshore wind	67	567	1 281	764	2 072	416	860
Solar PV	592	2 562	4 705	3 513	7 208	2 265	3 658
Concentrating solar power	12	67	196	153	805	46	104
Geothermal	90	182	316	282	552	161	258
Share of total generation	*26%*	*37%*	*44%*	*49%*	*67%*	*33%*	*36%*
Final consumption* (Mtoe)	**992**	**1 649**	**2 259**	**2 054**	**3 137**	**1 531**	**1 969**
Modern bioenergy	430	592	718	729	873	555	664
Of which biogas/biomethane	12	47	72	106	177	29	43
Electricity	488	916	1 337	1 138	1 951	848	1 135
*Share of global TFC**	*10%*	*14%*	*18%*	*21%*	*33%*	*13%*	*15%*
Heat consumption* (Mtoe)	**506**	**731**	**936**	**830**	**1176**	**704**	**869**
Modern bioenergy	342	423	492	428	495	419	493
Of which biogas/biomethane	12	27	45	81	132	18	30
Electricity	91	167	240	215	368	156	206
District heating	22	37	46	30	44	42	46
*Share of total heat demand**	*10%*	*13%*	*16%*	*19%*	*30%*	*13%*	*14%*
Transport* (Mtoe)	**96**	**199**	**302**	**354**	**606**	**153**	**203**
Biofuels (road)	88	149	186	248	243	130	162
Biofuels (aviation and shipping)	0	17	36	50	129	3	6
Electricity	8	33	79	56	234	21	35
*Share of total transport demand**	*3%*	*6%*	*8%*	*12%*	*23%*	*4%*	*5%*

* Includes indirect renewables, but excludes environmental heat and solid biomass.

Notes: Mtoe = million tonnes of oil equivalent; TWh = terawatt-hours; PV = photovoltaics; TFC = total final consumption. Solid biomass includes its traditional use in three-stone fires and in improved cookstoves.

Electricity generation from renewables continued to grow in 2018 with output up by 450 terawatt-hours (TWh) (or 7%) compared to the previous year and accounting for more than a quarter of total power generation output (this compares to around a fifth in 2010). Growth in output from solar photovoltaics (PV), wind and hydro accounted for 90% of the increase. Around 180 gigawatts (GW) of new renewable power capacity was added in 2018, which is the same level as the previous year, although the IEA's provisional estimate for 2019 suggests a resumption of robust growth in annual renewable additions.

Hydropower remains the largest source of renewables-based power generation today, although its rate of deployment slowed again in 2018: 20 GW of new capacity was added compared with 25 GW in 2017 and 36 GW in 2016. Wind power, the second-largest renewable energy power source, added 50 GW: this represents a slight increase compared with 2017. Offshore wind continues to pick up with 4.3 GW of new capacity, led by China with 1.6 GW, United Kingdom with 1.3 GW and Germany with 1.0 GW (See Chapter 14). Solar PV capacity additions expanded by almost 100 GW in 2018: China accounted for 44 GW or almost half of the increase, though this is a lower figure than in 2017. Electricity output from wind and solar PV combined was almost 20% higher in 2018 than in 2017.

The use of renewables in the transport sector also continued to expand in 2018. Biofuels are the only renewable energy source used directly in the transport sector, and they contributed around 90 Mtoe or almost 2 million barrels of oil equivalent (mboe) per day. About 70% of this was accounted for by ethanol, with biodiesel the next biggest contributor.

The use of renewables also increased in the heating sector, with renewable sources of heat excluding traditional use of solid biomass (over 500 Mtoe) accounting for 10% of heat supply. Direct use of biomass (67%) was the main source of renewable-based heat followed by electricity from renewable energy sources (18%) and solar thermal (7%).

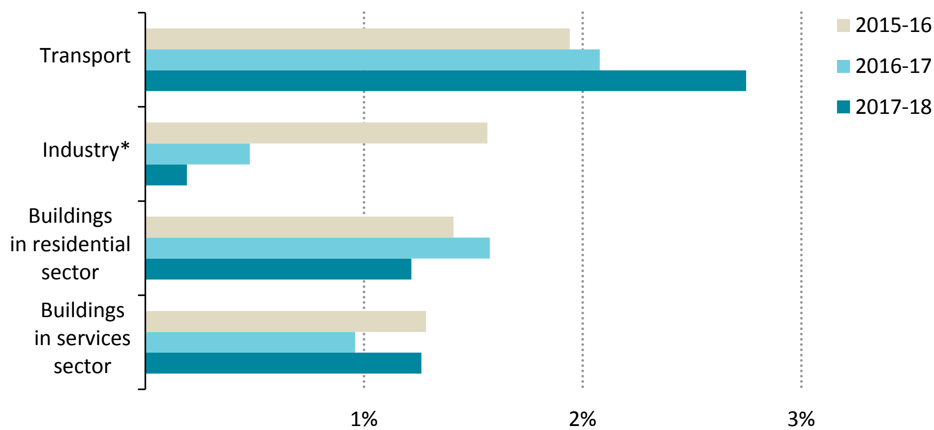
In the **Stated Policies Scenario**, the amount of renewables excluding traditional biomass in final energy consumption increases from more than 990 Mtoe today to almost 2 260 Mtoe in 2040 and its share of consumption nearly doubles to 20%. The share of renewables in global heat increases by 60% and reaches nearly 940 Mtoe in 2040, thanks to substantial increases in the modern use of biomass (pellets in boilers and stoves, biogas and biomethane, biofuels), renewable electricity and also of solar thermal. China, the European Union, India and the United States supply more than half of the of the world's renewable heat today and are expected to account for around 65% of the increase by 2040. Meanwhile the amount of renewables consumed in the transport sector triples to around 300 Mtoe, three-quarters of which comes from biofuels, with the remainder taking the form of renewable electricity consumed by electric vehicles and rail transport.

In the **Sustainable Development Scenario**, additional measures to incentivise investment in renewables-based electricity, biofuels, solar heat, geothermal heat and electrification push the share of renewables to two-thirds of electricity generation output and 37% of final energy consumption. By 2040, expected output from wind (8 300 TWh) and solar PV (7 200 TWh) are expected to exceed hydropower (6 950 TWh), while the share of heat coming from renewables in 2040 increases to 30% of the total or to 1 200 Mtoe. In the transport sector, consumption of energy from renewable sources is projected to increase to 600 Mtoe, with biofuels accounting for around 60% and electricity from renewable sources consumed by electric vehicles and rail accounting for the remainder.

7.3 Efficiency by sector and investments

The coverage and strength of mandatory energy efficiency policies continued to increase with policy coverage reaching 35% in 2018, a 1.3 percentage point change improvement since 2017 (Figure 7.2). Despite the cost effectiveness of efficiency investments, in many areas there has been limited progress in expanding policy coverage despite a small increase in industry and in residential buildings. Once again, almost all of the increase in coverage is attributable to more end-uses being covered by existing standards, rather than new standards (IEA, 2019a).

Figure 7.2 ▹ Year-on-year changes in the share of global energy consumption covered by mandatory efficiency standards by selected end-uses



Efficiency standards expanded for transport in 2018 while there was very little coverage increase in efficiency policies in the industry and buildings sectors

* In this case industry includes only final energy consumption of industry and not feedstock demand for chemicals or fuel transformation in blast furnaces and coke ovens.

Trends for passenger cars were not encouraging with a rise in market share by less-efficient sports utility vehicles which on average consume around 25% more oil than medium-size cars, leading to a stagnation of fuel economy for road transport (see Chapter 3). For the first time since the 2008 recession, key markets saw a slowdown or drop in sales of internal combustion engine (ICE) cars in 2018. New vehicle standards in India (2022) and the European Union (2022) are expected to support more efficiency-related spending in the future.

In the **Stated Policies Scenario**, energy demand in buildings increases by about 1% per year on average between today and 2040: this reflects a large increase in the number of electric appliances and connected devices and in demand for space cooling. In industry, efficiency improvements slow the average annual increase in demand between today and 2040 to

1.3%, an increase from the 0.9% recorded over the 2010-18 period. In the transport sector, efficiency improvements help to constrain growth in demand to around 25% despite the number of light-duty passenger vehicles increases by 70%.

In the **Sustainable Development Scenario**, stronger efficiency policies and greater access to clean cooking technologies such as more efficient stoves and LPG see energy consumption in the buildings sector fall by around 400 Mtoe or 13% over the period to 2040. Energy consumption in industry remains at a similar level as today, while oil demand in the transport sector decreases by as much as 40%, despite an increase in the global vehicle stock of 45%, reflecting more stringent efficiency standards and growth in electric vehicle sales, which reach 54% of the total vehicle stock by 2040.

Table 7.4 ▷ Annual average investment in energy efficiency in selected regions by scenario ($2018 billion)

		Stated Policies		Sustainable Development		Change 2031-40 versus 2018	
	2018	2019-30	2031-40	2019-30	2031-40	STEPS	SDS
United States	42	74	94	127	186	52	144
European Union	70	136	167	149	141	97	71
China	61	68	98	87	111	37	50
India	10	22	40	30	58	30	48
World	**240**	**445**	**635**	**625**	**916**	**395**	**676**
Cumulative		*5 338*	*6 345*	*7 498*	*9 156*		

In 2018, investment in energy efficiency across the buildings, transport and industry sectors totalled around $240 billion, the same level as the previous year. The buildings sector accounted for most energy efficiency spending despite declining by 2% to under $140 billion (IEA, 2019b).

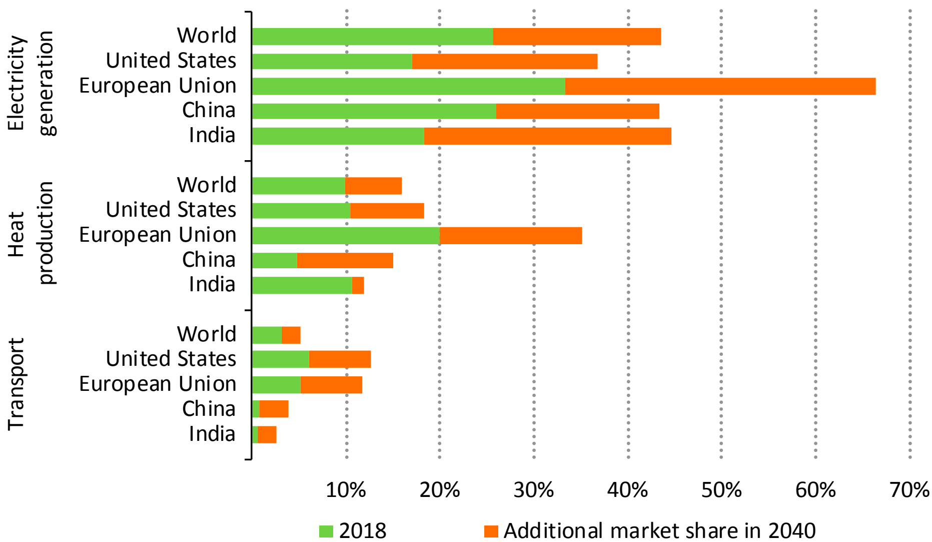
In the **Stated Policies Scenario**, investments in energy efficiency are expected to rise from current levels, averaging around $445 billion a year in the period from 2019 to 2030 and to around $635 billion a year from 2031 to 2040 (Table 7.4). The transport sector accounts for more than half of cumulative investment spending to 2040, followed by buildings and industry. The European Union, China and United States together account for more than half of all energy efficiency investments in 2040.

