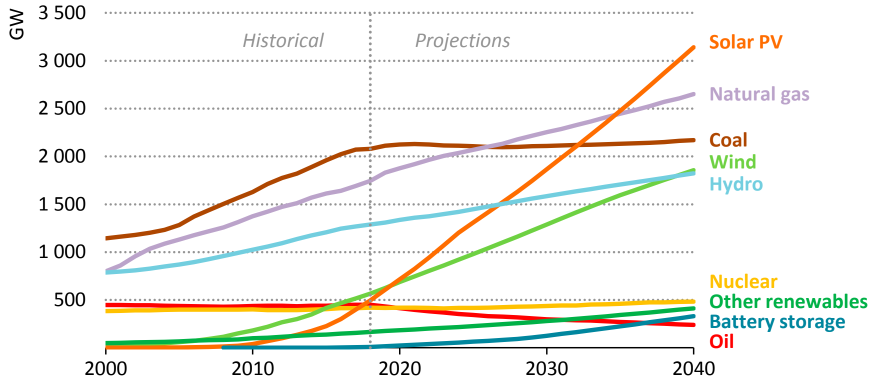
# Outlook for electricity

## Lighting the way?


### SUMMARY

- Electricity is at the heart of modern economies, powering communications, healthcare, industry, education, comfort and entertainment. In the Stated Policies Scenario, global electricity demand grows at 2.1% per year to 2040, twice the rate of primary energy demand. This raises electricity's share in total final energy consumption from 19% in 2018 to 24% in 2040. Electricity plays a larger role in the Sustainable Development Scenario, reaching 31% of final energy consumption.
- Electricity demand follows two distinct regional paths. In advanced economies, growth linked to increasing digitalisation and electrification is largely offset by energy efficiency improvements. In developing economies, rising incomes, expanding industrial output and a growing services sector push demand firmly up. Developing economies contribute nearly 90% of global electricity demand growth to 2040, but their demand per person remains 60% lower than in advanced economies.
- Industry and buildings account for over 90% of global electricity demand today, while transport makes up less than 2%. In the Stated Policies Scenario, the leading drivers of global electricity demand growth are industrial motors (over 30% of the total growth to 2040), space cooling (17%), and large appliances, small appliances and electric vehicles (10% each). Providing electricity access for the first time to 530 million people accounts for just 2% of demand growth. In the Sustainable Development Scenario, electric vehicles become the main source of demand growth.
- Electricity supply continues a major shift towards low-carbon sources. In the Stated Policies Scenario, the share of renewables rises from 26% in 2018 to 44% in 2040, as they provide three-quarters of the growth in electricity supply to 2040. Solar photovoltaics (PV) and wind rise from 7% to 24% of supply, thanks to falling costs and supportive government policies. At the same time, coal-fired output plateaus and its share declines from 38% today to 25% in 2040, while gas holds at 20% and nuclear at 10%. The centre of gravity for nuclear power shifts towards Asia.
- Solar becomes the largest source of installed capacity around 2035 in the Stated Policies Scenario, surpassing coal and gas (Figure 6.1). Global coal-fired capacity plateaus, with the project pipeline of 710 gigawatts (GW), mainly in Asia, just exceeding coal plant retirements, mainly in advanced economies. Renewables make up two-thirds of all capacity additions to 2040 globally. Wind power capacity triples, with offshore wind taking off in Europe, China and the United States. Gas-fired capacity grows in most markets for reliability purposes and battery storage skyrockets from 8 GW today to 330 GW in 2040. Annual power sector investment averages over $900 billion to 2040, including $500 billion for power plants, $400 billion for networks and more than $15 billion for battery storage.

**Figure 6.1 ⊳ Global power capacity by source in the Stated Policies Scenario**




*Falling costs and increasing competitiveness of solar PV push its installed capacity beyond all other technologies in the Stated Policies Scenario*

- Global power sector carbon dioxide ($CO_2$) emissions stabilise at today's level in the Stated Policies Scenario, while pollutant emissions decline thanks to wider use of pollution controls. In the Sustainable Development Scenario, the global average $CO_2$ intensity of electricity generation falls to 80 grammes per kilowatt-hour by 2040, about 80% below today's level. This is the result of 90% more growth for low carbon sources of electricity to 2040 compared with the Stated Policies Scenario, including renewables, nuclear power and carbon capture, utilisation and storage (CCUS).
- Coal-fired power has long provided reliable, flexible and affordable electricity, but it is the single largest source of greenhouse gas emissions today. Under current and proposed investment plans and policies, coal-fired generation would use up most of the remaining carbon budget consistent with meeting the stringent climate goals agreed at the United Nations. This reflects the fact that 60% of the 2 080 GW existing coal fleet is 20-years old or less. We outline a cost-effective strategy to "retrofit, repurpose, retire" existing capacity to address coal-related emissions. It includes retrofitting about 240 GW with CCUS or biomass co-firing equipment, with $225 billion of CCUS investment, and efforts to repurpose plants for more flexibility.
- Power system flexibility needs grow faster than electricity demand in the Stated Policies Scenario to 2040, due to rising shares of variable renewables and growing demand for cooling and electric vehicles. Flexibility needs grow even faster in the Sustainable Development Scenario. Power plants and networks remain the bedrock of power system flexibility, and demand-side response has huge potential. As the fastest growing flexibility option, battery storage capacity rises 40-fold by 2040 in the Stated Policies Scenario, due to its falling costs, short construction periods, widespread availability and scalability. Flexibility needs increase especially in India, where cheap batteries could offer a cost-effective flexibility option and eliminate the need for new coal-fired capacity after 2030.

# Introduction

Electricity is at the heart of modern economies and it is providing a rising share of energy services. Demand for electricity is set to increase further as the world gets wealthier, as its share of energy services continues to rise, and as new sources of demand expand, such as digital connected devices, air conditioning and electric vehicles. Electricity demand growth is set to be particularly strong in developing economies.

The commercial availability of a diverse suite of low emissions technologies puts electricity at the vanguard of efforts to combat climate change and pollution. Decarbonised electricity, in addition, could provide a platform for reducing carbon dioxide ($CO_2$) emissions in other sectors through electricity-based fuels such as hydrogen or synthetic liquid fuels. Renewable energy also has a major role to play in providing access to electricity for all. Rising electricity demand caused global $CO_2$ emissions from the power sector to reach a record high in 2018, signalling the need for the transformation that is underway to speed up.



The first part of this chapter describes the projections for the Stated Policies Scenario and the Sustainable Development Scenario, analysing electricity demand and supply, and looking at drivers of demand growth, the changing electricity generation mix, investment needs, and $CO_2$ and pollutant emissions.

The second part of the chapter looks at three key topics that build on the first in-depth focus on electricity presented in last year's *World Energy Outlook (WEO)* (IEA, 2018a):

- The affordability of electricity and of energy more generally. This continues to be a key concern for consumers and policy makers. We examine the outlook for electricity prices by scenario, explore the impact of uncertainties on fossil fuel prices, wind and solar photovoltaics (PV) costs and the cost of capital, and analyse how growing shares of electricity in final energy demand affect the average household energy bill.
- Emissions from coal-fired power plants, which pose a serious threat to achieving environmental goals. The existing fleet of coal power plants also represents more than $1 trillion in capital investment that has yet to be recovered. We examine a possible way forward.
- Rising needs for flexibility. It is clear that flexibility will be a cornerstone of electricity security in a changing power mix. We look at how it might be provided, and explore how low-cost batteries could turn India into a large-scale launch pad for battery storage technology.



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

# Scenarios

## 6.1 Overview

**Table 6.1 ▷ Global electricity demand and generation by scenario** (TWh)

| | | | Stated Policies | | Sustainable Development | | Current Policies | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2018 | 2030 | 2040 | 2030 | 2040 | 2030 | 2040 |
| **Electricity demand**[1] | **13 152** | **23 031** | **29 939** | **36 453** | **28 090** | **34 562** | **30 540** | **37 418** |
| Industry | 5 398 | 9 333 | 11 843 | 13 525 | 10 751 | 12 169 | 11 998 | 13 874 |
| Transport | 218 | 377 | 1 025 | 2 012 | 1 374 | 4 065 | 725 | 1 091 |
| Buildings | 6 738 | 11 755 | 15 198 | 18 893 | 14 264 | 16 606 | 15 835 | 20 176 |
| *Share of population with electricity access* | *73%* | *89%* | *93%* | *93%* | *100%* | *100%* | *93%* | *93%* |
| **Electricity generation**[2] | **15 427** | **26 607** | **34 140** | **41 373** | **31 800** | **38 713** | **34 988** | **42 824** |
| Coal | 5 994 | 10 123 | 10 408 | 10 431 | 5 504 | 2 428 | 11 464 | 12 923 |
| Natural gas | 2 750 | 6 122 | 7 529 | 8 899 | 7 043 | 5 584 | 8 086 | 10 186 |
| Nuclear | 2 591 | 2 718 | 3 073 | 3 475 | 3 435 | 4 409 | 3 112 | 3 597 |
| Renewables | 2 863 | 6 799 | 12 479 | 18 049 | 15 434 | 26 065 | 11 627 | 15 485 |

Note: TWh = terawatt-hours.

In the **Stated Policies Scenario**, electricity demand grows by 2.1% per year, resulting in over 13 000 terawatt-hours (TWh) more demand in 2040 than today (Table 6.1). Developing economies account for almost 90% of demand growth, of which two-thirds is in Asia where demand is rising in particular for electric motors, space cooling and household appliances. About 530 million people gain access to electricity around the world by 2040, mainly in Africa and developing Asia, accounting for 2% of global electricity demand growth.

Renewables, led by wind and solar PV, provide three-quarters of the increase in electricity supply, underpinned by policy support and declining technology costs. The share of generation from renewables increases from 26% today to 44% in 2040, with solar PV and wind together rising from 7% to 24%. The share from nuclear power decreases, but its output nevertheless rises in absolute terms, with growth in China and more than twenty other countries more than offsetting reductions in advanced economies.

The share of fossil fuels in electricity supply falls below 50% in 2040, down from two-thirds (where it has been for decades). Coal remains the largest source of electricity, though its share of overall generation declines from 38% to 25%, and its share of generation in advanced economies falls by more than half over the period to 2040. Gas-fired generation grows steadily, maintaining roughly its current share of generation, thanks to the availability of cheap gas in some regions and the role of gas in supporting flexibility.

[1] Electricity demand is defined as total gross electricity generated less own use generation, plus net trade (imports less exports), less transmission and distribution losses.

[2] Other sources are included in total electricity generation.

There have been a number of significant developments since the *WEO-2018*. An additional 30 million electric cars, reflecting policy targets, are now projected by 2040, adding to electricity demand growth (see Chapter 3.9). For electricity supply, solar PV projections have been boosted by some 20% to 2040, mainly reflecting policy changes: in China, where there has been a partial reversal of a previous decision to reduce subsidies; in India, where an ambition to reach 450 gigawatts (GW) of renewables-based capacity by 2030 (excluding hydropower) has been announced; and in the United States, where state-level policies have been strengthened. Projections for battery storage capacity have been raised by close to 50%, in part due to the increases for solar PV (see section 6.12), and offshore wind projections have been revised upward by some 80% with new policies and technology gains (see Chapter 14).

In the **Current Policies Scenario**, electricity demand increases by 2.2% per year, and by 2040 demand is nearly 1 000 terawatt-hours (TWh) higher than in the Stated Policies Scenario. This figure hides important differences in the structure of electricity demand growth between the two scenarios; without the implementation of proposed increases in the coverage and stringency of energy efficiency policies, electricity demand in buildings is nearly 1 300 TWh higher, while the difference in industry is 350 TWh, largely due to higher demand related to motor systems. Uptake of electric vehicles continues to accelerate under current policies, although not as rapidly as in the Stated Policies Scenario, as a result, transport electricity demand is nearly 1 000 TWh lower. Without the implementation of proposed policies, the pace of change for the power mix is slower than in the Stated Policies Scenario. Renewables provide half of the increase in electricity supply over the next two decades, though their share of global electricity generation to 2040 remains below 40%. At the same time, under current policies, fossil fuels continue to play a large role to 2040: coal-fired electricity generation still accounts for 30% of electricity supply and gas-fired generation for about 25%. Overall, power sector emissions rise by some 20% by 2040.

In the **Sustainable Development Scenario** the share of electricity in final consumption grows faster than in the Stated Policies Scenario, rising from 19% today to 31% in 2040. Increased energy efficiency dampens demand growth, and total electricity demand is just below 35 000 TWh in 2040. Full electricity access is achieved by 2030 and contributes 5% of demand growth. The growth of renewables generation exceeds electricity demand growth by almost 8 000 TWh, raising their share of generation to two-thirds by 2040. Wind and solar PV together provide 40% of generation in 2040. Solar PV and other renewables also play a critical role in providing electricity access to all, particularly in sub-Saharan Africa (see Chapter 10). Nuclear and power plants equipped with carbon capture, utilisation and storage (CCUS) supplement renewables, raising the global low-carbon share of generation to about 85% in 2040. Generation from fossil-fuelled power plants without carbon capture declines sharply. Coal-to-gas switching provides a bridge to a low-carbon future in the near term, though, in the longer term, the role of gas moves increasingly towards the provision of flexibility.

## 6.2 Electricity demand by region

In all scenarios, electricity accounts for the largest growth in final energy consumption and grows at double the pace of final energy demand, with today's global electricity demand of 23 000 TWh rising by 13 400 TWh to 2040 in the Stated Policies Scenario (+2.1% per year), and 11 500 TWh in the Sustainable Development Scenario (+1.9% per year) (Table 6.2).

In advanced economies, electricity demand growth has already started to flatten or even decline (18 out of the 30 IEA member countries have seen their electricity demand fall since 2010). The future level of demand in these countries is dictated by the balance between the increasing electrification of mobility and heat, speed of digitalisation and extent of further energy efficiency gains. In the Stated Policies Scenario, electricity demand flattens or declines in some countries (e.g. Japan); in others it rebounds (e.g. the United States). (For further analysis on the impacts of energy efficiency, electrification and digitalisation on electricity demand see the *WEO-2018 Special Focus on Electricity* [IEA, 2018a]).

**Table 6.2 ▷ Electricity demand by region and scenario** (TWh)

| | | | Stated Policies | | Sustainable Development | | Change 2018-2040 | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2018 | 2030 | 2040 | 2030 | 2040 | STEPS | SDS |
| North America | 4 260 | 4 786 | 5 160 | 5 626 | 4 966 | 5 602 | 840 | 816 |
| United States | 3 589 | 4 011 | 4 226 | 4 517 | 4 099 | 4 573 | 506 | 563 |
| Central & South America | 660 | 1 081 | 1 445 | 1 837 | 1 331 | 1 660 | 757 | 579 |
| Brazil | 327 | 517 | 675 | 845 | 619 | 745 | 328 | 228 |
| Europe | 3 114 | 3 631 | 3 975 | 4 346 | 3 926 | 4 724 | 715 | 1 093 |
| European Union | 2 604 | 2 884 | 3 045 | 3 243 | 3 050 | 3 645 | 359 | 761 |
| Africa | 380 | 703 | 1 086 | 1 653 | 1 073 | 1 696 | 950 | 993 |
| South Africa | 190 | 211 | 252 | 319 | 210 | 249 | 108 | 38 |
| Middle East | 361 | 954 | 1 309 | 1 817 | 1 189 | 1 621 | 863 | 667 |
| Eurasia | 809 | 1 084 | 1 302 | 1 474 | 1 132 | 1 220 | 390 | 137 |
| Russia | 677 | 893 | 1 043 | 1 149 | 916 | 971 | 256 | 77 |
| Asia Pacific | 3 569 | 10 792 | 15 662 | 19 699 | 14 474 | 18 038 | 8 907 | 7 246 |
| China | 1 174 | 6 330 | 9 127 | 10 912 | 8 415 | 10 052 | 4 582 | 3 723 |
| India | 376 | 1 243 | 2 417 | 3 718 | 2 254 | 3 263 | 2 475 | 2 020 |
| Japan | 962 | 994 | 980 | 989 | 926 | 942 | -4 | -52 |
| Southeast Asia | 323 | 935 | 1 510 | 2 091 | 1 346 | 1 888 | 1 156 | 953 |
| **World** | **13 152** | **23 031** | **29 939** | **36 453** | **28 090** | **34 562** | **13 422** | **11 531** |

Note: TWh = terawatt-hour; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

In developing economies, electricity demand has almost tripled since 2000. It continues to grow, but at a slower pace, with demand increasing by 3% annually. Demand growth continues to be driven by economic fundamentals: increases in industrial output, rising incomes and an expanding services sector.