In the **Sustainable Development Scenario**, expected cumulative spending on efficiency reaches $16.7 trillion between now and 2040, with an annual average of around $625 billion between 2019 and 2030 rising to almost $920 billion a year from 2031 to 2040.

7.4 Renewables policies and investments

Renewables have grown rapidly in recent years, accompanied by sharp cost reductions for solar PV and wind power in particular. By 2018, most countries in the world had some form of renewable energy targets in place, and more than 150 countries had renewable energy policies in place in the power sector. More than 45 countries also had policies in place to support the use of biofuels in the transport sector: no new countries added regulatory incentives or mandates for renewable transport in 2018, but some countries strengthened existing ones. In addition, around 45 countries had renewable energy policies specifically for heating and cooling (REN21, 2019).

Figure 7.3 ▷ Renewable energy in total primary energy demand by category and region in the Stated Policies Scenario, 2018 and 2040



Strong support policies for renewable-based electricity are boosting their penetration, but more policy action is needed in other sectors

Several new or revised renewable energy targets were established in 2018. China's National Energy Administration raised the country's renewable portfolio standard (RPS) in 2019 to 35% of electricity consumption by 2030. The amended RPS established local targets for the provinces in the form of minimum mandated levels of renewable electricity supply. In December 2018, the European Union's revised Renewables Energy Directive (2018/2001) established a new binding 2030 renewable energy target of at least 32% of gross final consumption of energy from renewable sources, with scope for possible upwards revision from 2023.

In the United States, the increase in renewable capacity in 2018 came mainly as a result of onshore wind expansion, although uncertainty about PV module import tariffs resulted in delays to some solar projects (IEA, 2019c). Elsewhere, renewable capacity expansion accelerated in many countries in the Middle East, North Africa and parts of Asia, reflecting declining wind and solar PV costs, strong policy support and commitments made under the Paris agreement (IEA, 2019c).

Table 7.5 ▷ Global annual average investment in renewables by scenario ($2018 billion)

		Stated Policies		Sustainable Development		Change 2031-40 versus 2018	
	2018	2019-30	2031-40	2019-30	2031-40	STEPS	SDS
Power	304	347	382	524	661	78	357
Wind	89	119	138	185	235	49	146
Solar PV	135	116	117	169	189	-18	54
End-use sectors	84	89	95	125	146	11	62
World	**388**	**436**	**477**	**649**	**807**	**89**	**419**
Cumulative		*5 233*	*4 772*	*7 793*	*8 075*		

Note: Renewables for end-use include solar thermal, bioenergy and geothermal applications for heating.

Renewables-based power investment declined modestly in 2018 to around $390 billion. A dollar of renewables spending continued to buy more generation capacity than in the past, putting downward pressure on spending levels (IEA, 2019b), and meaning that net additions to capacity remained at the same level as in 2017 despite the decline in investment. Solar PV spending declined by around 4% to $135 billion, mostly as a result of policy changes in China. Wind investment remained relatively flat compared to 2017 at around $90 billion, dominated by China and Europe, which together accounted for almost 60% of spending.

In the **Stated Policies Scenario**, investment in renewables is expected to continue to grow, reaching a cumulative total between now and 2040 of around $10 trillion (Table 7.5). Wind and solar PV account for around two-thirds of the expected spending on renewable electricity generation over the *Outlook* period. China and Europe see more than half of the expected investments in wind power while China, United States and India dominate the projected spend on solar PV with over 55%.

In the **Sustainable Development Scenario**, renewable investments grow at a faster rate, reflecting stronger policy support, and reach almost $840 billion in 2040. The cumulative total amounts to nearly $16 trillion. Wind and solar PV make up two-thirds of the investment in renewable electricity generation over the period, with China and Europe combined responsible for around half of the expected spend. China (27%) and Europe (27%) also lead investment in wind.

Key themes

7.5 Material efficiency in heavy industries

In 2018, the industry sector accounted for 29% of final consumption and 42% of direct CO_2 energy-related and process emissions. In the Stated Policies Scenario, this contribution will grow to 30% of final consumption and 43% of CO_2 emissions in 2040, driven by increasing demand for materials and other industrial products.

Emissions from industry are more difficult to abate than those from other sectors for a number of reasons. Some industrial processes require high-temperature heat and some involve chemical reactions that produce emissions. Furthermore, industrial products tend to have low profit margins and to be traded in highly competitive markets, and this makes it difficult for producers to adopt costly low-emission technologies while remaining competitive. A strong push on energy efficiency and on fuel and feedstock switching contributes to significant reductions in the emissions intensity of production in the Sustainable Development Scenario. Electrification, the development and deployment of carbon capture, utilisation and storage (CCUS) and the introduction of hydrogen and other innovative technologies also have roles to play.

Material efficiency – an often under-appreciated strategy – can assist with pushing reductions even further. Alongside the closely related topics of the circular economy and resource efficiency, it has been gaining increased prominence in public debate. Several recent policy developments have placed a new emphasis on material efficiency.[3] These include:

- The G20 Osaka Leaders Declaration of 28-29 June 2019, acknowledged that resource efficiency, including sustainable materials management, contributes to the Sustainable Development Goals and enhances competitiveness. Leaders also looked forward to the G20 Resource Efficiency Dialogue resulting in the development of a roadmap.
- In March 2019, the European Union approved a ban on single-use plastic cutlery, cotton buds, straws and stirrers by 2021 and introduced a requirement for plastic bottles to contain 30% recycled content by 2030. In June 2019, Canada announced a similar ban that would come into effect in 2021 or afterwards. In Africa, 34 nations have banned the use of plastic bags.
- The European Union (EU) Ecodesign Directive, adopted in 2009, established a requirement to improve the environmental performance of products, focusing on lifecycle impacts during product design, as well as material efficiency. The European Union's 2018 Circular Economy Action Plan includes strategies to reduce further the lifecycle impact of plastic products.

[3] Material efficiency refers to actions across value chains such as lightweighting, using products for longer and direct material reuse, which result in lower demand for materials. It also includes other changes in materials use and management that enable emissions reductions, such as switching to lower emissions construction materials and increasing metals recycling to enable more energy-efficient secondary production.

- In April 2019, the European Union adopted a new regulation for passenger cars and light commercial vehicles that requires an evaluation by 2023 of the potential to develop a common methodology for assessing and reporting full lifecycle CO_2 emissions of cars and vans.
- In 2017, the Netherlands adopted a mandatory carbon cap for the environmental profile of new homes and offices that includes taking into account emissions from buildings materials production.

In this section, we quantify the impact on material demand, energy needs and CO_2 emissions in industry arising from economy-wide resource efficiency strategies including those applied in other sectors, such as transport, buildings and power generation. Our analysis focuses on widely used emissions-intensive materials such as steel, cement and aluminium and, to a lesser extent, petrochemicals.

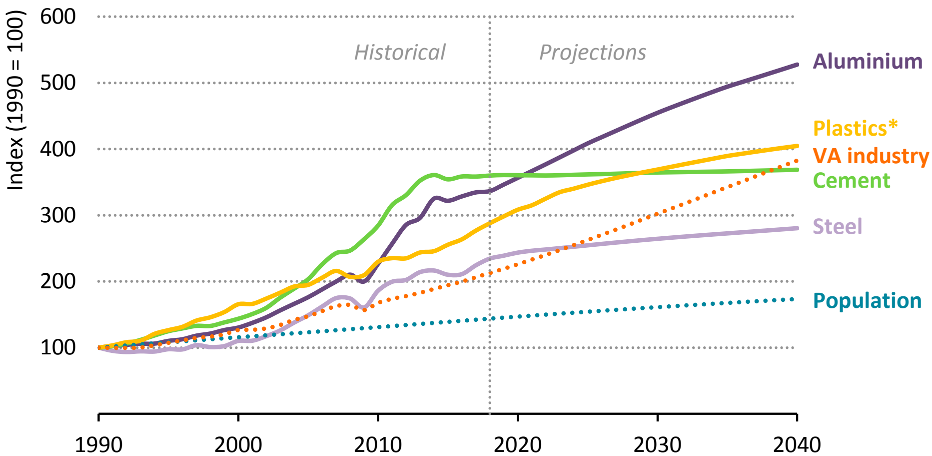
Demand for key materials

Material demand growth tends broadly to reflect economic and social development. At lower levels of economic development, per capita demand for materials is generally relatively low. As economies develop and urbanise, they consume more goods and build up their infrastructure (for example high-rise buildings, roads, railways and electricity generation infrastructure), and their material demand per capita tends to increase significantly. Demand for cement and steel for infrastructure generally rises sharply at this stage. Once an economy is industrialised, material demand per capita tends to level off or even decline: materials like cement and steel tend to be used primarily for replenishing and renovating stocks, though demand for other materials such as aluminium and plastics may increase, depending among other things on product demand, product lifetimes and behavioural patterns.

Global demand for materials has grown considerably in recent decades (Figure 7.4). Since 1990, global demand for steel has grown almost 2.5-times, for plastics by around three-times, and for aluminium and cement by around 3.5-times. This growth in demand has coincided with a 45% increase in global population and a doubling of industry's contribution to GDP growth.

There are differences in regional trends both in terms of the rate and magnitude of this growth in demand (Figure 7.5). Since 2000, the rapid development of China has fuelled global material demand growth, with per capita demand for some materials increasing to levels higher than in most developed economies. In recent years, however, demand in China for some materials appears to have levelled off: for example, cement production has declined from its 2014 peak and this decline is expected to continue in line with a slower pace of new infrastructure development. Even as demand growth slows in China, however, other developing economies including India (TERI, 2019) and economies in Asia, Latin America and Africa are set to drive growing global demand for materials.

Figure 7.4 ▷ Demand for key materials in the Stated Policies Scenario

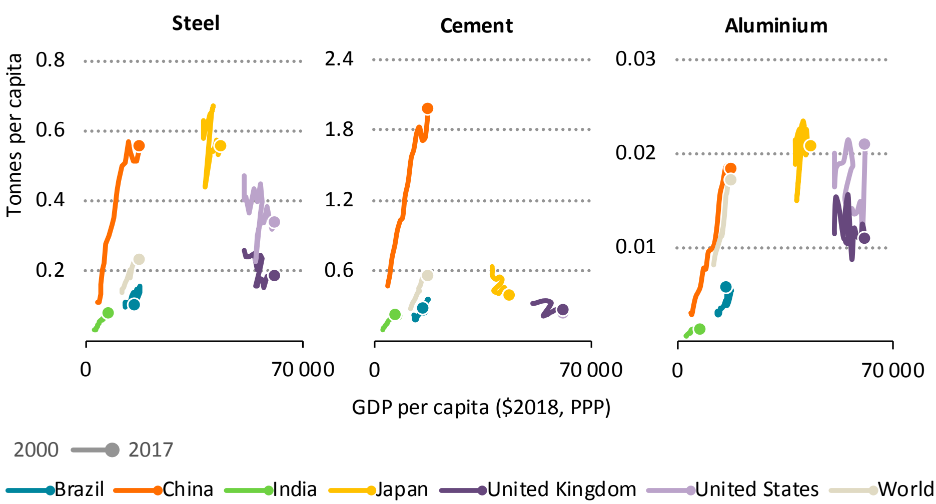


Demand for materials has increased considerably in recent decades and is set to continue for aluminium, plastics and steel

* Demand for high-value chemicals (ethylene, propylene, benzene, toluene and mixed xylenes), which are the key precursors to plastics, are used as a proxy for plastics demand. High-value chemicals are also precursors to synthetic fibre and rubber production. Note: VA = value added.

Sources: Platts (2019); USGS (2018a); USGS (2018b).

Figure 7.5 ▷ Per capita material consumption and GDP for selected countries, 2000-2017



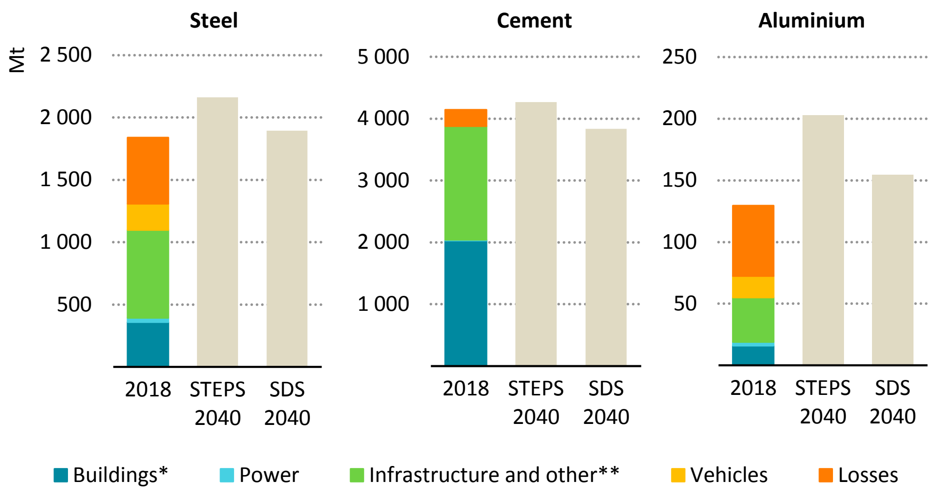
Per capita demand for materials is increasing but varies considerably by stage of economic development

The Stated Policies Scenario sees continued growth in material demand, including increases in demand by 2040 of 20% for steel, 57% for aluminium, 41% for high-value chemicals and 2% for cement. Industry emissions are projected to be 16% higher in 2040 than they are today. However, material efficiency gains have the potential to reduce this level of emissions by helping reduce demand for materials, complementing efforts to change the means by which materials are produced through energy efficiency improvements, fuel switching and the adoption of new low-carbon process routes that incorporate hydrogen or CCUS.

Material demand and interlinkages with CO_2 emissions abatement in other sectors

Energy transitions worldwide imply considerable changes in how we produce and use energy. Changes in activity in turn lead to changes in material demand and the share of materials going to various end-uses (Figure 7.6).

Figure 7.6 ▹ Material demand worldwide by scenario and end-use



Emissions abatement in the Sustainable Development Scenario reduces material demand. Buildings, infrastructure and other are the major end-use sectors to benefit.

* Buildings: For aluminium, this category includes all buildings and infrastructure, except for power infrastructure. ** Infrastructure and other: Includes transport infrastructure (e.g. roads, rail, bridges), other infrastructure (e.g. below-ground water supply networks, pipelines), ships, airplanes, mechanical and electrical equipment, consumer goods, domestic appliances and food packaging.

Notes: Mt = million tonnes; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Material demand changes include both activity levels and material efficiency. Losses are materials lost during manufacturing and semi-manufacturing stages, which do not end up in a specific end-use. Aluminium is liquid aluminium (includes internal scrap).

Road vehicles currently account for 12% of global demand for steel and for 14% of global demand for aluminium. In the Sustainable Development Scenario, there is a reduction of 12% in passenger light-duty vehicle sales and a 12% reduction in truck sales by

2040 compared with the Stated Policies Scenario, driven by a shift towards public transport, car sharing, improved fleet management aided by digitalisation, and increased average mileage per vehicle. This leads to fewer materials being needed for the manufacture of passenger vehicles and trucks, the effect of which is partially offset by increases in materials needed to produce more buses and railway stock. Considerable efforts go into vehicle lightweighting, i.e. making vehicles weigh less in order to increase their efficiency. Lightweighting reduces demand for steel, while increasing demand for aluminium, plastics and composites. It delivers overall lifecycle energy and CO_2 emissions savings: for example, it reduces the net lifecycle emissions in 2030 of the average internal combustion engine passenger car in the United States by around 4%.

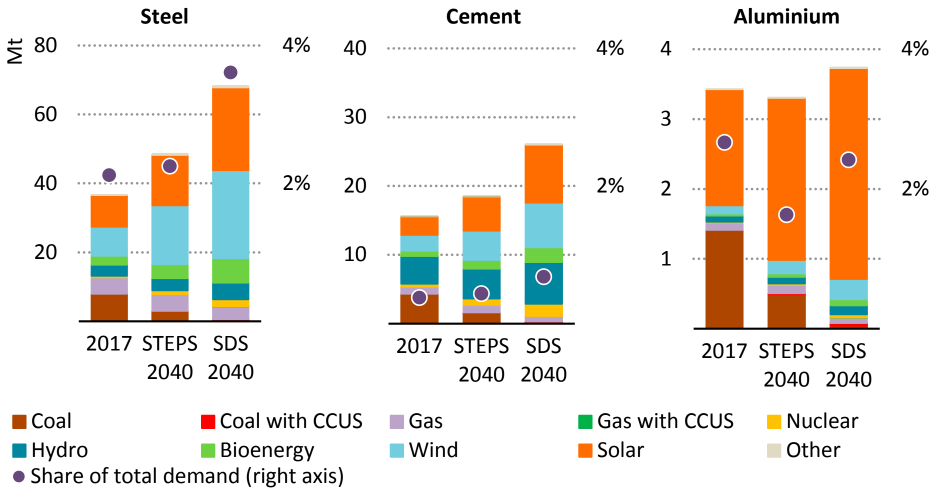
The increasing shift from internal combustion engine vehicles towards electric and (to a lesser extent) hydrogen fuel-cell vehicles also changes the nature of material requirements for manufacturing. Electric vehicles for example, contain less steel but more aluminium than internal combustion vehicles. In the Sustainable Development Scenario, material demand for vehicles in 2040 falls by 30% for steel and by around 20% for aluminium compared to the Stated Policies Scenario.

Requirements for transport infrastructure also change. By 2040, additional rail infrastructure leads to an increase in demand of about 35% for both steel and cement in the Sustainable Development Scenario relative to the Stated Policies Scenario. On the other hand, reduced vehicle travel requires less use of materials for the construction and maintenance of roads, leading to a decrease of about 15% in demand for these uses for both steel and cement. In the Sustainable Development Scenario, the combined material demand for rail and road transport infrastructure is 25% higher for steel and 5% higher for cement than in the Stated Policies Scenario, as the increase in demand for both materials for rail is higher than the decrease in demand from roads. The increase for cement is less than that for steel because roads require considerably more cement than railways do, and considerably more cement than steel.

Buildings account for an estimated 20% of global demand for steel and for about half of cement demand. Currently, many buildings, especially non-residential buildings, are demolished before the end of their useful lifetime. In the Sustainable Development Scenario, a large portion of the buildings stock undergoes deep retrofitting in an effort to improve the energy efficiency of building envelopes, thereby creating an incentive to continue using the building for longer in order to realise savings and reducing the need to construct new buildings. In 2040, demand for steel and cement for buildings is lower by around 15% in the Sustainable Development Scenario than it is in the Stated Policies Scenario.

Power capacity additions account for a small share of global demand for steel, cement and aluminium today. Demand from the power sector is likely to increase in the future. In the Sustainable Development Scenario, the power sector accounts for around 4% of steel demand, over 2% of aluminium and almost 1% of cement demand in 2040. Renewables make up a large share of power sector demand, accounting for up to 95% of some materials.

Figure 7.7 ▷ Power sector demand for steel, cement and aluminium by scenario



Energy transitions lead to increasing demand for materials for the power sector, but it accounts for a relatively small portion for steel, cement and aluminium demand

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Material intensity estimates for power were based on the work of Gibon et al., (2017). Percent of total demand accounts for material flows into final products; semi-manufacturing and manufacturing losses are not included.

The combined emissions from steel, cement and aluminium produced for use in power sector infrastructure in 2040 are about 4% higher in the Sustainable Development Scenario than they are in the Stated Policies Scenario, despite the much larger increases in material demand in the former scenario (Figure 7.7). This is the result of considerable reductions in the emissions intensity of materials production. Although materials production emissions account for a larger proportion of total power sector emissions in the Sustainable Development Scenario, this has to be seen in context: the combined overall emissions in 2040 from power generation and from steel, cement and aluminium production for power capacity additions in the Sustainable Development Scenario are less than 30% of those in the Stated Policies Scenario.