These two different pathways result in a continuing shift of global electricity demand towards developing economies. **Advanced economies** account for 44% of global electricity demand today, down from a share of 66% in 2000. In the Stated Policies Scenario, this share drops to 32% in 2040, with electricity demand seeing annual growth of 0.7%, which is four-times lower than the rate of growth in developing economies. Developing economies account for nearly 90% of global demand growth to 2040, this share is 83% in the Sustainable Development Scenario, with higher demand in advanced economies.

The United States and the European Union account for nearly 70% of electricity demand in advanced economies today, a share broadly maintained through to 2040 in the Stated Policies Scenario with demand increases of 510 TWh and 360 TWh respectively. The switch from gas to more efficient electric heat pumps in buildings and industry reduces total energy consumption, but drives up electricity demand. As a result, the share of electricity in final energy consumption reaches 29% in 2040 in the European Union, up from 21% today. In the United States, electricity's share rises from 21% to 24% in 2040. Demand in these economies rises even higher in the Sustainable Development Scenario as the impact of pushing energy efficiency towards its maximum potential is more than offset by increasing electrification, notably in transport. By 2040, 270 million additional electric vehicles (EVs) (cars, buses, trucks and two/three-wheelers) relative to the Stated Policies Scenario push up demand by over 900 TWh in advanced economies,[3] 190 million of these EVs are on the road in the United States and European Union.

The share of electricity in final energy demand is currently 29% in Japan and 25% in Korea, and it rises in both countries in the Stated Policies Scenario. In Japan, increasing electrification offsets the impact of higher efficiency and declining population, keeping demand in 2040 around today's level; in Korea, it helps push demand almost 130 TWh higher by 2040. In the Sustainable Development Scenario, additional energy efficiency sees lower electricity demand in 2040 in both countries relative to the Stated Policies Scenario.

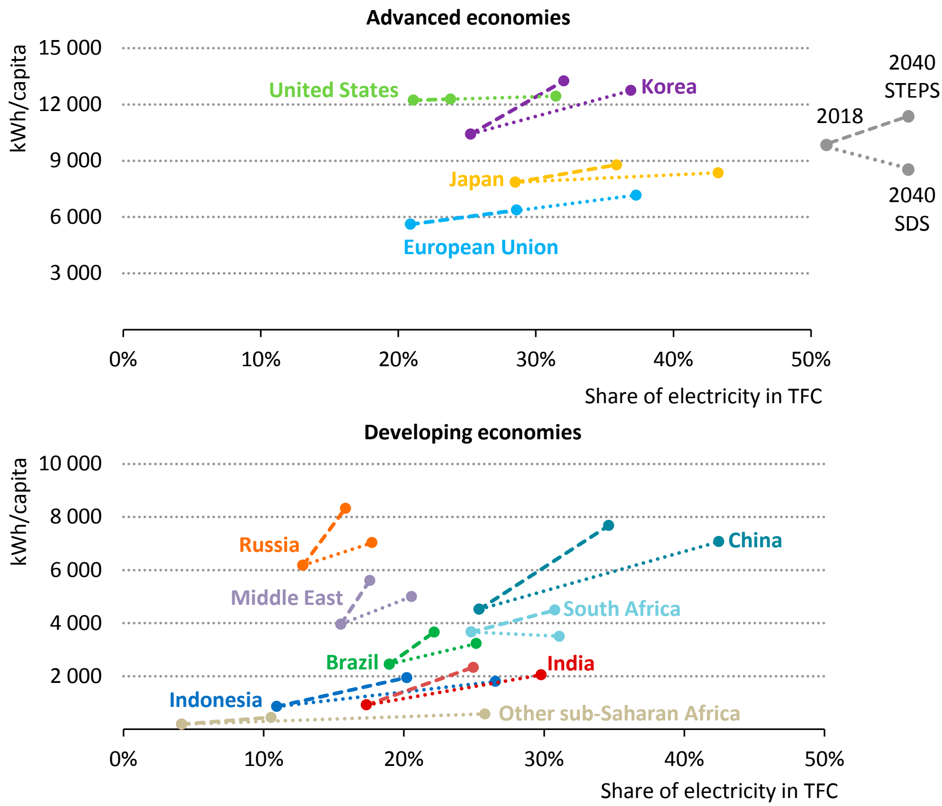
In **developing economies**, the 3% rate of average annual demand growth to 2040 is half the rate seen in the period between 2000 and 2018, but it still leads to electricity demand in the Stated Policies Scenario nearly doubling from today's levels by 2040. Demand in China, the largest user of electricity today, increases by more than 70% from today to 2040, accounting for 40% of global demand growth. Further economic development and rising standards of living also see demand almost triple in both India and Indonesia, with particularly strong demand growth in buildings. Despite this, per capita demand for electricity in India in 2040 is still less than a fifth of that in the United States today (Figure 6.2). Demand also increases across South America, with the largest growth in Brazil, where economic growth leads to a rise in electricity demand of almost 330 TWh.

In the Sustainable Development Scenario, electricity demand in developing economies in 2040 is 9% below that in the Stated Policies Scenario (2 200 TWh). Efficiency gains, notably in industry, are the primary driver of lower demand in major industrial centres, and their

[3] The additional electricity demand has been estimated based on regional annual average mileage of EVs.

impact is biggest in China (-860 TWh). These improvements more than offset the impact of over 500 million additional EVs in developing economies, of which 300 million are in China.

**Figure 6.2 ⊳ Per capita electricity demand and share of electricity in total final consumption in advanced and developing economies**




*All regions see higher electrification in the Sustainable Development Scenario, while levels of demand relative to the Stated Policies Scenario vary according to regional contexts*

Notes: TFC = total final consumption; kWh = kilowatt-hour; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. Other sub-Saharan Africa excludes South Africa.

Achieving universal access to electricity adds 470 TWh to demand in the Sustainable Development Scenario by 2040, with the biggest impact in sub-Saharan Africa, where over 900 million people gain access to electricity. The additional connections create opportunities for economic development and improve access to basic services, while increasing demand in 2040 by only 150 TWh more than the Stated Policies Scenario, which sees progress but does not deliver universal access (see Chapter 10). Despite universal access to electricity, per capita electricity demand in 2040 averages less than 700 kWh in sub-Saharan Africa, under a quarter of today's global average.

## 6.3 Electricity demand by sector

Buildings and industry are the two largest electricity consuming sectors today, accounting respectively for nearly 11 800 TWh and 9 300 TWh, while transport (mostly rail today) accounts for less than 2% of electricity consumption. The share of electricity in total final consumption (TFC) today is 19%; by 2040, further electrification of all sectors drives up the share of electricity in both the Stated Policies (24%) and Sustainable Development scenarios (31%). Given the higher efficiency of equipment using electricity, compared with equipment using fuels directly, the share of electricity in meeting useful energy demand[4] is even higher, surpassing 43% by 2040 in the Sustainable Development Scenario.

**Table 6.3 ▷ Electricity demand by sector and scenario** (TWh)

| | | | Stated Policies | | Sustainable Development | | Change 2018-2040 | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2018 | 2030 | 2040 | 2030 | 2040 | STEPS | SDS |
| **Total electricity demand** | **13 152** | **23 031** | **29 939** | **36 453** | **28 090** | **34 562** | **13 422** | **11 531** |
| *Share in TFC* | *16%* | *19%* | *22%* | *24%* | *24%* | *31%* | *4.9%* | *11.3%* |
| *Share in useful energy* | *21%* | *24%* | *28%* | *33%* | *31%* | *43%* | *9.0%* | *19.7%* |
| **Industry** | **5 406** | **9 346** | **11 857** | **13 540** | **10 768** | **12 188** | **4 194** | **2 842** |
| Electric motors | 3 414 | 6 930 | 9 427 | 11 418 | 8 160 | 9 290 | 4 488 | 2 359 |
| Heat pumps | - | - | 85 | 215 | 476 | 1 138 | 215 | 1 138 |
| *Share in industry final consumption* | *19%* | *21%* | *23%* | *24%* | *24%* | *28%* | *2.1%* | *6.1%* |
| *Share in useful energy* | *20%* | *22%* | *26%* | *27%* | *29%* | *36%* | *5.2%* | *14.0%* |
| **Buildings** | **6 738** | **11 755** | **15 198** | **18 892** | **14 264** | **16 606** | **7 137** | **4 851** |
| Space and water heating | 165 | 231 | 272 | 281 | 249 | 262 | 50 | 31 |
| Cooling | 948 | 1 850 | 2 904 | 4 072 | 2 530 | 3 040 | 2 222 | 1 190 |
| *Share in buildings final consumption* | *24%* | *33%* | *38%* | *43%* | *45%* | *53%* | *10.6%* | *20.1%* |
| *Share in useful energy* | *36%* | *45%* | *53%* | *60%* | *56%* | *68%* | *15.2%* | *23.7%* |
| **Transport** | **218** | **377** | **1 025** | **2 012** | **1 374** | **4 065** | **1 635** | **3 688** |
| Electric vehicles | 3 | 57 | 541 | 1 347 | 890 | 3 393 | 1 290 | 3 336 |
| *Share in transport final consumption* | *1.0%* | *1.1%* | *3%* | *5%* | *4%* | *13%* | *3.7%* | *12.2%* |
| *Share in useful energy* | *2%* | *3%* | *6%* | *10%* | *9%* | *26%* | *7.7%* | *23.1%* |

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

Most of the electricity used in the industry sector is for motor-driven systems (including pumps, fans and compressors). Motor systems currently account for 30% of global

[4] Useful energy refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As a result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has a higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

electricity demand, increasing to 31% in the Stated Policies Scenario by 2040 as demand grows by almost 4 500 TWh. Improving the efficiency of motors and wider motor systems (for example by installing variable speed drives, ensuring correct motor sizing and using energy management systems) plays an important role in slowing electricity demand growth. Today, low efficiency motors represent two-thirds of the current stock. In the Stated Policies Scenario, their use declines rapidly, and motors with an equivalent to or higher than IE3[5] standard represent close to 90% of the stock. In the Sustainable Development Scenario, increasing sales of motors compliant with the IE4+ standard avoids over 2 100 TWh of consumption compared with the Stated Policies Scenario (Table 6.3).

**Buildings** (including households and the services sector) continue to be both the biggest contributor to electricity demand and to its growth in the Stated Policies Scenario. Increasing ownership of cooling systems is one of the main drivers of growth. Today, only 8% of the 3 billion people that live in hot places[6] own a cooling system, compared with 90% of people in United States and Japan (IEA, 2018b). In China, air conditioner ownership has grown rapidly in recent years and is now around 60%. In Africa and India ownership levels for air-conditioners and household appliances remain very low. By 2040, increases in incomes, electricity access rates and ownership of appliances and air conditioners drives up electricity demand in the buildings sector by 4 200 TWh in developing economies, fourteen-fold the growth projected in advanced economies. Household electricity consumption in developing economies increases 60% in in the Stated Policies Scenario, although where implemented, minimum energy performance standards (MEPS) for air conditioners and large appliances help to slow electricity demand growth.

More stringent MEPS for air conditioners and large household appliances in the Sustainable Development Scenario avoid 1 350 TWh of electricity demand compared with the Stated Policies Scenario in 2040. Demand growth is slowed further in the Sustainable Development Scenario by more efficient heat pumps, better insulation and greater use of renewables for heating (biomass stoves, solar thermal).

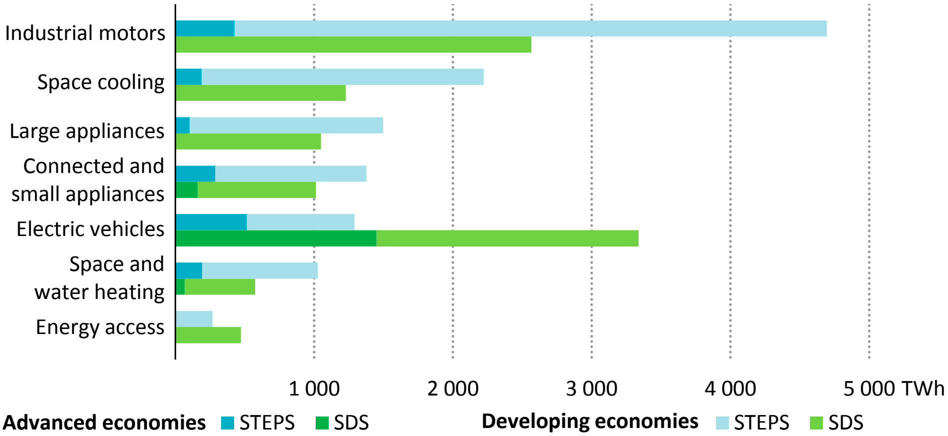
Among the end-use sectors, **transport** uses the least amount of electricity today (about 2%), most of it in rail. Yet, road transport electricity use is growing rapidly as the global electric vehicle fleet expands, underpinned by policy measures in many countries. In 2018, worldwide sales of electric cars grew 70%, led by China, the United States, Canada and the European Union. Growth in EV sales contrasts with a decline in overall car sales in many major economies. The total number of electric cars rises to 330 million by 2040 in the Stated Policies Scenario (one-out-of-six cars), and the total number of EVs (cars, buses, trucks and two/three-wheelers) rises to over 1 billion, corresponding to 30% of the total fleet. By the mid-2020s, EVs overtake railways as the largest consumer of electricity in transport, although there is strong potential for growth from rail (IEA, 2019a).

[5] There are a number of standards and classifications for motors. Many can be benchmarked to the International Electro-technical Commission's "International Efficiency" standards, which range from low (IE0) to super premium (IE4), with minimum efficiency requirements based on size and number of poles.

[6] Hot places are defined as experiencing average perceived daily temperature over 25 °C for the whole year.

Although electrification efforts still need to be bolstered in many countries, the IEA's *Tracking Clean Energy Progress* recognises EVs as one of the very few energy technologies that are on track to meet the requirements of the Sustainable Development Scenario (IEA, 2019b). In the Sustainable Development Scenario, the total number of EVs reaches 1.9 billion by 2040, with almost 900 million electric cars, leading demand growth (Figure 6.3). Heavier freight vehicles are more difficult to electrify than their passenger counterparts, and only 8% of freight vehicles are electric in the Stated Policies Scenario by 2040, although in the Sustainable Development Scenario this figure rises to 26%.