Material efficiency potential in the Sustainable Development Scenario

In addition to changes in material demand related to activity level changes, the Sustainable Development Scenario sees major efforts being undertaken to improve material efficiency – that is, to reduce material demand and to manage materials use and production in ways that reduce waste and increase recycling and reuse, in turn leading to lower energy use and emissions across value chains. These efforts are focused on steel, cement and aluminium, with a particular eye to material efficiency potential in the buildings and vehicles value chains.

Material efficiency improvements in the Sustainable Development Scenario stem from a diverse range of strategies applied to different materials and value chains (Table 7.6). Product or building design is a key determinant of lifecycle material demand, energy consumption and CO_2 emissions. Maximising the efficiency of fabrication and construction, optimising the useful lifetime of a product, and ensuring the appropriate treatment of its constituent materials at the end of its useful life are all also important.

Table 7.6 ⊳ Summary of material efficiency strategies in the Sustainable Development Scenario

Design	Manufacturing	Use	End-of-life
Overview			
• Lightweighting. • Reduce over-design, optimise design. • Design for use, long life and reuse.	• Reduce material losses. • Reduce material overuse.	• Lifetime extension and repair. • More intensive use.	• Remanufacture and repurpose. • Direct material reuse. • Recycle.
Steel			
☑ Vehicle lightweighting. ☑ Building design, reduce over-specification and concrete-steel composite construction; modular design for future materials reuse.	☑ Improve steel semi-manufacturing and end-use product manufacturing yields.	☑ Use buildings for longer through refurbishment. ☑ Mode shift to reduce the number of vehicles being produced.	☑ Direct reuse of steel (with highest potential in specific end-uses such as ships). ☑ Recycle.
Cement			
☑ Building design, reduce over-specification and concrete-steel composite construction; modular design for future materials reuse.	☑ Improved construction, including reducing onsite construction waste, reducing cement content in concrete and pre-cast fabrication.	☑ Using buildings for longer through refurbishment.	☑ Concrete reuse.
Aluminium			
☑ Vehicle lightweighting (steel-aluminium substitution) offsets some reductions from other strategies.	☑ Improve aluminium semi-manufacturing and end-use product manufacturing yields.	☑ Mode shift to reduce the number of vehicles being produced.	☑ Direct reuse of aluminium. ☑ Recycle.

☑ High potential ☑ Medium potential ☑ Low potential ☑ Increase in demand

By 2040, overall net demand in the Sustainable Development Scenario is reduced relative to the Stated Policies Scenario by 12% for steel, 10% for cement and 24% for aluminium. These net reductions occur despite some upward pressure from increased aluminium demand owing to vehicle lightweighting and increased material demand for power and transport infrastructure. They are achieved through a combination of material efficiency strategies and changing patterns of demand.

Some material efficiency strategies are focused on the nature of materials production. For example, increasing metal scrap collection rates, improving sorting and reducing contamination result in more scrap availability, thus enabling higher shares of secondary production, which is less energy and emissions intensive than production using virgin materials. However, material efficiency can also affect the total amount of scrap available. While improved end-of-life collection rates help increase the amount of scrap metal available, improved manufacturing yields and lifetime extension and reuse place downward pressure on scrap availability. In the Sustainable Development Scenario, the net impact of these pressures is a reduction in both steel and aluminium scrap availability. This underlines the importance of a systems approach: savings from material efficiency cannot simply be added on top of energy efficiency savings.

In the case of cement, reducing the clinker-to-cement ratio is an important way of improving materials efficiency during manufacturing. Clinker is the main active ingredient in cement and its production is the most emissions intensive part of cement production. While common Ordinary Portland Cement typically contains more than 90% clinker, it is possible to replace a considerable portion of clinker with alternative cement constituents, such as fly ash, granulated blast furnace slag, ground limestone, calcined clay, volcanic ash, rice husk ash and silica fume. This makes more efficient use of clinker and reduces the carbon footprint of cement substantially.

Improvements for other materials also play an important role. Improving recycling rates of plastics, for example, can displace considerable chemical sector demand (Box 7.1).

Box 7.1 ⊳ Plastics recycling is a key to reduce chemical material demand

Petrochemical products are found everywhere and are an integral part of modern society. They include plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents, tyres and many other products. Led by developing economies, demand for petrochemicals is surging and will continue to grow. As a result, petrochemicals are rapidly becoming the second-largest source of oil demand growth.

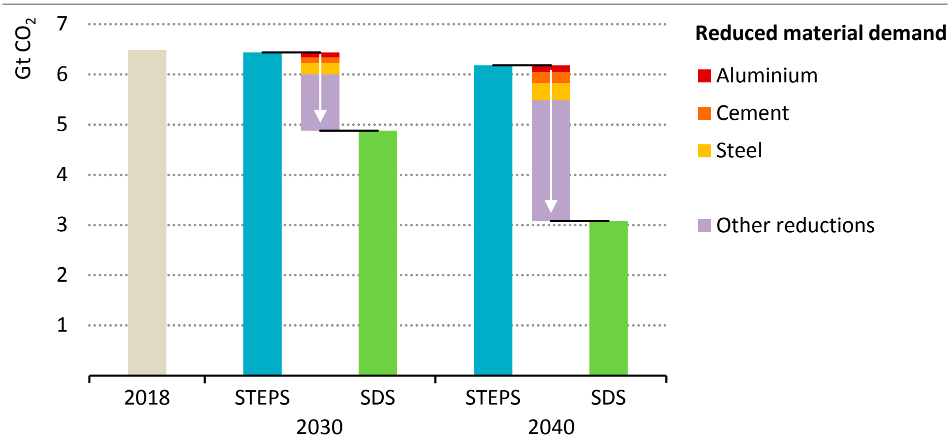
In 2018, the IEA examined the consequences of increased demand for these products, and what can be done to accelerate a clean energy transition for the petrochemical industry (IEA, 2018a). It found that the reduction in direct CO_2 emissions in the Sustainable Development Scenario would result in a decrease in environmental impacts associated with petrochemicals, but that a broad range of efforts will be required to tackle plastic pollution in oceans and other forms of environmental damage.

Plastic recycling is a key underlying source of emissions reduction in the Sustainable Development Scenario, which sees a substantial increase in waste plastic collection rates, recycling yield rates and displacement rates (the extent to which recycled plastics displace demand for their virgin counterparts). Recycling yield rates increase from an average of 75% in 2017 to nearly 85% in 2050. Displacement rates double, from about one-third today to two-thirds in 2050. However, achieving the improvements is dependent on significant technical advances in recycling processes.

Contribution of material demand changes to energy and CO_2 savings

The policy changes in buildings, transport and power generation, and the industrial material efficiency strategies included in the Sustainable Development Scenario together have the potential to bring about significant changes in energy demand and CO_2 emissions trends for key energy-intensive industries. Thanks to a combination of these and other policies to reduce the emissions intensity of material production, CO_2 emissions from steel, cement and aluminium stabilise after 2019 in the Sustainable Development Scenario and enter a steady decline thereafter. Without those policies, emissions trends instead plateau under the Stated Policies Scenario (Figure 7.8). Material demand reductions alone contribute to over 20% of the Sustainable Development Scenario reductions in 2040. Additional material efficiency strategies such as reducing the clinker-to-cement ratio and increases in secondary metals production also contribute to the overall emissions savings, while also bringing air quality and health benefits.

Figure 7.8 ⊳ CO_2 emissions reductions resulting from material demand reductions for steel, cement and aluminium



Policies in transport, buildings and power sectors can change material demand and contribute to a reduction in heavy industry emissions

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Emissions include direct energy-related, process and indirect electricity emissions. Other reductions include factors that reduce the emission intensity of material production, i.e. energy efficiency, fuel switching, CCUS, hydrogen-based production, other innovative technologies, and other aspects of material efficiency not directly related to demand reduction (e.g. increased secondary metals production).

Challenges, costs and enabling policies and actions

Various barriers and challenges prevent material efficiency from maximising its full potential even in cases where it would be economically beneficial. These include real and perceived risks; financial costs and time constraints; limited awareness of and training in material-efficient design and construction methods; fragmented supply chains that pose challenges for direct materials reuse; and restrictive design standards that may hamper the uptake of new materials or design methods.

As far as costs are concerned, comprehensive analysis of material efficiency costs found that some strategies may result in savings (car sharing, reducing waste in buildings construction and increasing collection rates of aluminium), while other strategies have moderate abatement costs (Material Economics, 2018). All the strategies in the analysis had costs of below EUR 100/tonne CO_2, which is below the level of most carbon prices in 2040 in the Sustainable Development Scenario.

Further efforts will be required to overcome non-financial barriers related to perceived risks, co-ordination and behaviour. This is a matter for governments to consider in the light of their own goals and circumstances, but also for industry, researchers and consumers. In pondering what might be useful, stakeholders might want to consider the scope to:

- **Improve data collection, lifecycle assessment, benchmarking and material flow analysis**: More robust data and better modelling tools would help to support the development of benchmarks. They would also support the development of regulations if governments adopt such measures.
- **Pay greater attention to the lifecycle impact at the design stage and in climate regulations**: Designers and manufacturers should take into account the trade-offs between production and use-phase emissions, and design for long lifespans, repurposing, reuse and recycling. Governments may wish to consider the case for underpinning this by moving towards lifecycle based requirements in emissions regulations.
- **Increase product lifespans and promote repurposing, reuse and recycling**: Government and industry should promote durability and long lifetimes for building and products, except in cases where doing so would lock in CO_2 emissions and lead to higher lifecycle emissions. Increased materials reuse and recycling could be facilitated by better supply chain integration, mandating the use of a share of recycled materials in products, adopting landfill disposal fees and expanding the coverage of recycling requirements.
- **Develop regulatory frameworks and fiscal incentives to support material efficiency**: Moving from prescriptive to performance-based design standards would facilitate efficient use of materials. Carbon pricing would incentivise material efficiency, green certification programmes and government procurement could also help to support it.
- **Adopt business models and practices that advance circular economy objectives**: Business models that promote a sharing economy and incorporate digitalisation may help to reduce materials use. Company monitoring and reporting requirements could deter practices that may increase material use.
- **Train, build capacity and share best practices**: Material efficiency has an important part to play in education programmes for designers, engineers, construction workers, and manufacturing and demolition companies. Government-supported capacity building could help, as could best practice sharing among companies.

- **Shift behaviour towards material efficiency**: Consumers can seek to make a difference by opting for products with materially efficient design, particularly if eco-labels give them relevant information, and can also play their part in improving recycling rates.

7.6 Smart electricity use: the power of the hour in reducing emissions

Emissions linked to the use of electricity are often calculated using average annual CO_2 emissions intensity of electricity supply. In reality, the CO_2 emissions intensity of electricity supply, and therefore electricity use, varies significantly depending on when the electricity is used and the electricity generation mix of the region. This variability is projected to increase in both the Stated Policies and Sustainable Development scenarios as shares of variable renewables increase and demand becomes more concentrated in peak hours.

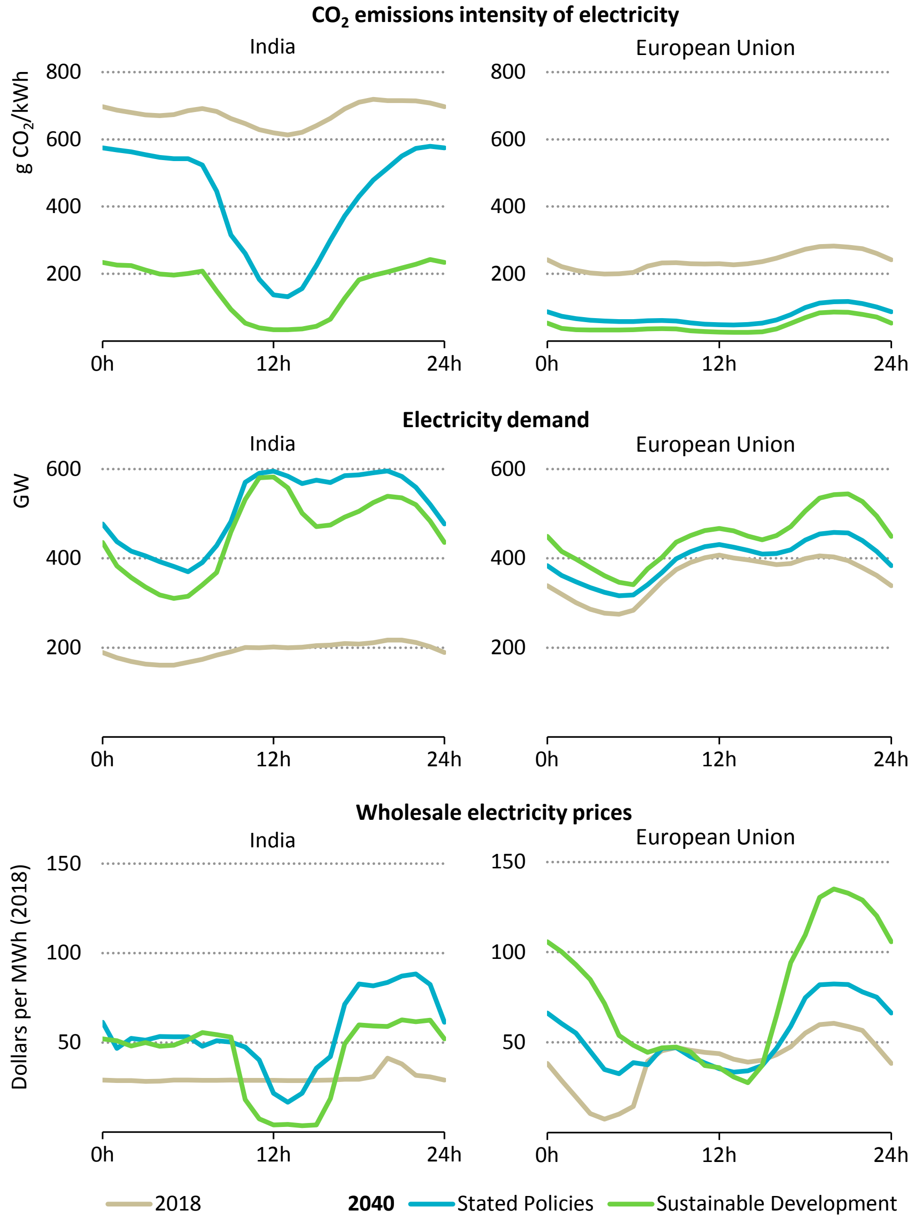
This presents opportunities for reducing CO_2 emissions. Targeted energy efficiency and demand-side response can significantly reduce CO_2 emissions linked to electricity use, as well as contributing to power system operation and flexibility needs, lower consumer electricity bills and improved air quality. Tapping these potential gains however depends on adequate and accessible markets for flexibility, and on electricity pricing models which incentivise consumers to reduce demand at peak periods.

7.6.1 Hourly electricity supply CO_2 emissions intensity: status and outlook

The time-based variation of the emissions intensity of electricity generation is a result of the changing contribution of different technologies to electricity generation at various times of the day. The variation in the hourly average carbon emissions intensity of electricity supply is especially affected by the increases in generation from variable renewables (VRE) such as solar PV and wind. The share of VRE in global electricity generation increased from under 2% in 2010 to 7% in 2018. By 2040, this share reaches 24% in the Stated Policies Scenario and rises to 40% in the Sustainable Development Scenario. Using the World Energy Model (WEM) hourly electricity supply model, we are able to determine the implications of increasing shares of VRE on the average hourly variation of electricity supply CO_2 intensity.

In some countries the carbon intensity of electricity supply in 2040 is generally lowest during the middle of the day when generation from solar PV is highest, with CO_2 emissions intensity becoming higher during evening peaks when the sun sets and more fossil fuel-fired generation is used to meet demand. This is especially the case in systems where solar PV and gas (or coal) represent the largest sources of generation. In both the Stated Policies and the Sustainable Development scenarios, India moves into this position in the years ahead. The share of solar PV in generation rises in India from 3% today to 31% by 2040 in the Sustainable Development Scenario, significantly reducing average electricity supply CO_2 intensity during the middle of the day. As a result, the CO_2 intensity of generation in 2040 varies by a factor of seven across an average day in this scenario.

Figure 7.9 ⊳ Average hourly CO_2 emissions intensity, electricity demand and wholesale electricity prices in India and the European Union



Daily variation in the average CO_2 intensity of electricity increases to a factor of seven in India, with generation oscillating between solar PV and gas or coal. The European Union, with higher shares of wind generation, reaches a factor of three.

Note: g CO_2/kWh = grammes of CO_2 per kilowatt-hour; MWh = megawatt-hour.

Power systems with a varied mix of generation technologies will have a different profile of average CO_2 emissions intensity of electricity supply. For example, in systems with large shares of generation from wind, the CO_2 intensity can be lowest during the night when demand is low and the wind is blowing. The European Union is an example of a system where wind emerges as the largest source of generation in both the Stated Policies and Sustainable Development scenarios. Hourly average CO_2 emissions intensity is lowest during the night and middle of the day, and peaks during winter evenings when demand is highest. The result is a difference of up to a factor of three in the average CO_2 intensity of electricity between certain hours of an average day (Figure 7.9).

7.6.2 Implications for policy makers and consumers

Two pathways offer policy makers and consumers opportunities to translate time-based electricity supply CO_2 intensity information into a reduction in the CO_2 emissions associated with electricity demand.

Targeted energy efficiency to deliver the Sustainable Development Scenario

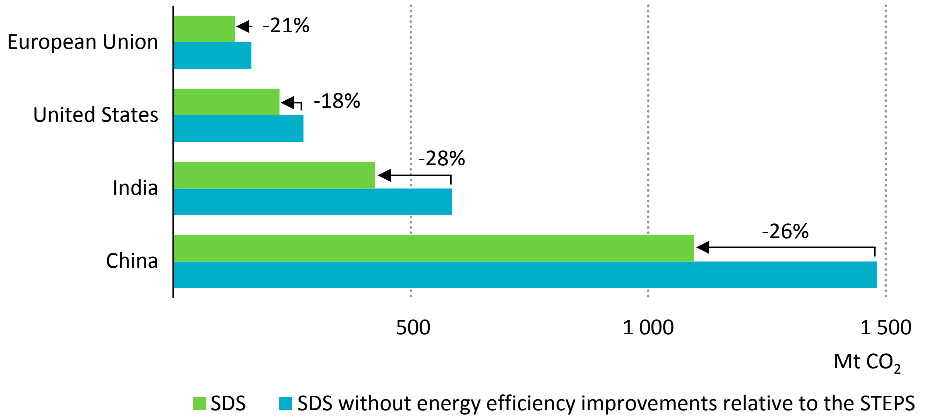
Decarbonisation of electricity supply accounts for the bulk of the difference in CO_2 emissions from electricity generation between the Stated Policies and Sustainable Development scenarios. Nevertheless, energy efficiency has a major role in reducing electricity sector emissions in the Sustainable Development Scenario, and energy efficiency policies could support the reduction of emissions by targeting demand reductions when the average emissions intensity of generation is high (for example evening peaks, or nights in solar PV dominated systems).

For the first time, this *World Energy Outlook* computes average CO_2 emissions intensity of different uses of electricity and provides an indication of where additional energy efficiency efforts could maximise emissions reductions. Our assessment of hourly electricity usage and the CO_2 intensity of electricity supply illustrates that the average annual CO_2 intensities of different uses of electricity can vary by over 30% in the Stated Policies Scenario. The largest variation is in India, where the majority coal and solar PV based power system sees the average CO_2 emissions intensity of end-uses vary by over 120 grammes of CO_2 per kilowatt-hour (g CO_2/kWh) in the Stated Policies Scenario in 2040. Space cooling in commercial buildings has the lowest average emissions intensity as a result of its strong correlation with generation from solar PV. Lighting in homes and electric vehicle (EV) charging have the highest CO_2 intensities as a result of the concentration of these uses during evening peak-load periods when solar PV is not available. By way of comparison, the CO_2 intensities of the lowest and highest end-uses in the Stated Policies Scenario vary by almost 30% in the European Union, 20% in China, and 15% in the United States in 2040.

Energy efficiency efforts in the Sustainable Development Scenario reduce electricity demand by 23% in India relative to the Stated Policies Scenario. Thanks to targeting of additional energy efficiency efforts towards the most carbon-intensive end-uses, this leads to a larger reduction in CO_2 emissions, with a decrease of almost 30% (Figure 7.10). In the

European Union and the United States, achieving energy efficiency gains in line with the Sustainable Development Scenario, including by targeting energy efficiency improvements on CO_2 intensive end-uses such as home appliances and air conditioners, also has more of an impact on CO_2 emissions than electricity demand. These reductions are additional to the impact of decarbonising electricity supply in the Sustainable Development Scenario.

Figure 7.10 ▷ Impact of energy efficiency on CO_2 emissions from electricity supply in the Sustainable Development Scenario, 2040



Energy efficiency reduces global emissions from electricity by one-quarter, on top of the benefits of decarbonising electricity supply in the Sustainable Development Scenario

Note: SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario; Mt CO_2 = million tonnes of carbon dioxide.