**Figure 6.3 ▷ Electricity demand growth by end-use and scenario in advanced and developing economies, 2018-2040**




***Electricity demand growth from industrial motors and cooling is nearly halved in the Sustainable Development Scenario, while most growth is from the almost 1 billion EVs***

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

**Box 6.1 ▷ What if the future is electric?**

Electricity demand growth is uncertain and could be accelerated by policy actions beyond those in the Stated Policies Scenario. In recognition of this, the Future is Electric Scenario was introduced in the *WEO-2018* (IEA, 2018a). It achieves the economic potential for the electrification of heat and transport, and sees an increasingly digital economy and the provision of universal access to electricity. In the Future is Electric Scenario, the share of electricity in total final consumption reaches 31% by 2040, and its share of useful energy demand reaches 48%. The buildings sector sees a share in useful energy of almost three-quarters, whereas electrification of some modes of transport (for example trucks) makes limited progress for economic or technical reasons. The Sustainable Development Scenario takes account of the assessment in the Future is Electric Scenario on electrification potential.

## 6.4 Electricity supply by source

In the **Stated Policies Scenario,** electricity generation from renewables increases rapidly, surpassing coal by 2026. Renewables contribute three-quarters of electricity supply growth to 2040, underpinned by policy support in nearly 170 countries (REN21, 2019), as well as their improving competitiveness (see section 6.8). Their share of generation rises from 26% in 2018 to 44% in 2040 (Table 6.4). Hydro remains the largest source of renewable power, at about 15% of generation through to 2040. Wind and solar PV together provide over half of the growth in electricity supply, raising their share from 7% in 2018 to 24% in 2040. Bioenergy adds to the renewables total, offering dispatchable low-carbon electricity. Rising shares of variable renewables transform power systems in a number of ways, including by increasing the need for flexibility (see section 6.12). They also raise concerns over whether some current electricity market designs will deliver efficient and timely investment.

**Table 6.4 ▷ Global electricity generation by source and scenario** (TWh)

| | | | Stated Policies | | | | Sustainable Development | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2018 | 2025 | 2030 | 2035 | 2040 | 2030 | 2040 |
| Coal | 5 994 | 10 123 | 10 291 | 10 408 | 10 444 | 10 431 | 5 504 | 2 428 |
| of which CCUS | - | 0 | 1 | 16 | 43 | 69 | 246 | 994 |
| Natural gas | 2 750 | 6 118 | 6 984 | 7 529 | 8 165 | 8 899 | 7 043 | 5 584 |
| of which CCUS | - | - | - | 0 | 0 | 1 | 220 | 915 |
| Oil | 1 207 | 808 | 724 | 622 | 556 | 490 | 355 | 197 |
| Nuclear | 2 591 | 2 718 | 2 801 | 3 073 | 3 282 | 3 475 | 3 435 | 4 409 |
| Renewables | 2 863 | 6 799 | 9 972 | 12 479 | 15 204 | 18 049 | 15 434 | 26 065 |
| Hydro | 2 613 | 4 203 | 4 759 | 5 255 | 5 685 | 6 098 | 5 685 | 6 934 |
| Bioenergy | 164 | 636 | 916 | 1 085 | 1 266 | 1 459 | 1 335 | 2 196 |
| Wind | 31 | 1 265 | 2 411 | 3 317 | 4 305 | 5 226 | 4 453 | 8 295 |
| Solar PV | 1 | 592 | 1 730 | 2 562 | 3 551 | 4 705 | 3 513 | 7 208 |
| Geothermal | 52 | 90 | 125 | 182 | 248 | 316 | 282 | 552 |
| CSP | 1 | 12 | 28 | 67 | 124 | 196 | 153 | 805 |
| Marine | 1 | 1 | 2 | 10 | 25 | 49 | 14 | 75 |
| **Total** | **15 427** | **26 603** | **30 803** | **34 140** | **37 682** | **41 373** | **31 800** | **38 713** |

Note: TWh = terawatt-hours; CCUS = carbon capture, utilisation and storage; PV = photovoltaics; CSP = concentrating solar power.

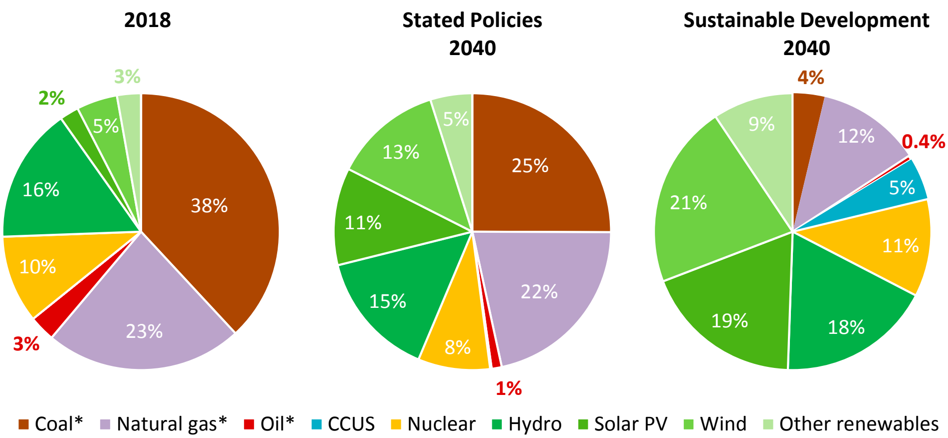
Global coal-fired electricity generation plateaus after more than a century of growth, but remains the largest source of electricity through to 2040. From 1970 to 2013, it grew fivefold, an average of 3.8% per year, but slowed to 1% in the last five years. In 2018, final investment decisions for new coal plants were at their lowest level in a century (IEA, 2019b). To 2040, coal-fired generation rises by just 0.1% per year. As a result, coal's share in electricity generation declines from 38% in 2018 to 25% in 2040 (Figure 6.4). Without additional efforts to develop the technology, CCUS in coal-fired power remains limited.

Natural gas-fired generation tripled over the past 22 years, and is set to increase by nearly 50% to 2040, thanks in part to its role in providing flexibility to power systems. The global share of gas in total electricity supply remains stable at about one-fifth, though its share declines in Europe and Japan. The availability of large, low-cost gas resources in the United States is having an impact on gas markets around the world and has spurred coal-to-gas switching: in total such switching avoided around 500 million tonnes (Mt) of $CO_2$ emissions from 2010 to 2018, and it has the potential to avoid more in the future (IEA, 2019c).

Nuclear power generation increases by 30% worldwide to 2040, though its share of supply declines slightly. Two regional pathways emerge. In advanced economies, nuclear power is the largest low-carbon source of electricity today (18% of generation), but falls to the third-largest in 2040, behind wind and hydro, and just ahead of solar PV. This trajectory for nuclear power includes many planned lifetime extensions as well as new construction, but there is a risk that nuclear power will fade away faster in advanced economies (IEA, 2019d). In developing economies, the role of nuclear power is maintained at about 5% of electricity supply to 2040, though electricity production increases by 150% over the period to 2040.



**Figure 6.4 ⊳ Global electricity generation mix by scenario**




***Electricity supply shifts towards renewable energy under current and proposed policies, but all low-carbon technologies are needed to support clean energy transitions***

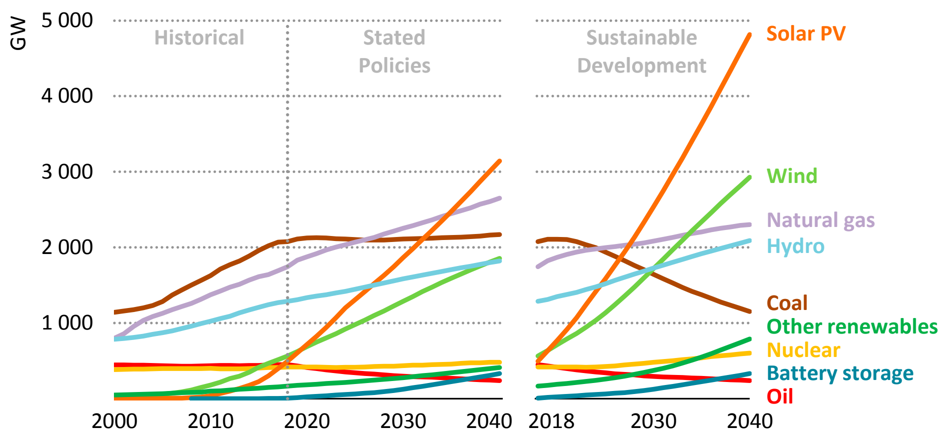
* Excludes capacity equipped with CCUS.

In the **Sustainable Development Scenario**, renewables provide two-thirds of electricity supply worldwide by 2040: solar PV and wind together provide 40%, with a further 25% from dispatchable renewables, including hydro and bioenergy. Nuclear power makes a moderate additional contribution, and close to 320 GW of coal- and gas-fired capacity is equipped with CCUS. Unabated coal-fired generation is cut in half by 2030, and its share falls from 38% in 2018 to less than 5% by 2040. The role of gas moves away from supplying bulk energy and towards providing system flexibility, with its share of generation cut by one-third by 2040 as a result.

## 6.5 Installed capacity by source

In the **Stated Policies Scenario**, global power generation capacity expands by 80% by 2040, to over 13 000 GW from 7 220 GW in 2018. Renewables' share in global power capacity rises from 35% today to 55% in 2040. Solar PV becomes the largest source of power capacity around 2035 overtaking wind in 2020, hydro in 2027, coal in 2033 and gas in 2035 (Figure 6.5). Wind power also rises steadily to over 1 850 GW of capacity by 2040, on par with hydropower, with an increasing emphasis on offshore wind (see Chapter 14).

**Figure 6.5 ▷ Global power generation capacity by source and scenario**




*Policy support and improving competitiveness of solar PV lead to rapid growth, and by 2040 its total capacity is higher than any other technology*

Global coal-fired power capacity flattens out in the near term, ending a century of growth. At the start of 2019, the global pipeline for new coal-fired capacity totalled 710 GW, with 170 GW under construction and 540 GW of planned projects. This compares with coal-fired capacity additions of 690 GW by 2040 in the Stated Policies Scenario, with more than 90% of this capacity being built in developing economies, principally in India, China and Southeast Asia. Cumulative retirements of coal-fired capacity by 2040 total nearly 600 GW, reflective of ageing fleets, challenging market conditions and phase-out commitments. The majority of retirements occur in advanced economies. As a result, the share of coal in global power capacity falls from 29% in 2018 to 17% in 2040.

Nuclear power capacity worldwide increases to 2040, declining by one-quarter in advanced economies but more than doubling in developing economies. At the start of 2019, 60 GW (gross) of nuclear power projects were under construction in nearly 20 countries. Increased capacity to 2040 is driven by programmes in China, India, Russia and the Middle East. China is set to become the leader in nuclear power capacity around 2030, overtaking the United States and Europe. Several new projects in China were announced in 2019, after two years without a new start. In most advanced economies, nuclear power capacity is set to decline as a result of existing plants reaching the end of their life and of concerns about the economic feasibility of new projects. However, small modular reactors are gaining interest because they would require less upfront capital investment and could offer a dispatchable source of low-carbon electricity, with a potential market of over 20 GW (OECD/NEA, 2016).

Natural gas-fired capacity and battery storage are very important sources of flexibility to support the integration of variable renewables and for electricity security. In the Stated Policies Scenario, combined-cycle gas turbines (CCGTs) account for the vast majority of the average of 60 GW of gas-fired capacity built each year, though lower efficiency gas-fired capacity takes up an increasing share to meet rising flexibility needs. About 330 GW of battery storage are deployed by 2040, reducing the need for new thermal capacity. The future costs are uncertain, but battery storage has significant potential and new developments could change the landscape of electricity supply (see section 6.12).

**Figure 6.6 ▷ Renewables share in capacity additions by region in the Stated Policies and Sustainable Development scenarios, 2019-2040**

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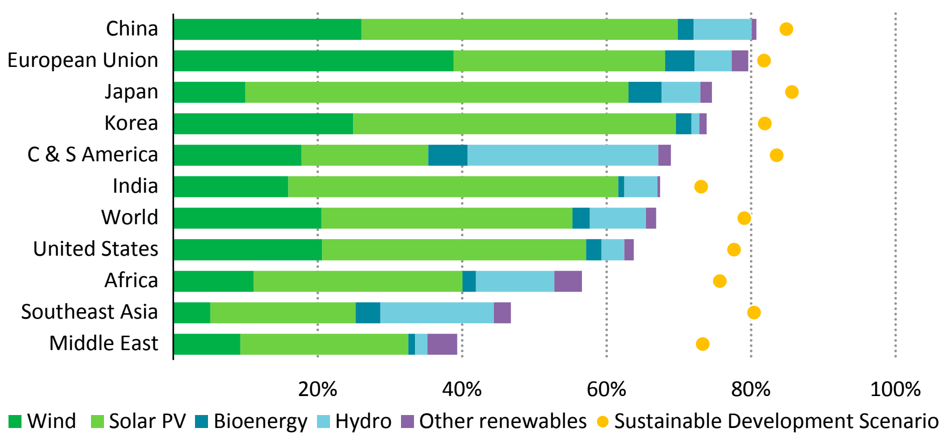



***Renewables account for the majority of new capacity built to 2040 in most regions in the Stated Policies Scenario and rise to higher shares in the Sustainable Development Scenario***

Note: C & S America = Central and South America.

In the Stated Policies Scenario, nearly 8 500 GW of new power capacity is added globally by 2040, of which two-thirds is renewables (Figure 6.6). Renewables account for the majority of capacity additions in most regions. This includes about 80% of additions in the European Union and China, but they provide less than half of additions in Southeast Asia and the Middle East. Solar PV provides the largest share of renewable capacity additions in most regions, including China and India, helping the global solar market return to growth after a pause in 2018. Wind power provides the second-largest share of renewables capacity additions in many regions and leads the way in the European Union.

In the **Sustainable Development Scenario**, the deployment of all low-carbon technologies accelerates. Renewables make up the vast majority of capacity additions in all regions, and about 80% of all capacity additions worldwide through to 2040. The pace of solar PV deployment increases from 97 GW in 2017 and 2018 to nearly 210 GW in 2030 and over 300 GW in 2040. Wind power additions average close to 130 GW per year through to 2040, two-and-a-half times the additions in 2018. Nuclear power capacity additions average about 15 GW per year, up from the 11 GW completed in 2018. Starting in the late 2020s, the deployment of power generation capacity equipped with CCUS averages over 20 GW per year to 2040, with two-thirds as retrofits that extend the operational life of relatively young and efficient coal- and gas-fired capacity. Addressing the $CO_2$ emissions from the existing fleet of coal-fired power plants calls for a multifaceted strategy (see section 6.11).

## *6.6 Electricity supply by region*

The transformation of electricity supply is underway around the world, but the extent of change varies widely. Regional outlooks depend critically on four factors: policy environment; technology preferences; available resources; and the relative economics of different power generation technologies. The policy environment is of central importance, and more than 95% of power sector investment in recent years was directly related to policies or regulation (IEA, 2018c). Regional technology preferences, mainly expressed through financial support or restrictions, are important considerations and vary widely. This section focuses on the outlook envisaged in the Stated Policies Scenario.

**China** is the largest power market by far and poised for strong growth, making it a key determinant of global electricity trends. Coal accounts for two-thirds of China's electricity supply today, but efforts are underway to limit its growth to address pollution concerns and limit $CO_2$ emissions. Even with over 60 GW under construction at the start of 2019, coal-fired capacity and generation are set to plateau (Figure 6.7). China is already the global leader in a wide array of low-carbon technologies and maintains this position: it accounts for 30-40% of the global market to 2040 for solar PV, wind, hydro and nuclear power. The solar PV outlook improved in 2019 when new subsidy allocations for utility-scale solar PV were announced that partially reversed sudden cuts to support in the previous year.

In the **United States**, cheap natural gas has reshaped electricity supply in recent years, helping to cut the share of coal by 18 percentage points from 2010 to 2018. Wind and solar PV have been gaining momentum thanks to falling costs, state-level renewable energy targets and federal tax incentives. Growth is set to continue due to improved competitiveness and corporate demand, overcoming the impact of expiring federal tax credits. The growth in renewables and low gas prices are contributing to challenging market conditions for all generators, trimming the margins for existing capacity and making new investment difficult. Natural gas prices are set to remain low for some time, contributing to the retirement of about 90 GW of coal-fired capacity by 2030. Nuclear power is set to decline as the existing fleet is nearly 40 years old on average and no large-scale projects are in view after two new units are completed at Plant Vogtle. Nuclear power's share of generation is set to be cut from 19% in 2018 to 11% in 2040, even with recent decisions to support nuclear power in several states.

In the **European Union**, there is increasing emphasis on developing renewables. The "Clean Energy for All Europeans" package sets a renewable energy target of 32% of gross final consumption by 2030. In effect, this calls for the share of renewables in electricity to exceed 50%. Wind power is set to become the European Union's leading source of electricity around 2025, overtaking gas and nuclear, offshore wind is poised for rapid growth with country-level targets targeting at least a tripling of installed capacity by 2030 (see Chapter 14). Thirteen member states have plans to phase out all coal-fired power: together, these plans cover close to 100 GW of coal and aim to phase out more than 80% of it by 2030. In 2018, nuclear power provided 25% of electricity in the European Union, with several member states getting more than half their supply from nuclear. However, phase-out plans have been announced in Germany, Belgium and Spain (in 2019) and France aims to reduce its nuclear share of generation to 50%.



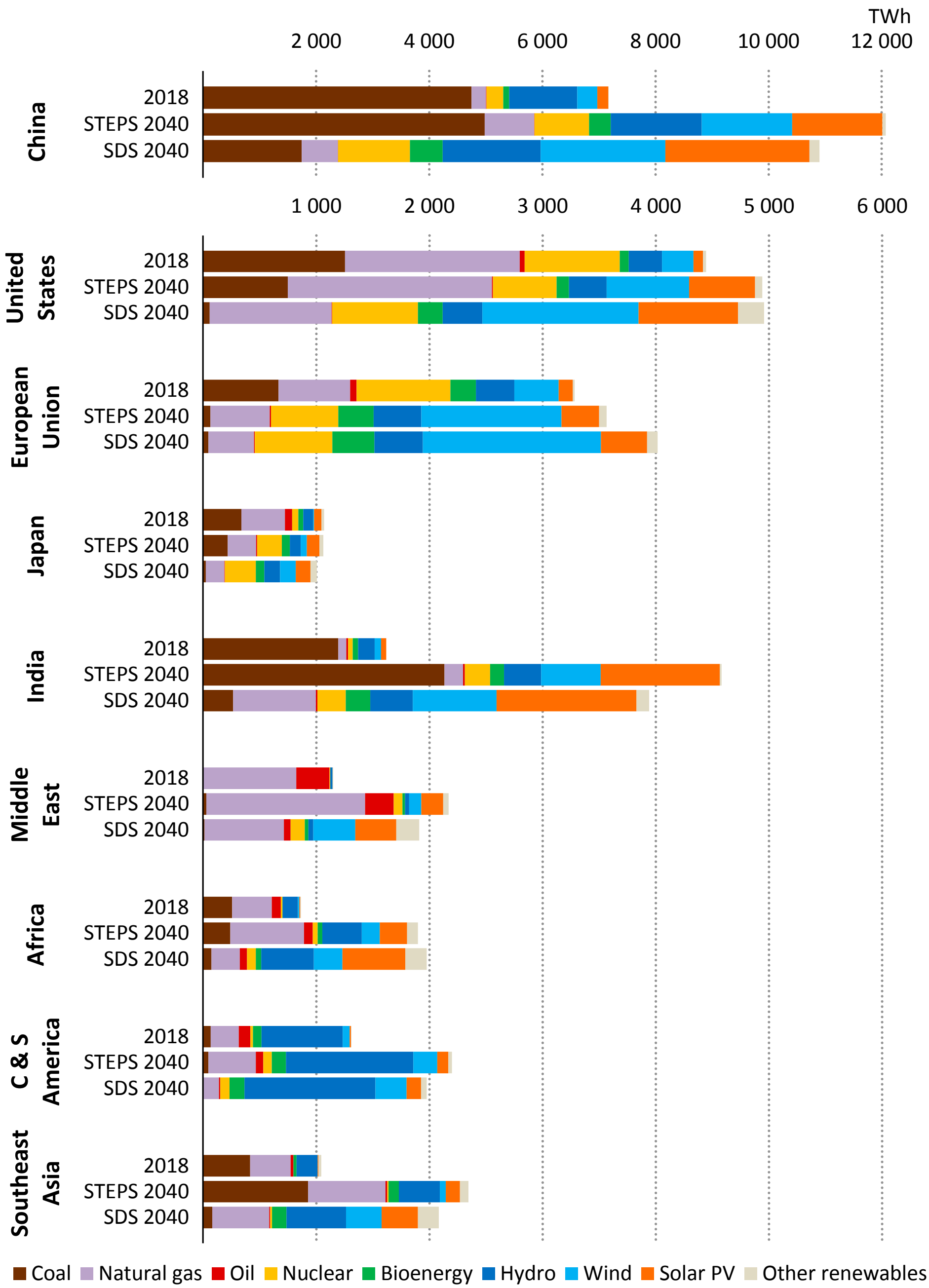
The future of electricity supply in **Japan** is guided by the 5th Strategic Energy Plan, published in 2018. It sets targets for the energy mix in 2030 and considers the path towards 2050. One key issue is the restarting of the nuclear fleet, with many plants having remained idle since the accident at the Fukushima Daiichi Nuclear Power Plant in 2011. As of May 2019, nine reactors had restarted operations and six more had received approval to do so from the nuclear regulator. A new order calling for anti-terrorism facilities at nuclear power plants is adding uncertainty about the pace of the nuclear restart. Japan is also targeting expansion of renewable energy to 22-24% in 2030, led by hydro and solar PV. Both nuclear and renewables would help Japan to reduce its reliance on imported coal and natural gas.

In **India,** three-quarters of electricity today comes from coal. Coal-fired capacity of 40 GW is currently under construction. Further capacity additions are planned to meet increasing demand, including peak loads and to ensure reliability with more dispatchable capacity. India is looking to diversify its power mix away from coal with a target of 175 GW of renewable energy capacity by 2022 (excluding large hydro), including 100 GW of solar PV. A longer term target of 500 GW of renewables capacity by 2030 (including large hydro) has also been announced. Battery storage, among other options, could support diversification away from coal, if costs can fall far enough (see section 6.12).

Expanding populations and rising incomes in developing economies are driving strong electricity supply growth in **Africa**, the focus region in this *World Energy Outlook*. Africa is rich in energy resources but poor in energy supply and aims to provide reliable and affordable electricity to a population that is set to grow to over 2 billion by 2040. Electricity demand is set to more than double to 2040 and many countries are actively developing renewable energy resources to meet rising needs (see Chapter 10).

**Southeast Asia** is set to achieve access to electricity for all in the near term. Countries in the region are seeking to develop a variety of sources of energy and expand regional trade to meet rising demand while maintaining affordability (IEA, 2019e).

**Figure 6.7 ▷ Electricity generation by region in the Stated Policies (STEPS) and Sustainable Development (SDS) scenarios**




*A suite of low-carbon sources play a larger role in the Stated Policies Scenario, but all regions need to accelerate efforts to drive clean energy transitions*

## 6.7 Power sector investment

In the Stated Policies Scenario, global power sector investment totals $20 trillion over the period to 2040, on average this is 20% higher than annual spending from 2010 to 2018 (Figure 6.8). The power sector represents 50% of total energy supply investment worldwide and includes spending on new power plants, transmission and distribution lines, as well as refurbishments and upgrades. Renewables account for about $360 billion per year, most of it for solar PV and wind power, an increase of about one-fifth from recent levels, plus falling costs mean that this investment also buys more capacity per unit of spend than in the past. Investment in transmission and distribution networks represents nearly 45% of total power sector investment, with average spending of about $400 billion per year, about 3% of which is for fast chargers for EVs. Network spending also rises from recent levels to support replacements, upgrades and extensions to assure the security of electricity supply and to integrate rising shares of variable renewables. Spending is cut by half for coal-fired power plants and by 90% for oil-fired capacity. The vast majority of new investment in coal-fired power plants is in developing economies, mainly in India, China and Southeast Asia, but alternatives are rapidly emerging that are more compatible with environmental goals including reducing air pollution (see section 6.11).

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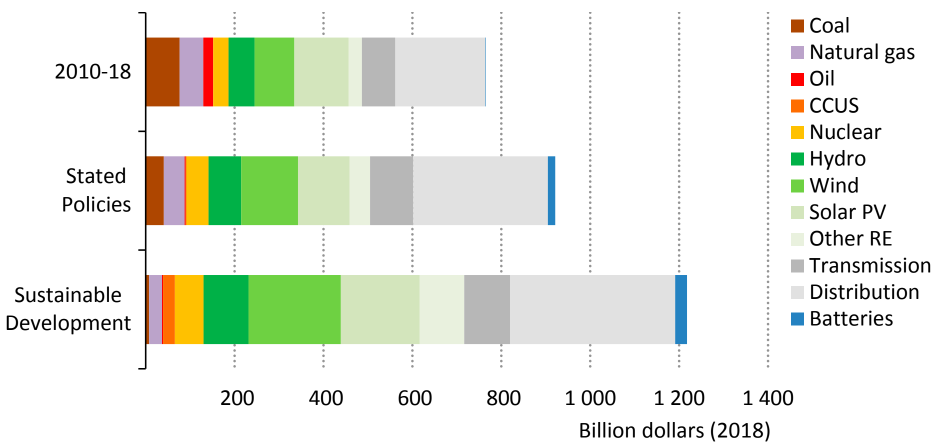
**Figure 6.8 ▷ Global annual average power sector investment, historical and by scenario, 2019-2040**

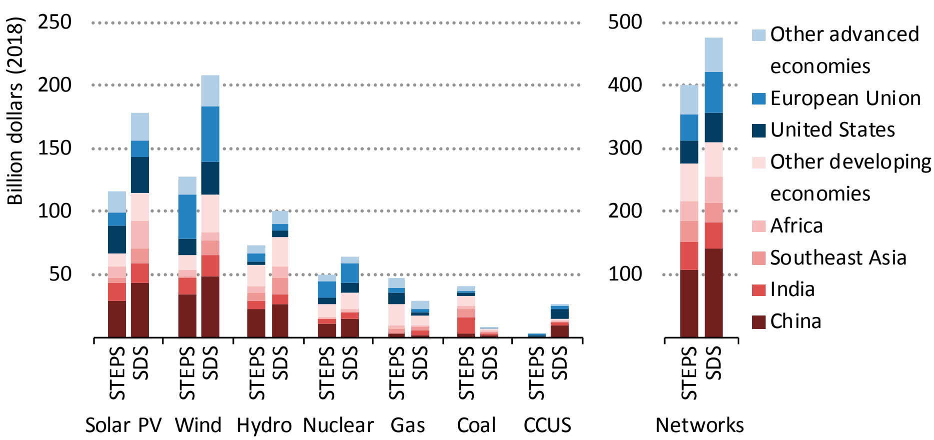



***Solar PV and wind make up half of power plant investment and grid spending rises in both scenarios. Overall power sector investment rises by 60% in the SDS from recent levels***

Note: CCUS in this figure represents coal- and gas-fired plants equipped with carbon capture, utilisation and storage equipment; RE = renewable energy technologies.

In the Sustainable Development Scenario, power sector investment reaches nearly $1.2 trillion per year on average, or $27 trillion in total to 2040. This is around 60% higher than recent spending levels. In this scenario, power sector investment accounts for two-thirds of total energy supply investment, compared with almost half today. Annual spending on renewables doubles as the primary means of decarbonising electricity supply in markets around the world. Annual spending on wind power increases to $210 billion, followed by solar PV at $180 billion, hydropower at $100 billion and other renewables at $100 billion (Figure 6.9). Spending on nuclear power doubles from recent levels, with more than 10% to extend the lifetime of existing reactors: such extensions are one of the most cost-effective ways of sourcing low-carbon electricity. After the fossil fuel power projects currently under construction (including around 170 GW of coal-fired and 120 GW of gas-fired generation) are completed, investment in fossil-fuelled power plants without CCUS slows dramatically to around $40 billion per year or 75% less than average annual spending from 2010 to 2018, while annual spending on fossil-fuelled plants equipped with CCUS rises to almost $30 billion per year, with most of this increase coming in the second-half of the outlook period. Close to 40% of annual spending, some $475 billion per year, is for electricity networks, with 80% for distribution networks.

**Figure 6.9 ⊳ Average annual power sector investment by region, 2019-2040**




*In both scenarios, developing economies make up over 60% of investment in power plants, accounting for 80% of hydropower and coal, and over 60% in solar PV and nuclear*

Notes: STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario. CCUS in this figure represents coal- and gas-fired plants equipped with carbon capture, utilisation and storage equipment.

In the Sustainable Development Scenario, total power plant investment is over 40% higher than in the Stated Policies Scenario. Over 60% of global power sector investments are made in developing economies, with China leading the way in solar PV, wind and hydro, and coal plants equipped with CCUS. About two-thirds of investment in electricity networks is in developing economies in both scenarios. Among advanced economies, the United States leads investment in solar PV in both scenarios and remains the largest investor in gas-fired power plants. Europe leads investment in wind, with particularly strong development of offshore wind in the Sustainable Development Scenario (see Chapter 14).