The emission reductions in Figure 7.10 depend on measures being taken to incentivise them. Equipment with a long lifetime can in effect lock in electricity demand at times when variable renewables are rarely available to meet demand, and this has the potential to prolong reliance on CO_2 emissions intensive sources of generation if storage or other dispatchable low-carbon sources of supply are not available. Governments can take advantage of the opportunity to multiply the CO_2 emissions abatement impact of energy efficiency measures by improving minimum energy performance standards for appliances and equipment (especially in the residential sector); providing financial incentives for building retrofits and replacement of inefficient equipment, and supporting the further digitalisation of electricity use and associated opportunities.

Demand-side response and consumer awareness: unlocking further reductions

Demand-side response (DSR) draws on the willingness and ability of certain users of electricity to shift electricity demand in time in response to signals from the market or system operator. Typically DSR is used to provide flexibility to power systems by reducing demand during periods of high relative electricity prices, drawing principally on the flexibility of large-scale industrial and commercial customers.

DSR can also be utilised as a tool for CO_2 emissions reduction, shifting demand from periods of CO_2-intensive electricity supply to less CO_2-intensive periods, reducing the curtailment of variable renewables and lowering CO_2 emissions. The projected increase in the average hourly variation of the CO_2 intensity of electricity offers opportunities for exactly this.

If enough consumers are willing to participate in demand-side response and be flexible in their electricity consumption behaviours, the potential of DSR could be considerably increased beyond what is seen in the Sustainable Development Scenario. The impacts of such enhanced DSR were assessed using the WEM hourly electricity supply model, with economic dispatch that maintains systems reliability. Analysis showed that up to 20% of peak load could potentially be shifted to periods of lower CO_2 intensity in electricity supply, thus reducing overall CO_2 emissions. In addition to tapping DSR potential from uses such as water heating, refrigeration, heating and cooling, drawing on low-cost demand-side flexibility resources such as optimised EV charging is central to enhancing DSR (see Spotlight).

S P O T L I G H T

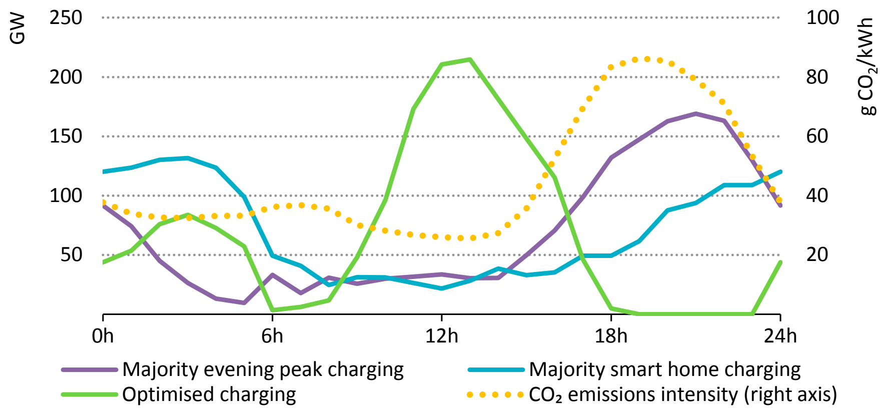
When to plug in: the system impact of EV charging times

With stronger policy support and battery costs falling, the global electric vehicle (EV) market is growing rapidly. EVs account for 75% of new vehicles sales by 2040 in the Sustainable Development Scenario. Rapid growth in EV deployment could have major implications for power systems. Currently the majority of EV charging occurs at home (IEA, 2019d). If charging is concentrated during evening peaks when people return from work, and storage is not deployed at scale, the average CO_2 emissions intensity of road transport in 2040 would be the highest of all electricity end-uses; up to 25% higher than the average CO_2 emissions intensity of electricity use in India and the European Union in the Sustainable Development Scenario, and close to 20% higher than in China and the United States.

The flexibility of EV charging times and locations creates an opportunity to further improve the CO_2 emissions benefit of switching to EVs. "Smart charging" at home could use overnight off-peak electricity (Figure 7.11). If widely adopted, this type of charging would reduce peak electricity demand and also reduce overall CO_2 emissions. In Europe for example, the average CO_2 intensity of EV charging in 2040 using smart charging would be around 20% less than if charging was concentrated during evening peaks.

An increase in the share of vehicles charging at workplaces or communal charging locations during the day, when solar PV output is at its highest, offers the greatest potential for CO_2 emissions reductions. A balanced approach combining daytime workplace charging and night time home charging could reduce the average CO_2 emissions intensity of EV charging by 45% in the European Union and more than double CO_2 emissions reductions relative to majority smart charging at home. Vehicles could also be used to supply electricity and other services to the grid or buildings during peak times, known as "Vehicle2X". With the right regulatory framework and incentives, this approach could unlock further emissions reductions and system benefits.

Figure 7.11 ▷ **EV charging patterns and average hourly CO_2 emissions intensity of electricity in the European Union in the Sustainable Development Scenario, 2040**



Changing behaviour to increase EV charging during times of low CO_2 intensity of electricity supply could reduce EV CO_2 emissions by over 45%

In an enhanced DSR case in China, an average of around 250 GW of electricity demand are shifted by 2040 from hours of high average CO_2 intensity of electricity supply to periods of near-zero average CO_2 intensity (Figure 7.12). The additional demand during the middle of the day allows for the integration of a further 330 GW of solar PV, representing an increase of 20%, without increasing curtailment rates. Enhanced use of DSR could see CO_2 emissions from electricity supply reduced by 16% relative to levels of DSR in the Sustainable Development Scenario.

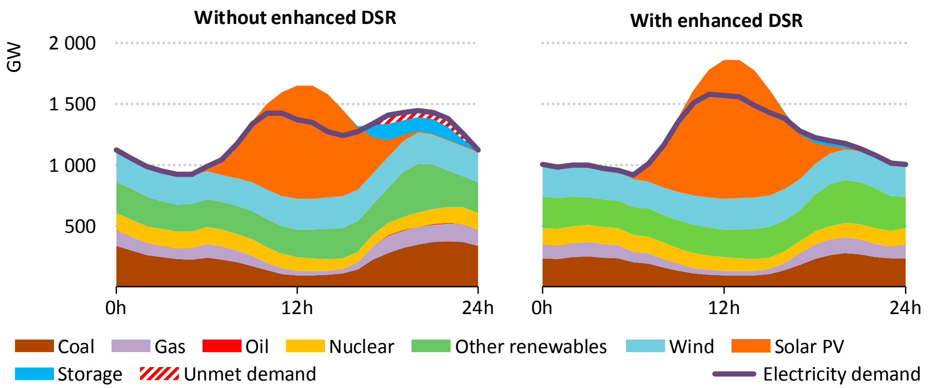
The United States would also see important gains from significant increases in the use of DSR, with the possibility of shifting an average of over 100 GW of load to the middle of the day and integrating an additional 130 GW of solar PV, potentially reducing emissions from electricity supply by up to 65 Mt CO_2 (-25%). The exact emissions savings from enhanced DSR would depend on what technologies are used to meet the increase in demand during the middle of the day (Box 7.2).

Achieving the potential for CO_2 emissions abatement from DSR requires the existence of market opportunities for DSR and incentives for consumer participation. In some markets today, regulatory and market barriers either prohibit the participation of aggregators[4] or other DSR providers in flexibility and energy markets, or render participation expensive (IEA, 2018b). Policy makers have a role to play in creating adequate markets for flexibility

[4] A typical DSR aggregator is a third-party company that contracts with individual demand sites (industrial, commercial or residential consumers) and aggregates them to operate as a single DSR provider.

with access for a range of actors including aggregators, and also in legislating connectivity as part of energy efficiency standards, while ensuring that cybersecurity risks and other consumer concerns are adequately addressed. Standardising market and regulatory frameworks across jurisdictions would help to accelerate deployment. Progress is already being made in many major markets and DSR is beginning to spread beyond the traditional centres of the United States and Europe (IEA, 2018b).

Figure 7.12 ▷ Average hourly electricity supply and demand in China in the Sustainable Development Scenario, 2040



Tapping additional demand-side flexibility can shift electricity demand to periods of lower CO_2 intensity of electricity supply, with the potential to reduce emissions by 16% in China

Box 7.2 ▷ Measuring the benefits: average or marginal CO_2 intensity?

The World Energy Model includes a module simulating hourly electricity demand and supply through economic dispatch. Dispatch modelling captures the effects of generator availability and changing demand on the mix of generators dispatched and therefore the CO_2 emissions associated with electricity supply. This effectively captures the marginal effect of higher utilisation of demand-side flexibility on CO_2 emissions.

Without the use of an economic dispatch model, assessing the impact of shifting demand on power sector CO_2 emissions could be estimated using the average CO_2 intensity of electricity supply or the marginal CO_2 intensity. However, either approach would miss parts of the complex dynamics of power system operation, limiting the accuracy of estimates.

Applying the average CO_2 intensity of electricity supply overlooks the fact that the marginal unit responding to increases (or decreases) in demand often has a higher CO_2 intensity than the average, and this could lead to overestimation of the CO_2 emissions reductions. However, in the case of structural changes to electricity demand, such as energy efficiency, using the average CO_2 intensity provides a reasonable estimate of the minimum impact on emissions.

Applying the CO_2 intensity of the marginal unit approach may not pick up all the changes in the generation mix and overall CO_2 emissions that may result from an economic dispatch modelling based on a new demand profile incorporating enhanced DSR. For example, increasing day-ahead demand may lead nuclear power plants to increase operation during all hours of the day, not just during periods of increased demand, and thus lower CO_2 emissions.

Small dispersed loads in the buildings sector such as residential air conditioners and water heaters represent the largest opportunity for DSR globally. For this potential to be realised, digital infrastructure such as smart meters and price incentives for consumers are necessary, as are aggregators or electricity retailers able to connect consumers to markets that value their flexibility.

How and what share of the value of DSR is channelled to consumers will depend on business models, electricity tariff design, taxation and other charges. Real-time pricing exposes consumers to variations in wholesale prices, creating direct incentivises to shift flexible demand to times of low prices, but they can also expose consumers to unexpected price hikes, since consumers are unlikely to be able and willing to monitor and manage their domestic electricity consumption more or less continuously. Fixed time of use tariffs provide more predictable incentives, but have less ability to reflect the variability of the intensity of CO_2 emissions. Business models which rely on the automation of DSR from household appliances and equipment may be of wider appeal to consumers, and also be capable of generating significant savings in CO_2 emissions.

7.6.3 System benefits

Optimising electricity demand for CO_2 emissions reductions also has wider system benefits: using targeted energy efficiency and demand-side response has the potential to assist power system operation, reduce electricity bills and moderate air pollution.

Implications for flexibility

Flexibility needs globally are expected to increase much faster than electricity demand in the Stated Policies Scenario, owing to a combination of a rising share of variable renewables in electricity supply and a rapid rise in demand for uses such as cooling and EV charging which tend to add to peak demand (see Chapter 6).

Focusing energy efficiency efforts on the most CO_2 intensive end-uses will reduce not only CO_2 emissions but also peak electricity demand. Lowering peak demand reduces hourly ramping requirements for power systems, and this reduces the need for flexibility.

The deployment of demand-side response to shift electricity usage from times of high CO_2 intensity of supply to times of high shares of generation from variable renewables will also tend to reduce hourly ramping requirements, as, in general, it implies moving demand away from peak hours when the system is constrained and flexibility needs are highest. The ability of electricity demand to be a source of flexibility for the system, with the potential to shift demand in time, is a subject explored in detail in the Special Focus on Electricity in the *World Energy Outlook-2018* (IEA, 2018b).

Implications for consumer bills

Energy efficiency lowers consumer bills directly by reducing overall electricity demand. DSR can also lower consumer bills, but its effect is less direct. Variable renewables such as wind and solar PV have a short-run marginal cost of near-zero, so using DSR to shift electricity demand to periods when a very high share of electricity comes from solar PV or wind can result in a considerable reduction in average wholesale prices. Enhanced deployment of DSR reduces average annual wholesale prices by 5% in the United States and almost 10% in China. The share of this price reduction passed on to consumers will depend on a number of factors, including the share of energy costs in consumer bills in each jurisdiction.

Optimising electricity demand for CO_2 emissions reductions will also have an impact on the fixed component of consumer bills, albeit over a longer timeframe. Reducing peak demand and using DSR to provide low-cost flexibility to power systems will reduce the need for other flexibility solutions such as transmission capacity and distribution network upgrades. This is especially relevant in the case of EV charging, where uncoordinated charging has the potential to place considerable strain on distribution networks.

7.7 Biogas: turning organic matter into renewable energy

Over one billion tonnes of organic by-products and waste are thrown away or abandoned every year. Their decomposition can lead to emissions of methane, which has a significantly higher global warming potential than CO_2: the waste, if left unmanaged, can cause land and groundwater contamination. If these waste products were collected and processed in an appropriate way, they could provide a valuable source of renewable energy in the form of biogas.

The technologies to produce biogas are not new, yet only a handful of countries produce biogas today. Nonetheless recent years have seen a resurgence of interest in how biogas technologies might aid progress towards the energy-related Sustainable Development Goals while improving sanitation and waste management. Biogas can provide a local source of power and heat for rural communities, as well as a source of clean energy for cooking and heating in communities that lack access to energy and sanitation, and that suffer from indoor air pollution. If biogas is upgraded to pipeline-quality gas, it is typically then known as biomethane and it could help to reduce the emissions intensity of gas supply in gas-consuming economies. In addition, when it results in the productive use of methane that would otherwise be released into the atmosphere, the use of biogas can lead to an additional reduction in GHG emissions.

This section provides an overview of the key technologies and production pathways for biogas (Box 7.3), explores potential volumes and production costs, and discusses various biogas applications. There is further discussion about the potential role of biogas in helping to achieve clean cooking access in African countries in Chapter 9 and about its role in decarbonising gas supply in Chapter 13.

Box 7.3 ▷ Glossary: biogas and biomethane

Biogas: A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment. The composition of biogas depends on the type of feedstock and the production pathway. The methane content of biogas typically ranges from 45% to 75% and the CO_2 content from 25% to 55% by volume.

Biomethane (also called "renewable natural gas"): A near-pure source of methane produced either by "upgrading" biogas (a process that removes any CO_2 and other contaminants present in the biogas), or through the gasification of solid biomass followed by methanation.

Energy content: The net calorific value of biogas is less than that of methane due to its higher CO_2 content. The lower heating value (LHV) of biogas varies by feedstock between 16 and 28 megajoules per cubic metre (MJ/m^3). Biomethane is assumed here to have an LHV of 36 MJ/m^3 (natural gas is around 35 MJ/m^3). Biogas and biomethane are reported here in million tonnes of oil equivalent (Mtoe); biomethane can also be given in volumes that are equivalent to natural gas (i.e. billion cubic metres).

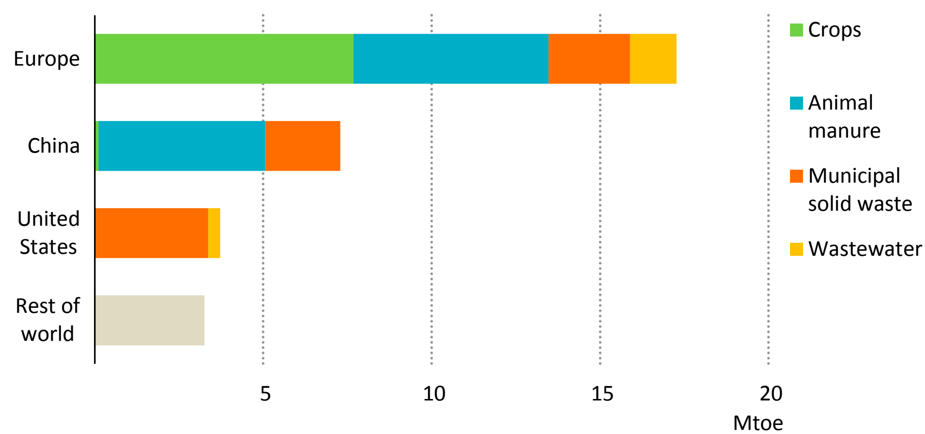
State of play: main technologies, uses and production today

Around 30 Mtoe of biogas was produced worldwide in 2017, of which 90% was in Europe, China and United States (Figure 7.13). Around 60% of production is used for electricity and heat generation: in terms of electricity, there is some 18 GW of biogas electricity capacity globally, half of which is in Germany and the United States. Around 30% of global biogas production is consumed in buildings, mainly in the residential sector. A further 8% production is upgraded to biomethane and is blended into the gas networks, and a small proportion is used directly as transport fuel.

A wide variety of feedstocks can be used to produce biogas. In a detailed bottom-up analysis of global supply potential conducted for this *Outlook*, we considered 17 individual types of residue or waste, grouped into four broad feedstock categories: crop residues, animal manure, wastewater sludge, and municipal solid waste (MSW) which includes landfill gas.[5] Biogas production pathways vary by feedstock and region and rely on the following main technologies:

- Biodigesters: Naturally occurring micro-organisms break down crop, manure or MSW feedstock to produce biogas through anaerobic digestion. Contaminants and moisture are usually removed prior to use of the biogas.
- Landfill gas recovery systems: The decomposition of MSW under anaerobic conditions at landfill sites produces biogas. Capturing this gas requires pipes and extraction wells within the landfill site along with compressors to induce flow to a central collection point.
- Wastewater treatment plants (WWTP): These are designed to treat and recover wastewater, but biogas can be produced as a by-product. Anaerobic digestion is used, but with an additional filtration and drying step because of the high moisture content of sewage sludge.

Figure 7.13 ▷ Biogas production by region and feedstock, 2017



Agricultural feedstock is the main source of biogas production in Europe today, China relies mostly on animal manure, while municipal solid waste is the primary feedstock in the United States

Notes: Crops include energy crops, crop residues and sequential crops. Sequential crops are grown between two harvested crops as a soil management solution that helps to preserve the fertility of soil and avoid erosion; they do not compete with food for agricultural land.

[5] Another possible feedstock source is industrial waste, especially from the food processing sector (sometimes called "agro-industrial" feedstock). This could have a strong economic case since the feedstock is produced on-site and a co-located biodigester plant can offset on-site energy demand; however there is limited data available on its potential. In our analysis, we include only distiller dry grain, a by-product from ethanol production, for which comprehensive and reliable data are available. This source is included in the MSW category.

The growth of biogas across the three main production regions to date – Europe, China and United States – has been shaped by three main factors: local conditions, policy support and feedstock availability.

- In Europe, biodigesters processing agricultural and municipal wastes, most notably in Germany, have provided the majority of the two-thirds growth in biogas production since 2009 (EBA, 2017). Energy crops have played a key role as biogas feedstock in the growth of Germany's biogas industry, but there is a vigorous debate about their land-use impacts, and so policy has shifted towards the use of crop residues, sequential crops, livestock waste and the capture of methane from landfill sites (Theuerl et al., 2019).
- In China, policies have supported the installation of household-scale digesters in rural areas as part of a drive to increase access to modern energy and clean cooking fuels. This type of deployment accounts for around 70% of installed biogas capacity in the country, but it has increasingly been accompanied by larger scale combined heat and power plants, which currently provide around 600 MW capacity, and by the production of biomethane.
- In the United States, policies and regulations have traditionally focused on landfill gas collection, which today accounts for nearly 90% of total biogas production in the United States. There is also growing interest in biogas production from agricultural waste, since domestic livestock markets are responsible for almost one-third of methane emissions in the United States part of which could be reduced producing biogas (USDA, 2016). The United States is also leading the way globally on the use of biomethane in the transport sector, primarily because of policy support in the form of the federal Renewable Fuel Standard (US EPA, 2018) and California's Low Carbon Fuel Standard (California Air Resources Board, 2019).
- Around half of the remaining production comes from developing countries in Asia. Access to the Clean Development Mechanism[6] (CDM) was a key factor underpinning this growth, particularly between 2007 and 2011: the development of new projects fell sharply after 2011 when the value of emission reduction credits awarded under the CDM fell. Today, most production in the region comes from Thailand and India. Thailand produces biogas from the waste streams of its cassava starch sector, its biofuel industry and pig farms (Suwanasri et al., 2015). Despite the stalling of projects incentivised through the CDM, India expects to see the development of 5 000 compressed biogas plants over the next five years (GMI, 2019).

Biogas cost supply curve

For this *Outlook*, we have developed a new global assessment of the sustainable technical potential and costs of biogas supply, and how this might evolve in the future. This is based on a detailed assessment of the availability of 17 individual residues and wastes across the

[6] Under the Clean Development Mechanism of the Kyoto Protocol emission-reduction projects in developing countries can earn certified emission reduction credits.

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25 regions modelled in the World Energy Model. Biogas production pathways were generated for each feedstock based on the range of technologies available, including different sizes of biodigesters and the availability of sustainable feedstocks. On this point, we have assumed that most of the organic content of MSW (when not composted or recycled) could be recovered sustainably even though a considerable amount is at present incinerated or disposed of in landfills. We have also assumed that the use of crop residues for biogas is limited to half of annual production in order to avoid soil erosion and soil nutrient depletion. Our estimates of biogas supply potential and production costs today were then projected forward taking account of GDP and population growth, urbanisation trends, changes in waste management processes and rates of technology evolution.