## 6.8 Competitiveness of power generation technologies

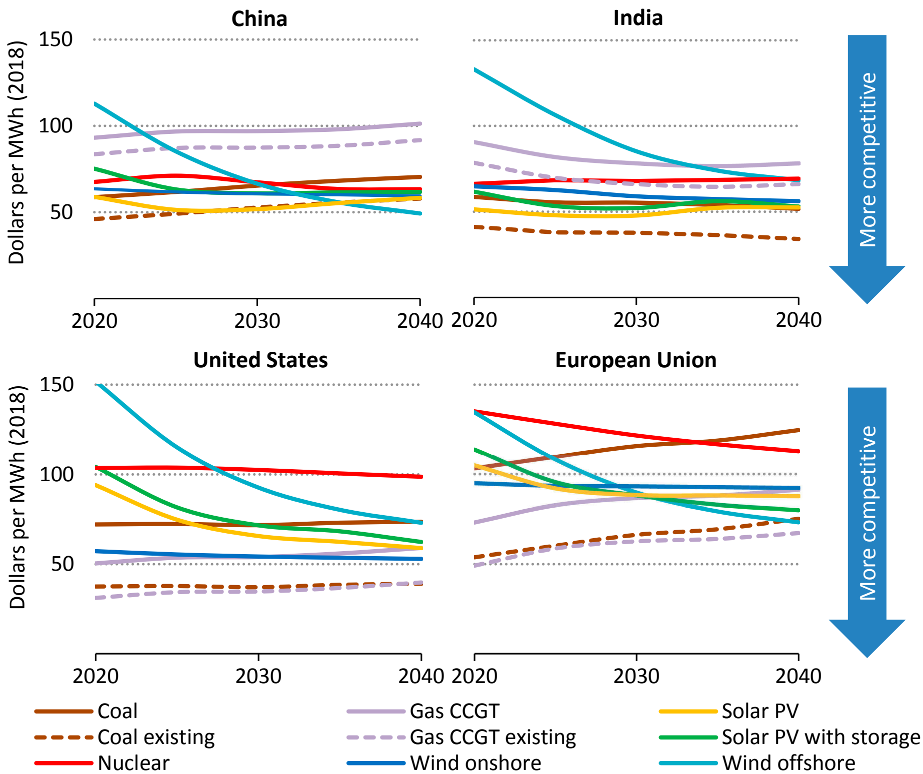
Power systems are undergoing unprecedented changes, including rising shares of variable renewables and an increasing need to source power system flexibility. This calls for new metrics to assess the competitiveness of various power generation technologies. The levelised cost of electricity (LCOE) is the most commonly used metric for competitiveness and it remains useful in certain cases, but it needs to be complemented with additional system-specific information. The value-adjusted LCOE, introduced in the *WEO-2018*, provides a single metric for evaluating competitiveness under market conditions, considering both the costs and value for each technology in a system at a given time (IEA, 2018a). The value-adjusted LCOE does not include the costs of environmental externalities where they are not priced in the market, nor does it include network integration costs that are extremely site-specific. Other metrics, including the system LCOE (Ueckerdt et al., 2013) and value-cost ratio (US EIA, 2019) also offer approaches to capture both costs and value.

As a result of continued cost reductions, solar PV becomes the most competitive source of electricity in 2020 in China and India, and largely closes the gap with other sources by 2030 in the European Union and United States (Figure 6.10). In the Stated Policies Scenario, the global average LCOE of solar PV declines by about 50% from 2018 to 2030. After 2030, solar PV has the lowest LCOE of any power generation technology in many markets, including China and India (see Annex B).[7] However, the competitiveness of solar PV and resulting deployment should not be taken for granted, because the system value of solar PV tends to decline relative to the system average as its share of generation rises and this offsets further cost reductions in many cases. The output of all solar PV projects in a region is concentrated in the same hours of the day, so as the share of solar PV increases, then the value of additional output in those hours tends to decline (Hirth, 2013). This means that exponential growth for solar PV is not necessarily an obvious conclusion (Wanner, 2019). However, energy storage, such as batteries, can help by shifting solar power output to when it is valuable. As a result, solar PV plus storage becomes an increasingly competitive option in several leading markets, including India (see section 6.12).

Other renewables can also provide competitive new sources of electricity. Hydropower has long been a low-cost source of electricity, where high quality resources were able to offset relatively high upfront costs. Some new hydro projects are underway, mostly in developing economies. Onshore wind power has been one of the cheapest sources of electricity in mature markets for several years, and offshore wind is catching up as a result of recent technology gains (see Chapter 14). Geothermal can also be a competitive power generation technology where high quality resources are available at shallow depths, as for example in the East Africa Rift Valley. Bioenergy for electricity production and concentrating solar power are not at present generally competitive, though the technologies involved may well be developed further, and as dispatchable renewable energy technologies they could become more important.

[7] For additional power technology cost assumptions and projections, see iea.org/weo/weomodel/#power.

**Figure 6.10 ⊳ Value-adjusted levelised cost of electricity by technology in selected regions in the Stated Policies Scenario, 2020-2040**




*Considering both the changing technology costs and system value, solar PV is set to become one of the most competitive new sources of electricity by 2030*

Note: CCGT = combined-cycle gas turbine.

The competitiveness of conventional power plants depends heavily on the availability of low-cost resources and market conditions. Coal-fired power plants remain one of the most competitive new sources of electricity wherever $CO_2$ or pollutant emissions have low or zero prices. Efficient gas-fired power plants are competitive especially where natural gas prices are very low, as they are in the United States. New nuclear power plants have proved to be high-cost endeavours in recent years, often involving delays and cost overruns, with notable exceptions in China, Korea and the United Arab Emirates. However, lifetime extensions for existing nuclear reactors are one of the most competitive sources of clean energy (IEA, 2019d). In general, existing conventional power plants are more competitive with renewables than new builds, because they usually need to cover only their short-run fuel and maintenance costs to continue operations, and capital investment for refurbishment is lower than for new construction. Just as with new builds, both the costs and value of existing projects need to be considered.

The competitiveness of power generation technologies is not fixed and is influenced by decisions taken by policy makers, regulators and the industry. For example, pricing $CO_2$ and other pollutant emissions would fundamentally change the comparisons, improving the competitiveness of all low-carbon sources compared with fossil fuels. A lower cost of capital would also improve the case for most low-carbon technologies. For comparison purposes, the results shown in Figure 6.10 assume the same weighted average cost of capital (WACC) for all technologies within a given region (7-8% in real terms depending on the stage of economic development). Where market risks are relatively low, cheaper financing might be available and this would improve their competitiveness. Supportive policy frameworks, for example reducing revenue risk by guaranteeing prices, can also enable access to cheap financing. A sensitivity analysis on the impact of lower costs of capital is included in the offshore wind outlook (see Chapter 14). Demand-side response can also improve the case for variable renewables: to the extent that it enables demand to be shifted to align with available supply, it reduces the effect of declining value of wind and solar PV. The development of transmission and distribution networks also strongly influences the value of additional power plants: congestion in the network for example could otherwise limit the ability to tap high quality renewable energy resources.



## 6.9 Power sector emissions

### $CO_2$ emissions

**Table 6.5 ▷ Annual $CO_2$ emissions from the power sector by scenario** (Mt)

| | | | Stated Policies | | | | Sustainable Development | |
|---|---|---|---|---|---|---|---|---|
| | 2000 | 2018 | 2025 | 2030 | 2035 | 2040 | 2030 | 2040 |
| **Electricity generation** | **8 247** | **12 655** | **12 608** | **12 643** | **12 703** | **12 759** | **7 544** | **3 129** |
| Coal | 5 920 | 9 357 | 9 262 | 9 263 | 9 175 | 9 048 | 4 665 | 1 323 |
| Natural gas | 1 341 | 2 656 | 2 770 | 2 897 | 3 099 | 3 330 | 2 594 | 1 732 |
| Oil | 986 | 641 | 575 | 483 | 429 | 381 | 285 | 168 |
| Bioenergy with CCUS | - | - | - | - | - | - | -1 | -94 |
| **Heat production** | **1 055** | **1 163** | **1 151** | **1 135** | **1 110** | **1 075** | **916** | **651** |
| Coal | 532 | 708 | 679 | 657 | 627 | 593 | 461 | 228 |
| Natural gas | 415 | 403 | 426 | 435 | 443 | 445 | 415 | 391 |
| Oil | 108 | 51 | 45 | 43 | 40 | 37 | 40 | 32 |
| **Total** | **9 302** | **13 818** | **13 759** | **13 777** | **13 813** | **13 834** | **8 460** | **3 780** |
| $CO_2$ captured with CCUS | - | 1 | 1 | 14 | 37 | 59 | 309 | 1 323 |

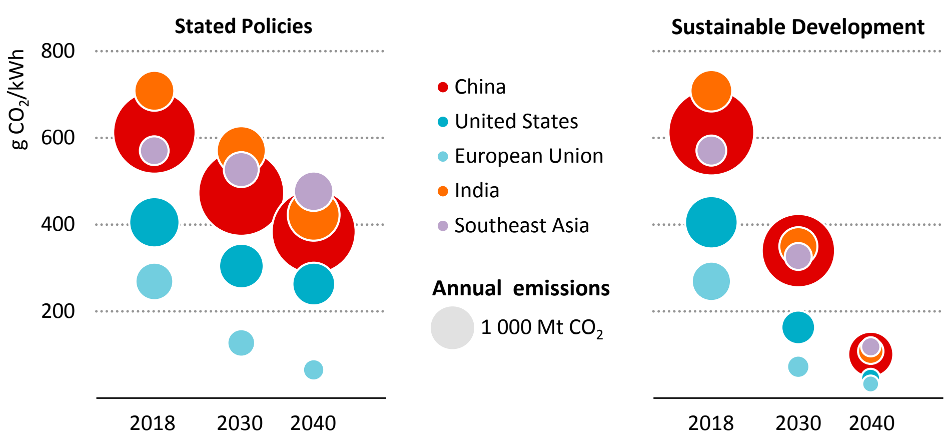
Note: Mt = million tonnes; CCUS = carbon capture, utilisation and storage equipment.

In the Stated Policies Scenario, global $CO_2$ emissions from the power sector remain stable to 2040 (Table 6.5), even though electricity generation rises by almost 60%. This is not only due to the rising share of renewables but also to continuing efficiency improvements in fossil fuel power plants, especially natural gas-fired power plants. Electricity generation makes up more than 90% of total power sector emissions, with the rest coming from the production of heat. Stable power sector $CO_2$ emissions to 2040 compares with a 50% increase over the period from 2000 to 2018.

Coal-fired power plants are the single largest source of energy-related $CO_2$ emissions today and represent about three-quarters from the power sector. To 2040, coal-fired power emissions decline by less than 5% compared with today. Tackling the emissions from the existing coal fleet is central to meet global climate objectives (see section 6.11). Although it is the least carbon-intensive fossil fuel, the 25% increase in the use of natural gas leads to an increase in emissions, and gas accounts for almost 30% of total emissions from the power sector in 2040. However, gas-fired power plants run more efficiently in 2040 producing 55% more electricity than now, while emitting 25% more emissions.

Power sector emission trends differ significantly by region. India overtakes United States before 2030 to become the second-biggest emitter behind China in terms of power-related $CO_2$ emissions, while Southeast Asia overtakes the European Union even earlier. In the United States, $CO_2$ emissions in the power sector decline by more than 25% to 2040. China sees its power sector emissions peak by 2030 and then falls by about 5% to 2040.

**Figure 6.11 ▷ $CO_2$ intensity of electricity generation by region and scenario**




*Carbon intensity of electricity generation declines in each region and scenario, though to a much greater extent in the Sustainable Development Scenario*

The global carbon intensity of electricity generation declines by more than one-third on average from today to 2040, from 475 grammes of carbon dioxide per kilowatt-hour (g $CO_2$/kWh) to 310 g $CO_2$/kWh in the Stated Policies Scenario. This is the result of falling intensities in all regions, including a 75% reduction in the European Union and about 40% declines in China, India and the United States (Figure 6.11). In the Sustainable Development

Scenario, faster adoption of low-carbon technologies and addressing emissions from the existing coal fleet means that all regions are converging to $CO_2$ intensities below 100 g $CO_2$/kWh, with reductions of about 90% in the European Union, the United States, Japan and Korea, and at least 75% in China, India, Southeast Asia, Middle East and Africa.

### *Pollutant emissions*

In the Stated Policies Scenario, global emissions of sulfur dioxide ($SO_2$) fall by 40%, and nitrogen oxides ($NO_X$) by 25% and particulate matter ($PM_{2.5}$) emissions decrease by one-third. These outcomes are driven by a shift to renewables and by a reduction in the use of coal in power (Figure 6.12). Most regions see reductions in these air pollutants, including the United States, the European Union, China and India. The main exceptions are Southeast Asia and other developing economies in Asia, where the use of coal in power increases significantly over the next two decades.

In the Sustainable Development Scenario, $SO_2$, $NO_X$ and $PM_{2.5}$ emissions decline dramatically in all regions as a result of reduced use of fossil fuels and enhanced end-of-pipe measures. These reductions contribute to improve air quality around the world and reduce negative impacts on human health.

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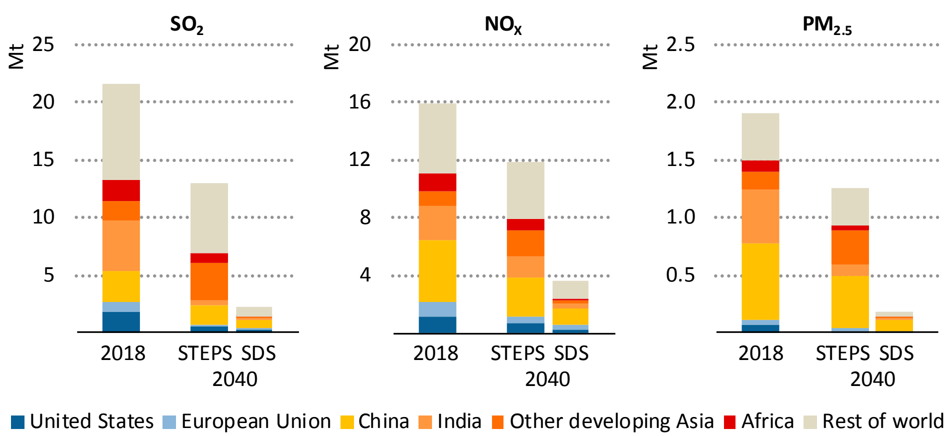
**Figure 6.12 ▷ $SO_2$, $NO_X$ and $PM_{2.5}$ emissions in the power sector by region and scenario, 2018-2040**




***Pollutant emissions from the power sector, mainly driven by coal use in Asia, are projected to reduce by 2040, most significantly in the Sustainable Development Scenario, where end-of-pipe technologies and lower fossil fuel use drive the change***

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

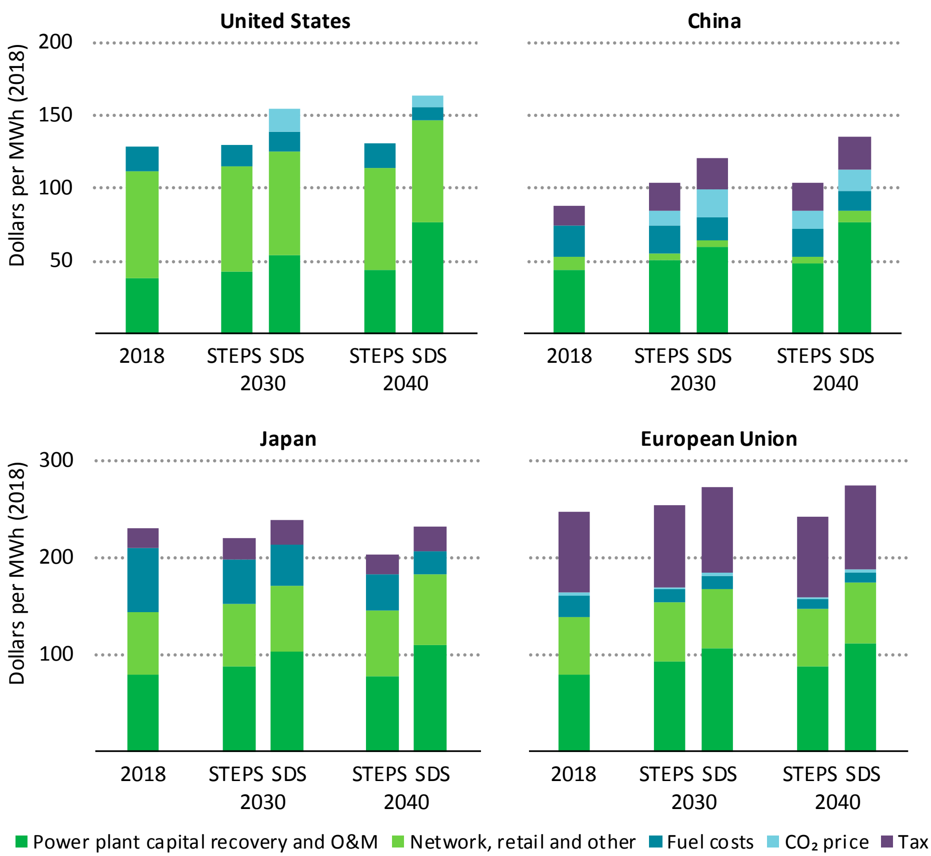
Source: International Institute for Applied Systems Analysis.