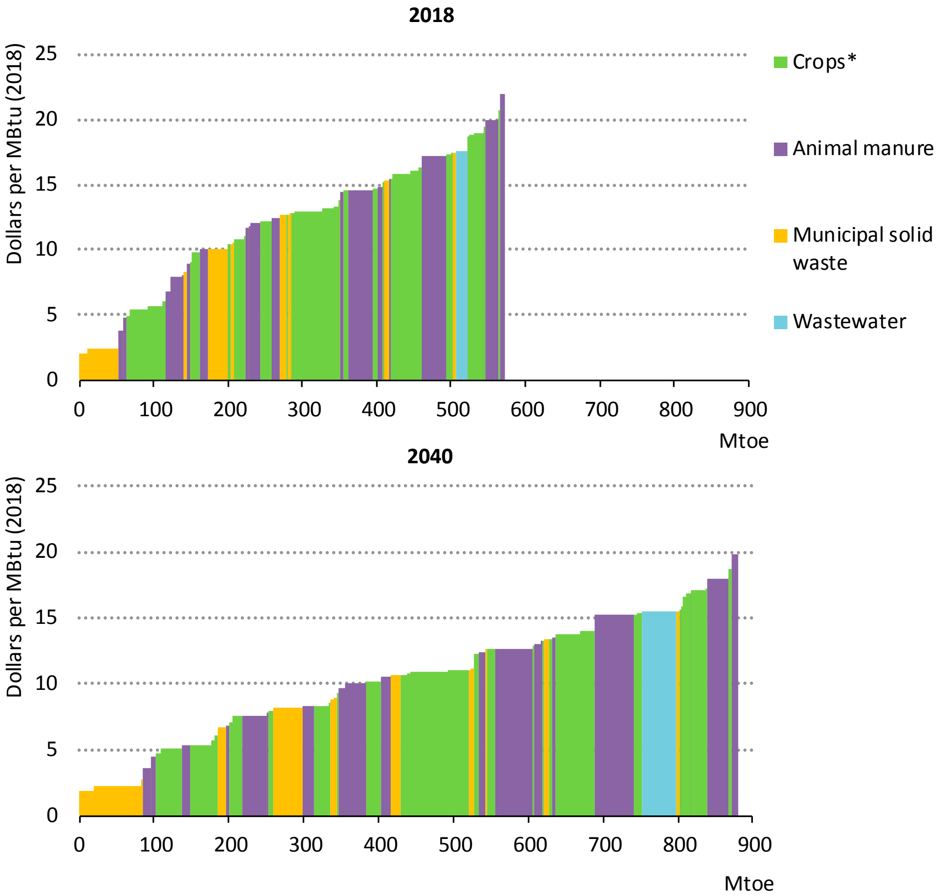
We estimate that over 570 Mtoe of biogas could be produced sustainably today, which is the equivalent of almost 20% of global natural gas demand. By 2040, this potential increases to over 880 Mtoe (Figure 7.14). Of the different feedstocks:

- Crop residues account for almost half of the global biogas potential today and over 40% in 2040. Maize residues alone account for over 40% of the crop residues global potential.
- Among wastes, animal manure is the largest potential source of biogas; its availability is projected to increase by around 2.5% on average each year, double the rate of increase for crop residues.
- Municipal solid waste provides a smaller fraction of total potential, but landfill gas is the lowest cost source of supply. A global shift over time towards more sophisticated and sustainable waste management practices is likely to limit the long-term potential for landfill gas, but there is still scope for more than 80 Mtoe to be produced in 2040.
- The level of wastewater feedstock increases by around 6% annually to 2040. However, the primary purpose of wastewater facilities is water treatment and recovery and not the production of biogas: their contribution to global supply potential is about 5%, and they tend to be a relatively expensive way to produce biogas.

The potential for biogas supply varies widely between different countries and regions. Developing economies currently account for two-thirds of all potential supply, and their potential supply grows at twice the rate of advanced economies. In India and Southeast Asia, the rationalisation of waste management programmes leads to huge growth in the potential from MSW (reaching 36 Mtoe in 2040, three-times the current potential). In Brazil, crop residues are the most promising feedstock: maize and sugar cane residue traditionally used by the sugar and ethanol industries, each represent a quarter of the country's total biogas potential in 2040. There is a more homogenous picture among the advanced economies. In both Europe and the United States, over 70% of the total potential comes from manure and crop residues, but the cheapest production options are generally from MSW.

Only a fraction of the potential for biogas is exploited today. The main reason is the relatively high cost of biogas production: the average cost is currently around $12 per million British thermal units (MBtu). While constructing larger and more industrialised facilities could provide some economies of scale, there is only modest scope for costs to fall because the technology is generally mature. In our new assessment, the average cost of production falls slightly to around $10/MBtu in 2040, but this is still considerably higher than average projected natural gas prices around the world at that time.

Figure 7.14 ▷ Cost curves of potential global biogas supply by feedstock



Landfill gas (MSW) is the lowest cost source of biogas. By 2040, 880 Mtoe of biogas could be produced globally, around half of which would cost of less than $10/MBtu.

* Includes crop residues only, energy crops are excluded given concerns over their sustainability.

Notes: MBtu = million British thermal units; Mtoe = million tonnes of oil equivalent.

Biodigesters provide the largest proportion of overall biogas potential, but their use is considerably more expensive than the cheap landfill gas. The cost of purchasing and operating a biodigester accounts for between 70% and 90% of the final biogas cost, with the variation stemming from differences in the size of the biodigester used, and the quality and weight of various feedstocks across different regions. For example, in Southeast Asia the cost of collecting and processing feedstocks is around 10% of the final biogas cost, while in Europe and Australia, the high cost of collection means that feedstocks can represent over 20% of final biogas cost.

There are however cheaper biogas options that could be cost competitive with natural gas. In all regions, landfills equipped with a gas recovery system could provide biogas for less than $3/MBtu. Around 8% of the global potential could be produced at this cost, a proportion that slightly increases over time.

In total, we estimate that around 130 Mtoe of today's biogas potential could be exploited at a cost equal to or lower than regional gas prices. This is three-and-a-half times the current level of production. China and Southeast Asia are well positioned to increase their levels of biogas production, largely due to relatively high natural gas prices. Biogas production costs are projected to decrease slightly over time while natural gas prices tend to increase. As a result, we estimate that around 300 Mtoe of biogas could be produced globally for less than the respective regional price of natural gas by 2040.

Outlook for biogas

In the Stated Policies Scenario, biogas production grows globally by around 7% per year over the *Outlook* period. Most of the production increase comes from developing economies in Asia where there is widespread availability of relatively low-cost biogas feedstock and where natural gas prices are rising. By 2040, over 70 Mtoe of biogas is consumed globally and a further 80 Mtoe of biogas is upgraded to biomethane. Over 40% of this is in China and India, reflecting their ambitious biogas output goals.

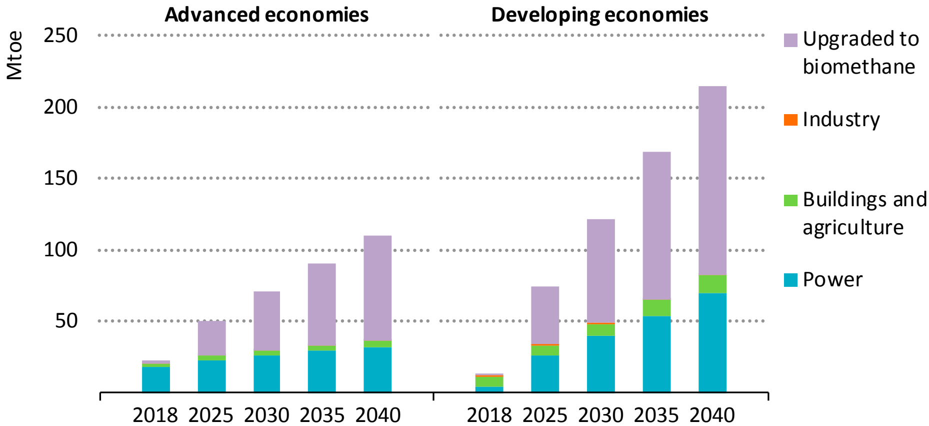
In the Sustainable Development Scenario, there is a more pronounced increase in biogas production: globally nearly 120 Mtoe of biogas is consumed directly in 2040 and a further 200 Mtoe is upgraded to biomethane (Figure 7.15). Nevertheless, less than 40% of the total sustainable technical potential is used globally in 2040.

In advanced economies, especially in countries with well-established gas infrastructure, such as Europe and the United States, around two-thirds of the biogas produced in the Sustainable Development Scenario is upgraded to biomethane. Biomethane can be injected into existing networks to reduce emissions across all end-use sectors that rely on natural gas (see Chapter 13). Most of the biogas that is consumed directly is used in the power sector.

In developing economies, over 210 Mtoe of biogas is produced in 2040 in the Sustainable Development Scenario. It plays an important role as a household fuel, helping to reduce indoor air pollution by displacing the traditional use of solid biomass and contributing significantly to improving access to clean cooking in poor rural areas. By 2030, around 200 million people move away from the traditional use of biomass through biogas; over 100 million people gain access to clean cooking in this way in Africa alone (see Chapter 9).

Using biogas for clean cooking requires around 20 toe gas per 1 000 people each year, and this improvement in welfare for such a large number of people requires around 4 Mtoe of biogas in 2030.

Figure 7.15 ▷ Global biogas demand in the Sustainable Development Scenario



In 2040, biogas is still mostly used as fuel for electricity and heat production, but it is also increasingly used for clean cooking and for the production of biomethane

Note: Biomethane here does not include production through thermal gasification.

In summary, our analysis suggests that there is significant potential for biogas globally, but that most of this requires supportive policies if it is to be exploited. Biogas is relatively expensive to produce, but it offers benefits including GHG emissions savings, improved waste management, enhanced security of supply, improved access to clean cooking facilities, local and rural job creation, and the production of sustainable fertiliser. The case for biogas improves considerably if these non-economic benefits are fully taken into account.

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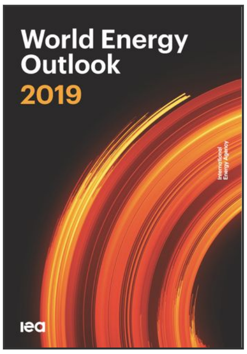

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