## Key themes

### *6.10 Affordability of electricity*

As electrification of the economy continues, the affordability of electricity is an increasingly central concern of consumers and policy makers. Residential electricity prices are the most visible metric for most consumers by which affordability is considered. There are significant differences in average annual electricity prices across regions (Figure 6.13). The production costs of electricity hinge on fuel costs and technology investments, and these can vary from one country to another, while the final price paid by the consumer is also affected by taxes, $CO_2$ prices, network costs and subsidies.

**Figure 6.13 ▷ Residential electricity prices in selected regions by scenario**




*Electricity prices are set to rise in most regions, but depend on many regional factors*

Note: MWh = megawatt-hours; O&M = operation and maintenance; STEPS = Stated Policies Scenario; SDS = Sustainable Development Scenario.

Residential electricity prices in the United States today are lower than most other advanced economies. This is thanks to relatively abundant and affordable indigenous resources like coal and gas, a well-established fleet of existing power plants, low investment needs in the face of subdued demand growth, and very low taxes on average. Electricity prices in Japan are notably higher today, having increased following the Fukushima Daiichi accident and the subsequent suspension of output from nuclear plants that made the country more reliant on more expensive liquefied natural gas imports. In the European Union, residential electricity prices are relatively high, in large part due to high taxes, which account for about one-third of the final price paid by consumers. In China, electricity prices are very low for households. This reflects both low electricity production costs that are a result of abundant and relatively cheap domestic coal resources and the fact that residential electricity prices benefit from cross-subsidies from the industry sector.

The cost structure of electricity becomes more capital-intensive across almost all regions in the Stated Policies Scenario because of increased reliance on technologies with low or zero fuel costs but higher upfront costs per unit of electricity produced. Where they are introduced, $CO_2$ prices push costs up in regions that rely heavily on coal-fired power generation, with a smaller impact in regions more reliant on gas. Despite cross-subsidies from industry, China sees growing electricity prices for households due to the introduction of a $CO_2$ price and to continuing investment in capital-intensive technologies. Electricity prices decline in Japan where the gradual restart of nuclear plants drives prices down by reducing costs from imported fuels. Residential electricity prices are relatively stable in the United States and the European Union in the Stated Policies Scenario.



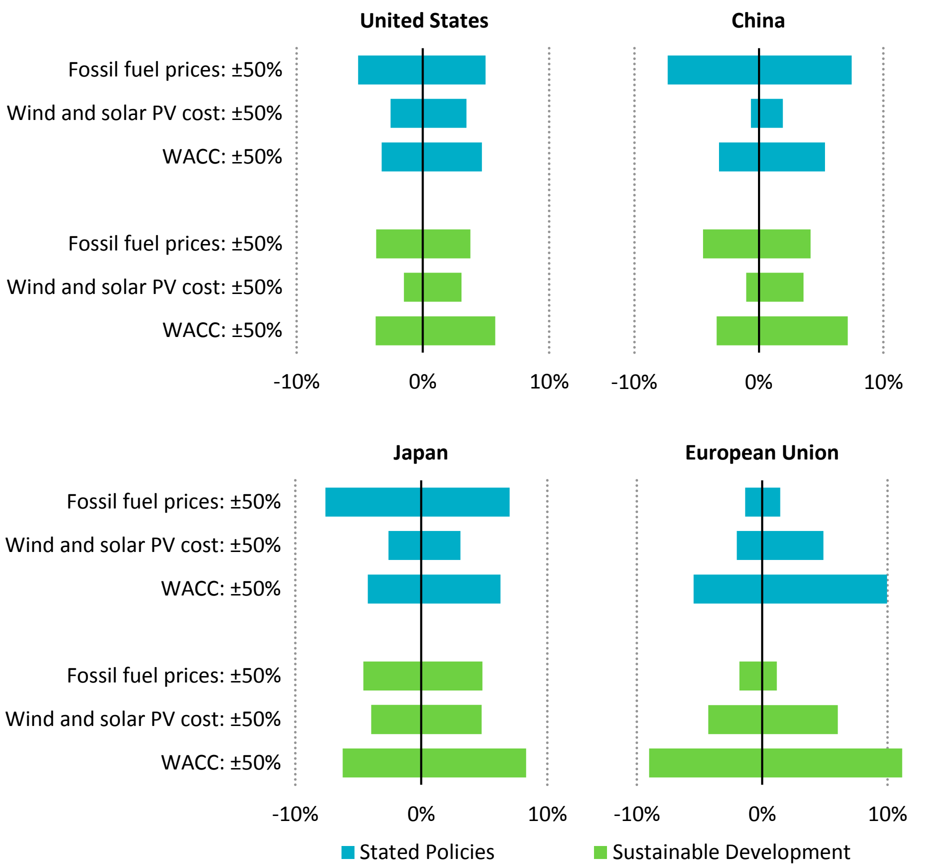
In the Sustainable Development Scenario, residential electricity prices tend to be higher as a result of a more rapid move away from reliance on existing fossil-fuelled power plants and a faster roll-out of new capital-intensive investments in low-carbon technologies. The costs of renewable energy technologies decline faster than in the Stated Policies Scenario with accelerated deployment, but they are not enough to offset the expanded investment needs. In this scenario, residential electricity prices increase by about 10% in the European Union and 25% in the United States, while staying broadly stable in Japan. Accelerated efforts to reduce $CO_2$ emissions in China bring an increase of about one-half although prices in China still remain below today's US prices.

There are some areas in which action could help to improve the affordability of electricity. Any reduction in policy uncertainty would help to boost investor confidence, reduce risks and lower the cost of finance. Support for innovation through research, development, demonstration and deployment activities could facilitate new and cheaper technologies. Bills could also be lowered by subsidies for low-income households to buy more energy-efficient equipment.

### *Sensitivity analysis*

Market dynamics, technology costs and policy decisions all have to be considered in any assessment of projected electricity prices. This section examines how sensitive residential electricity prices are to three of the largest uncertainties in our scenarios: fossil fuel prices, the cost of wind and solar PV, and the cost of capital (i.e. financing costs) for all power generation technologies (excluding transmission). No single factor yields changes higher than 12%, but all have a significant impact on electricity prices in the Stated Policies and Sustainable Development scenarios (Figure 6.14).

**Figure 6.14 ▷ Sensitivity analysis of residential electricity prices by scenario, 2040**




*All factors influence electricity prices and their impact is determined by regional circumstances*

Notes: WACC = weighted average cost of capital. All sensitivities are compared with the projected residential electricity price in 2040. Additional information on fossil fuel prices and power generation technology costs is available in Annex B.

The variability of fossil fuel prices has the biggest impact in countries like Japan that rely heavily on fossil fuel energy imports and such as China where fossil-fuelled power provides the biggest share of the electricity supply. However, even in these countries, 50% lower fossil fuel prices in 2040 in the Stated Policies Scenario would reduce residential electricity prices by only 7-8%. In the Sustainable Development Scenario, consumers are less exposed to changes in fossil fuel prices.

The sensitivity of electricity prices to wind and solar PV costs is relatively low, less than a 5% reduction for 50% lower costs, despite the fact that they dominate power plant investment over the next two decades in both the Stated Policies and Sustainable Development scenarios. In part, this reflects the fact that the existing power plant fleet represents a large part of electricity supply costs for years to come, as power plants have operational lifetimes measured in decades. The cost of wind and solar is particularly important in the European Union, where wind alone accounts for 40% of new capacity additions in both scenarios, more than one-third of which takes the form of offshore wind. The United States and Japan are less sensitive to the cost of wind and solar PV because these technologies account for a smaller share of their total capacity additions than is the case in the European Union. In China, the cost of wind and solar PV has an even smaller effect on the final electricity price than elsewhere because its technology costs are among the lowest in the world.



The WACC for power generation technologies affects the affordability of electricity across all regions and is particularly important in those characterised by a shift towards more capital-intensive technologies such as renewables and nuclear power. Reducing the WACC by 50% would reduce residential electricity prices by 3-6% in the Stated Policies Scenario in all four regions. In the Sustainable Development Scenario, the shift away from fossil fuels increases the effect on electricity bills due to variations in the WACC and of the cost of wind and solar PV, especially in the European Union where the impact would reach nearly 10%.

### *Role of electricity in household energy spending*

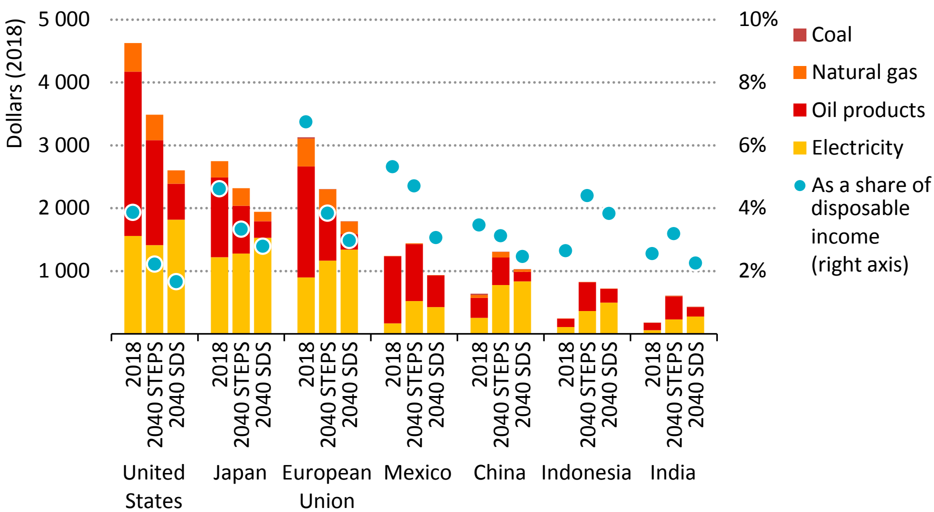
The level of consumer energy spending today varies substantially across regions, with marked differences between advanced and developing economies attributable to a combination of different consumption patterns, tax policies and fossil fuel subsidies (Figure 6.15). While energy bills are highest in advanced economies, they tend to account for a similar share of disposable income in most countries, although taxes and subsidies mean that there are plenty of exceptions to this. Expenditure on oil products generally constitutes the largest component of household spending on energy and accounts for between 40% and 60% of the total.

In advanced economies, overall energy spending is set to decline over the projection period as a share of disposable income in the Stated Policies Scenario, mainly thanks to more energy-efficient cars and heating systems. Expenditure on electricity increases as a proportion of the total and expenditure on fossil fuels declines. In developing economies, total household energy bills are projected to increase in all regions, as households become increasingly affluent and demand more energy services. These increases more than offset energy efficiency improvements. Both electricity and fossil fuel related bills are set to rise, though electricity tends to increase as a share of overall household energy spending.

In the Sustainable Development Scenario, stronger energy efficiency measures reduce overall consumer energy spending even further in advanced economies and mitigate the effects of increased consumption in developing economies, thus reducing the impact of energy purchases on disposable income.

Electricity bills today account for between one-third and one-half of consumer energy payments in most regions. The electricity share of overall consumer energy expenditure is set to rise in both scenarios. Electricity spending increases on average to over 40% of total household energy spending in the Stated Policies Scenario and to two-thirds in the Sustainable Development Scenario, where there is more electrification of end-uses.

**Figure 6.15 ▷ Household energy bill by fuel, 2018 and 2040 by scenario**




*Electrification and energy efficiency reduce the impact of energy bills on household disposable income*

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

This increase in spending on electricity as a result of increasing electrification is combined with a reduction in spending on other fuels, for example as consumers turn from conventional to electric cars. This shift has implications for costs. In the case of cars, for instance, it costs more at the outset to buy an electric car than it does to buy a conventional one, but there are significant subsequent savings in annual fuel bills. In the Stated Policies Scenario, payback periods are five to six years in China, European Union and United States in 2025: these reduce by half by 2040.

## 6.11 Tackling emissions from coal-fired power plants

### Overview

Coal-fired power plants have been providing reliable, flexible and affordable electricity for well over a century. In recent decades they have helped to bring access to electricity to hundreds of millions of people across China, India and Southeast Asia, and have been a catalyst for economic development.

Coal-fired power generation, however, is the single largest source of greenhouse gas (GHG) emissions. It accounts for 30% of energy-related $CO_2$ emissions and around a quarter of energy-related GHG overall. Addressing these emissions is central to meet global climate objectives. The continued operation of the world's existing coal fleet would "lock in" a significant amount of $CO_2$ emissions and contribute to air pollution, potentially putting sustainable development targets out of reach.

The Paris Agreement and other commitments look to sharply reduce global $CO_2$ emissions. For example, the Paris Agreement aims to hold "the increase in the global average temperature to well below 2 degrees Celsius above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels". Keeping the temperature rise below such limits implies a global budget for $CO_2$ emissions, beyond which climate goals become unattainable. If operations continued at current levels, emissions from coal-fired power plants in the period to 2050 would use up most of the remaining carbon budget consistent with meeting the stringent climate goals agreed at the United Nations.

Retrofitting coal-fired power plants with CCUS technologies, repurposing coal-fired plants to provide flexibility and, in some cases, gradually phasing out coal-fired plants where CCUS is not possible would create considerable room to manoeuvre to achieve climate goals. Such a strategy would also require rapidly scaling up other low-carbon sources, led by renewables (see Chapter 2).

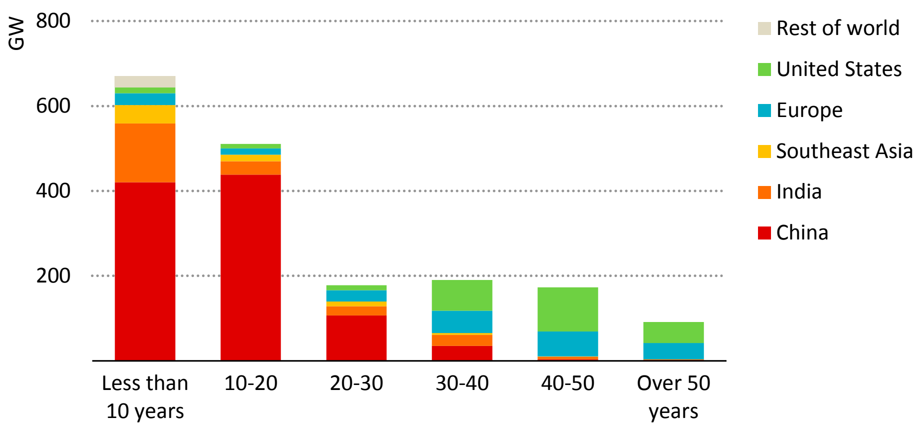
New coal-fired power plants are still being built today. Over 170 GW of coal-fired power capacity was under construction at the start of 2019. Their completion would expand the global coal fleet by close to 10% and risk locking-in another 15 Gt of $CO_2$ emissions over the next two decades.

This section provides an analysis of the potential emissions from existing coal-fired power plants around the world. It then assesses region specific least-cost options for making the existing coal-fired power plant fleet compatible with global goals to tackle climate change, reduce air pollution and increase energy access.

*Where are $CO_2$ emissions from coal-fired power generation locked in?*

There are 2 080 GW of coal-fired power plants in operation worldwide, accounting for 38% of global electricity generation, more than any other source. Coal's share today is the same as it was throughout the 1970s. Almost 60% of the existing coal fleet is 20 years old or younger (Figure 6.16). In developing economies in Asia, existing coal plants are on average just 12 years old, meaning they are likely to operate for decades to come. Over the past 20 years, Asia accounted for 90% of all coal-fired capacity built worldwide, including 880 GW in China, by far the most of any country, followed by India (173 GW) and Southeast Asia (63 GW). Elsewhere there were smaller additions of coal-fired capacity in Europe (45 GW), Korea (28 GW), United States (25 GW), Japan (20.5 GW) and Africa (10 GW).

**Figure 6.16 ▷ Global coal-fired power capacity by plant age, 2018**

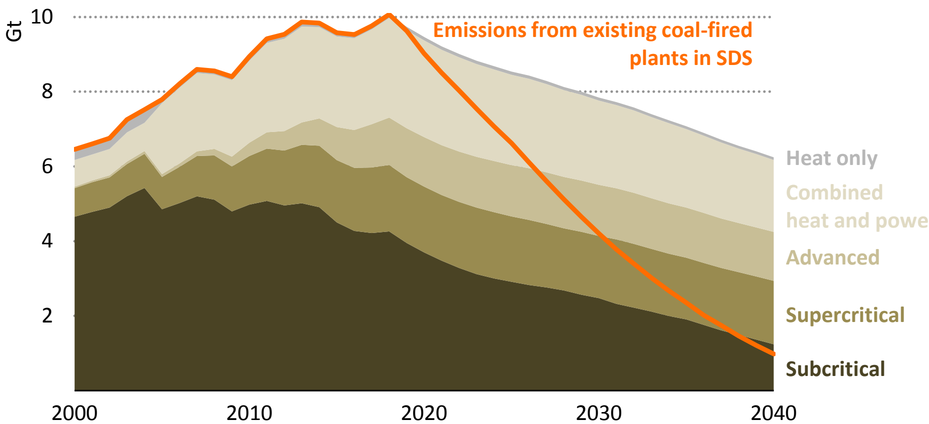



***Asia is home to 90% of coal-fired power plants under 20 years of age***

As matters stand, the existing global fleet of coal-fired power plants would continue to produce electricity and release $CO_2$ emissions for many years to come. The design lifetime of coal plants is typically 50 years. On the basis of continued operations and economics in line with stated policies, $CO_2$ emissions from the existing coal fleet would steadily decline to 2040, falling by about 40% over the next two decades (Figure 6.17).

Subcritical coal-fired power plants, the least efficient designs when producing only electricity, have been built around the world and account for over 40% of global $CO_2$ emissions from the coal fleet today. Subcritical plants produce significantly more emissions per unit of power generated than more modern coal plants. Close to half of subcritical plants in operation are under 20 years of age, and could emit more than 60 gigatonnes (Gt) of $CO_2$ over the next two decades. More efficient supercritical and advanced designs account for about 30% of coal plant $CO_2$ emissions today, with the remainder coming from combined heat and power plants. To 2040, $CO_2$ emissions from efficient coal-fired power plants are set to remain largely unchanged under stated policies.

**Figure 6.17 ⊳ Global $CO_2$ emissions from existing coal-fired power plants by technology with a 50-year lifetime in the Stated Policies Scenario**




*With a 50-year lifetime, existing coal-fired power plants would produce 175 Gt $CO_2$ in the period to 2040*

Note: SDS = Sustainable Development Scenario.

### *Recent developments around the world*

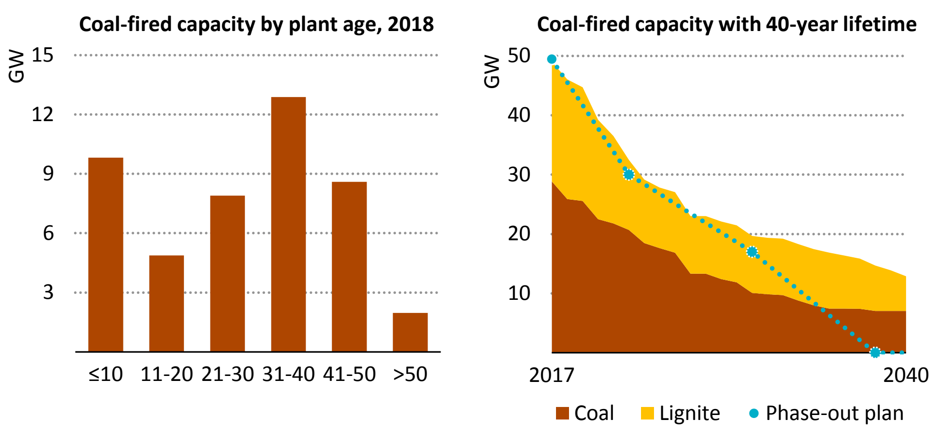
Government policies towards coal differ significantly from country to country. This section provides an overview of recent major developments in key regions.

Excess power capacity, cheaper renewables and concerns about local pollution have prompted China's central government to look closely at the country's fleet of coal-fired power plants in recent years. Efforts to fight pollution and reduce emissions have led to ultra-low emissions retrofits, efficiency improvements and flexibility retrofits. Over the past decade, more than 700 GW of coal-fired power units – nearly 70% of its total installed coal capacity – have been retrofitted to reduce their pollutant emissions to around the level of gas-fired units (for $SO_2$, $NO_X$ and $PM_{2.5}$). In addition over the past decade, 650 GW of coal-fired capacity completed efficiency upgrades, and at least 54 GW was retired, all of it small scale and of subcritical design.

In the United States, the total capacity of the ageing coal fleet has declined by 20% over the past decade, due to challenging market conditions and stricter pollution standards. On average, the 75 GW of retired capacity had operated for 53 years, and three-quarters of it used subcritical designs. Low natural gas prices have driven down wholesale electricity prices and tightened margins for participants in competitive markets, including coal-fired capacity, while stricter pollution controls have raised costs. For example, the Mercury and Air Toxics Standards rule was established in 2011, setting limits on pollutants such as mercury, arsenic and heavy metals. As a result, nearly 90 GW of coal capacity added pollution control equipment by mid-2016, at a cost of less than $10 million for most facilities (US EIA, 2016). In 2018, the United States raised the 45Q tax credits that provide a financial boost for CCUS development in power and industry, tied to the amount of $CO_2$ captured and the type of storage employed.

Germany offers a real-world example of the challenges and opportunities of looking to address coal plant retirements. It announced plans in January 2019 to end its use of coal-fired power plants by 2038, with the possibility of bringing the deadline forward to 2035. Germany is Europe's largest coal consumer, and about 35% of its electricity was from coal plants in 2018. In recent decades, coal-fired plants in Germany were retired when reaching 35 or 40 years of age on average. The average age of the coal fleet in Germany today is about 30 years and a quarter of it is more than 40 years old (Figure 6.18). The installed coal-fired power capacity was 46 GW in 2018.

**Figure 6.18 ▷ Germany's existing coal-fired power capacity by age and phase-out plan**




*Germany's fleet of coal-fired power plants is a mix of old and young facilities, and the announced phase-out plan will accelerate retirements*

Launched by the United Kingdom and Canada in 2017, the Powering Past Coal Alliance includes Germany along with 31 other countries, 25 states and cities, and 34 private sector members that have committed to phase out existing coal-fired power plants and to introduce a moratorium on new coal power stations not equipped with CCUS. Alliance members have over 110 GW of coal plants currently in operation, accounting for 5% of the total global coal fleet, of which about 60% is more than 30 years old. The move to phase out coal is driven by concerns about the associated emissions. In some cases there are emissions performance standards and air quality regulations that reflect those concerns. For example, half of the Alliance countries are European Union members, accounting for some 60% of the EU's coal-fired capacity. By 2021, all coal-fired power plants in the European Union need to meet tighter environmental standards and about 82% of plants currently do not meet the new standards (Climate Analytics, 2019). The cost of upgrading them to meet the new standards could be around EUR 11 billion, plus operating costs would rise if they are not shuttered. Plant owners may therefore be better off decommissioning the plants rather than retrofitting them.

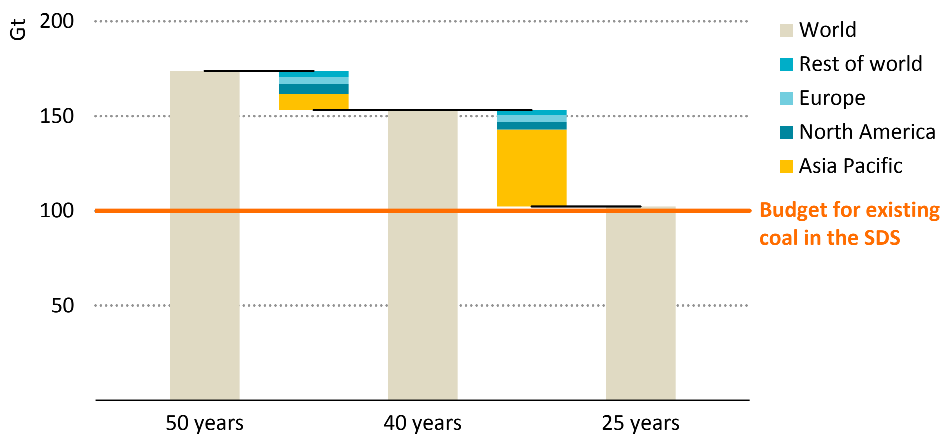
### *What are the options?*

A crucial question for tackling $CO_2$ emissions is what average lifetime for the world's coal-fired power plants would be compatible with climate goals. To illustrate the point, capping the lifetime of all existing coal-fired power plants at 25 years would bring their emissions in line with the Sustainable Development Scenario. Applying a strict 40-year limit would result in emissions exceeding climate goals by 50% (Figure 6.19).

Restricting the lifespan of operating coal-fired power plants is appealing in its simplicity, but it would not be practical for reasons of cost and energy security. Almost 700 GW of coal-fired capacity in operation today is more than 25 years of age. If these plants were to shut down immediately, it would leave many countries short of sufficient supply and significantly compromise electricity security. Applying a strict lifespan limit to existing coal-fired power plants would also entail immediate financial challenges to the owners, which are a mix of state-owned and privately held companies.



**Figure 6.19 ▷ Cumulative $CO_2$ emissions from existing coal-fired power plants by assumed lifespan, 2019-2040**




***Limiting coal plants to 25-year lifetimes would bring emissions in line with the Sustainable Development Scenario, but would have consequences for costs and energy security***

Note: SDS = Sustainable Development Scenario.

A multifaceted approach needs to be considered, analysing each plant and the market in which it operates as well as the economic implications of various options. There are several options that could move the dial on emissions from existing coal-fired power plants besides limiting their lifetimes. These include: *retrofitting* with CCUS or biomass co-firing equipment; *repurposing* facilities to focus on providing power system adequacy and flexibility while reducing operations (i.e. electricity produced); and *retiring* early if the above options are not viable. Each option would offer $CO_2$ emission reductions ranging from only a few percentage points with limited changes in operations to close to 100% for high levels of CCUS or CCUS in combination with biomass co-firing.

Further investment is likely to be needed to make existing coal-fired power plants more compatible with a sustainable energy pathway. Increasing flexibility or enabling biomass co-firing would require millions of dollars per gigawatt of capacity, and equipping with CCUS would cost $1 billion or more per gigawatt at current technology costs. Allowing coal plants to continue operating would help to maintain system adequacy and reliability, and would delay or soften the financial impact of closures (Table 6.6). Other considerations, such as the potential costs of remediating the site of a decommissioned facility or a plant's suitability for CCUS retrofits, also influence the attractiveness of each option.

**Table 6.6 ▷ Measures to reduce $CO_2$ emissions from coal-fired power plants**

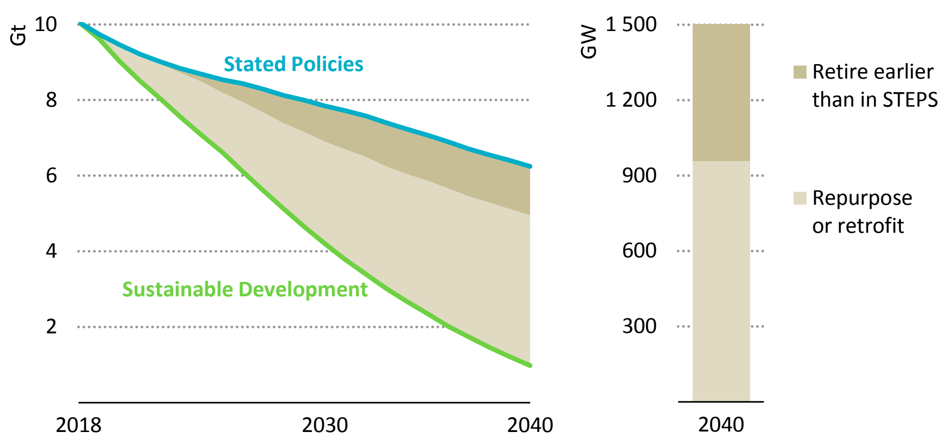
| | Retrofit | | Repurpose operations, focus on flexibility | Retire |
|---|---|---|---|---|
| | CCUS | Biomass co-firing | | |
| **Impact at facility** | | | | |
| $CO_2$ emission reductions | Up to 99.7% | 5-20% | 1-80% | 100% |
| **Considerations** | | | | |
| Certainty of emissions reductions | High | Medium | Low | High |
| Additional investment scale per GW | Billions | Millions | Millions | None |
| Provides system adequacy & flexibility | ● (green) | ● (green) | ● (green) | ● (red) |
| Delays financial impact | ● (green) | ● (green) | ● (green) | ● (red) |
| Other | Site suitability | Biomass availability | | Costs of site remediation, employment impacts |

Meeting global climate goals in a cost-effective manner requires a combination of the available options in order to reduce $CO_2$ emissions from the existing fleet of coal-fired power plants by 70 Gt over the next two decades. We assessed the lowest cost option for each plant worldwide in a scenario compatible with meeting global climate goals and other sustainable development targets. Retrofitting capacity to capture carbon or co-fire with biomass plays an important role, particularly in China. In this analysis, about 110 GW of coal plants are retrofitted with CCUS by 2040 in China, offering an asset protection strategy and supporting energy security with capital investment of around $160 billion. In 2016, an assessment of the existing fleet in China concluded that over 300 GW of existing coal-fired power plants met the basic criteria to be suitable for retrofit (IEA, 2016). CCUS retrofits are most attractive for young and efficient coal-fired power plants that are located near places with opportunities to use or store $CO_2$, including for enhanced oil recovery and where alternative generation options are limited. Although significant cost reductions have been identified through early operational experience, widespread adoption of retrofitting would require substantially enhanced policy support, including preferential dispatch to ensure high utilisation rates, together with some combination of feed-in tariffs, capital grant funding and tax credits. In this analysis, some 10 GW of US coal-fired power plants are retrofitted with CCUS, as the technology benefits from the recently increased tax credit. Other countries such as Canada, Norway and United Kingdom are also looking to scale up efforts on CCUS.

Repurposing coal-fired power plants to provide system flexibility while reducing electricity generation plays the largest role in our assessment, accounting for about 60% of the emissions reduction. Several countries, including India, are looking at ways to make coal an integral part of system flexibility while transitioning to a low-carbon power sector, providing electricity access to all and maintaining system reliability. The option of retiring coal-fired capacity before 50 years of operations accounts for about one-quarter of the emissions reduction in the assessment (Figure 6.20).



**Figure 6.20 ▷ Reducing $CO_2$ emissions from existing coal-fired power capacity by measure**




*Curbing $CO_2$ emissions from coal-fired power plants can be done cost effectively by retrofitting, repurposing and retiring the existing fleet*

Most of the 2 080 GW of existing coal-fired capacity worldwide would be affected by a shift in policies to meet global sustainability goals. About 600 GW reaches 50 years of age and retires (as in the Stated Policies Scenario). In addition, around 240 GW of existing coal-fired capacity would be retrofitted with CCUS or biomass co-firing equipment. Some 720 GW of would reduce operations to cut emissions, limiting electricity production but still providing system adequacy and flexibility. About one-quarter of the existing fleet would be retired in the Sustainable Development Scenario before reaching the typical 50-year lifespan.

### *What would be the financial impact?*

Implementing the retrofit, repurpose, retire strategy to make the world's existing coal-fired power plant fleet compliant with climate goals would entail CCUS investment of $225 billion over the period to 2040 and lead to balance sheet write-downs for some owners of existing facilities. Coal plant retirements would also call for greater investment in lower-carbon sources of electricity and the associated network infrastructure. While immediate action is needed, most of the financial impact would not occur until the 2030s.

More than $1 trillion of capital invested in the existing fleet of coal plants has yet to be recovered, most of it in Asia. Asset owners would normally look to recover this capital through revenues that exceed short-term fuel and operating costs. Continued operations while lower carbon sources of electricity were scaled up would provide an opportunity to most facilities to recover some of the remaining capital at risk. Some facilities would need to shut down before fully recovering their upfront capital investment, whether because of policy changes or changes in market conditions.

### *Implications*

Action must be taken to curb emissions from the existing fleet of coal-fired power plants around the world in order to keep the door open to limiting global average temperature increases to 2 °C or less, and to address air pollution. There are a number of options available, providing some flexibility for governments to adopt policies that reflect the opportunities and constraints of their respective energy systems. The options chosen have financial and social implications, as well as impacts on electricity security.

Coal-fired power plants provided 38% of global electricity supply in 2018. Filling the gap created by an accelerated reduction in output from existing coal capacity would involve a range of sources. Varying combinations of renewables, natural gas and nuclear power – all of which have lower $CO_2$ intensities than existing coal plants – could be used, depending on conditions and resources. Existing coal-fired power plants can have very low operating costs of $20 per megawatt-hour (MWh) or less, making it challenging to replace existing facilities with new sources of electricity without raising electricity supply costs. However, the falling costs of renewables are closing the gap with the operating costs of coal plants.

Tackling emissions from coal-fired power plants clearly has potential employment and social implications. Policies that support the development and deployment of CCUS technologies would spur investment in the technology and support related research, engineering and construction jobs. CCUS deployment would also boost employment and local economies in coal producing regions. Putting the power sector on a path to meet sustainable development goals could mean the potential closure of more than 500 GW of coal-fired power capacity, which would have significant negative consequences for local employment and local economies. Clear plans for retraining and other support measures would be vital to mitigate the impact in affected areas. Addressing emissions from coal power generation worldwide also raises the challenge for policy makers of how to finance the transition, which is global in scale and unevenly distributed geographically. Developing countries may also face a significant share of the burden.

## 6.12 Exploring the new frontiers of flexibility

### *Power system flexibility requirements will increase*

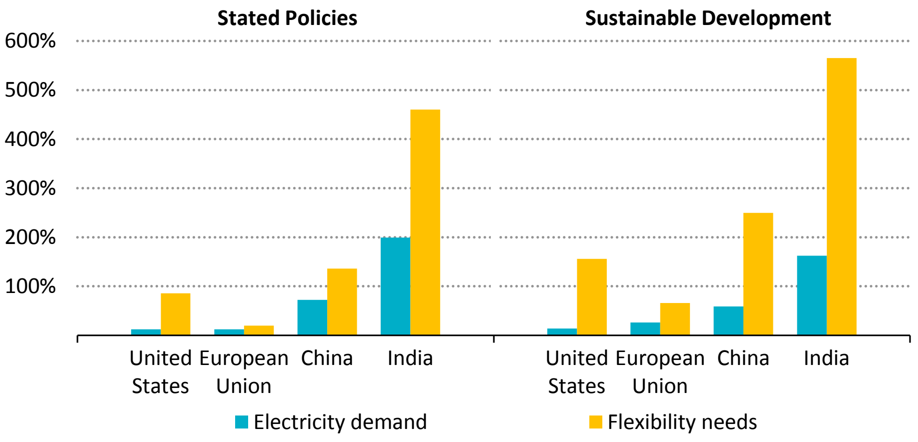
The Stated Policies Scenario sees a significant increase in the need for flexibility – the ability of power systems to respond in a timely way to changes in electricity supply and demand. All regions will need more flexibility. Expressed as peak ramping requirements, flexibility needs[8] will increase much faster than electricity demand. They increase fastest in developing economies where almost 90% of the electricity demand growth in this scenario takes place, and particularly in India (Figure 6.21).

The speed of that increase depends mainly on how fast the share of variable renewable energy expands. The share of variable renewables in the power generation mix is set to more than triple in China and the United States in the Stated Policies Scenario, as well as at the global level. In India, it increases fivefold, and in Southeast Asia sevenfold.

Flexibility needs are also affected by the changing demand profile, how well the rising variable renewables supply matches the demand profile of a particular power system and its size. Increasing use of air conditioners is adding to loads during the summer, particularly during peak periods. Electric vehicles potentially may strongly affect peak demand, especially if smart charging is not fully developed (See Chapter 7).

6

**Figure 6.21 ▹ Growth in electricity demand and flexibility needs by selected region and scenario, 2018-2040**




*Flexibility needs increase much faster than electricity demand, driven by rising shares of variable renewables, more electric vehicles and higher demand for cooling*

[8] Flexibility is a multifaceted concept that refers to the ability of power systems to balance demand and supply, and can be provided by different services (e.g. frequency regulation, operational reserves, load balancing). The change in the net load from one hour to the next (hourly ramping requirements) provides a useful indicator of flexibility and is used in this analysis. For more information on the drivers of increasing demand for flexibility and flexibility sources, see the *WEO-2018 Special Focus on Electricity* (IEA, 2018a).

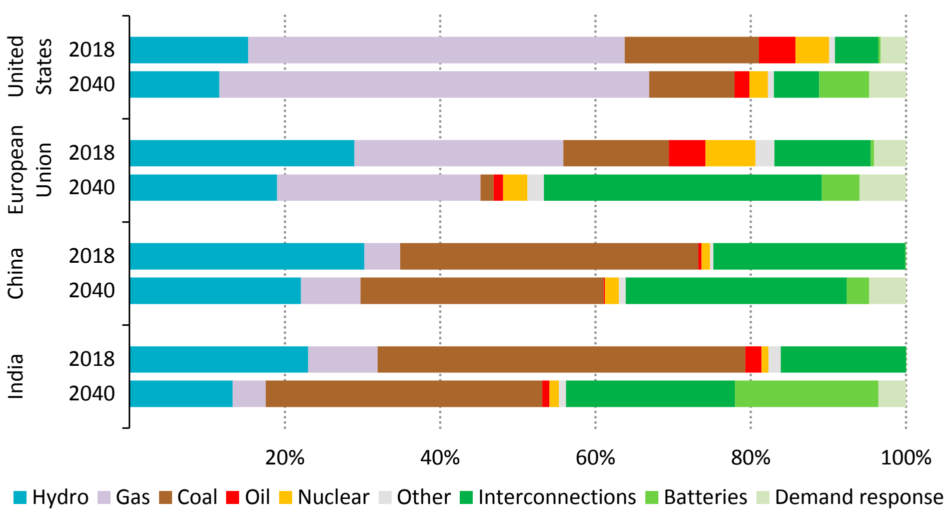
In the Sustainable Development Scenario, as the power sector moves towards decarbonisation and as electric mobility spreads, flexibility needs increase even more strongly. In this scenario, flexibility requirements in India's power system are six times today's level, in China they more than triple and in the United States they are 150% higher.

### *A diverse portfolio of flexibility options will be required*

Flexibility needs in the scenarios are based on analysis in which hourly demand profiles for projected years in different regions are assessed and fluctuations in net load are calculated in our World Energy Model. Based on the capacity mix of the specific region, the capability of the power system assets to change their output by the hour is simulated to identify which technologies can provide the flexibility required.

Conventional sources of flexibility in the form of power plants and interconnections have long maintained the reliability of power systems around the world. Today thermal power plants provide the bulk of the flexibility required by many electricity systems and this remains the case to 2040 in the Stated Policies Scenario (Figure 6.22). This is made possible by the retrofitting of existing thermal power plants, which helps increase ramp rates (IEA, 2018d), and by the construction of more flexible power plants such as gas turbines. Hydropower also remains an important source of flexibility in many regions. Interconnections between power systems and regions continue to alleviate network congestion by taking advantage of varying supply and demand patterns and pooling available flexibility resources.

**Figure 6.22 ▷ Sources of flexibility by region in the Stated Policies Scenario**




***Thermal power plants continue to provide the bulk of flexibility needs, along with interconnections, but batteries and demand-side response are rising fast***

Nonetheless, new flexibility sources will be needed. Batteries, demand response and sector coupling are poised to play pivotal roles in making sure future power systems are secure and reliable. Demand-side response also has a large part to play in meeting rising flexibility needs, for example by shaving peak demand and redistributing electricity to time periods when the load is smaller and electricity is cheaper. Distributed resources including variable renewables themselves, storage and demand response can also become key flexibility sources with appropriate market designs, as is happening in several countries (IEA, 2019f). Digitalisation is likely to have a major role to capitalise on the flexibility options.

Regional trends to 2040 show there is no one-size-fits-all approach to flexibility. The European Union is expected to source a significant portion of its flexibility needs from the large-scale deployment of interconnections. China is set to rely on more flexible coal-fired power plants and large-scale interconnections. In the United States gas-fired power plants are set to remain a cheap source of power system flexibility through to 2040. Most of India's additional flexibility needs are to be met by flexible coal-fired power plants, batteries and interconnections.



Changes in policy and regulatory frameworks, as well as economic incentives, are essential to ensure timely investment in flexibility assets and to make the most of the flexibility potential of existing power plants. Competitive electricity markets were originally designed with dispatchable power plants in mind. The rise of variable renewables is now challenging the suitability of those market designs to deliver efficient and timely investment. For example, there is a widening gap between electricity supply costs and revenues from energy sales, particularly in the European Union and the United States (IEA, 2018a). These markets may require reforms to spur investment and to establish a cost-effective set of flexibility measures.

The transformation of the power generation fleet is even more pronounced in the Sustainable Development Scenario, with variable renewables making up 40% of electricity generation by 2040. The increased reliance on variable renewables often translates into higher hourly ramps, which requires more flexibility including from batteries and demand-response measures.

### *Focus on battery storage*

The use of battery storage in the power sector is accelerating worldwide. In 2018, the global power sector added 3 GW of batteries boosting the total installed capacity to 8 GW. Major cost reductions – down 45% from 2012 to 2018 – and increased policy support in many regions underpin this development. For example, several US states, including New York and California, have introduced specific targets for batteries. Australia has subsidy schemes for residential storage and funding for utility-scale batteries.

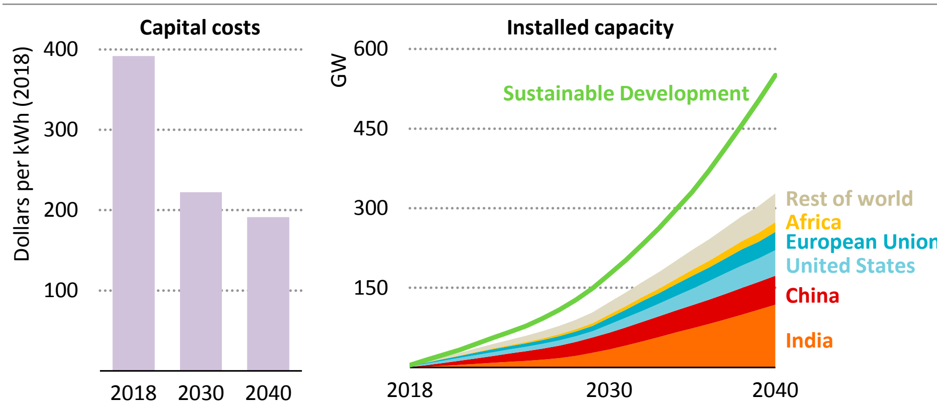
Battery storage is the fastest growing source of power system flexibility today and over the next 20 years. The modularity of batteries and their simple design allow them to be installed almost anywhere. They can provide fast response flexibility and help to balance the network through the provision of various remunerated services. They can also increase the value of variable renewables by enabling the electricity produced from solar and wind to be stored and injected into the grid at another time when system needs are higher.

The outlook for batteries is improved further by the prospect of economies of scale, learning from experience and advances in chemistry. Battery storage system costs are projected to halve in the next two decades, e.g. four-hour storage systems falling from $400 per kilowatt-hour (kWh) to less than $200/kWh. By 2040, batteries provide 330 GW of flexibility in the Stated Policies Scenario and 550 GW in the Sustainable Development Scenario (Figure 6.23). India is projected to lead the way in battery storage deployment, reaching 120 GW of installed capacity by 2040 in the Stated Policies Scenario, with most of this capacity being coupled with variable renewables such as solar PV and wind. China and the United States both install around 50 GW of utility-scale batteries in this scenario, while the European Union installs 35 GW.

Batteries are projected to become more and more competitive with other flexibility options as a result of cost reductions and the value of the energy arbitrage opportunities. Batteries can charge for a number of hours when electricity prices are low and then discharge during periods of higher prices.

The widespread deployment of battery storage requires electricity market reforms to incentivise sufficient investment in flexibility, together with other supporting conditions. Electricity market reforms ranging from scarcity pricing, operating reserve prices (as in US markets), frequency control ancillary services (as in Australia) and capacity mechanisms already appear in various places. Many of these market measures would help the business case for investment in battery storage, rewarding their dispatchability, fast response and contributions to system adequacy and reliability.

**Figure 6.23 ▷ Battery storage capital costs and installed capacity by scenario**




*In the next two decades, batteries are projected to be the fastest growing technology in the power sector, thanks to reduced costs and policies supporting deployment*

Note: the figure refers to four-hour battery storage.

### *Battery storage in India*

With ambitious plans for renewables, in particular solar PV, to satisfy rapidly increasing electricity demand, particularly at peak times, India has the most significant need for additional power sector flexibility among the countries in the Stated Policies Scenario. How India tackles its rapidly rising flexibility needs is critical for its energy transition, and also has global implications. Current flexibility needs are met by coal, hydro and gas-fired power plants, and by interconnections. But new and cheaper sources of flexibility are becoming available. India's significant uptake of variable renewables makes it a potential large-scale launch pad for battery storage technology. This section explores how that could happen.

**Demand soars:** In the Stated Policies Scenario, electricity demand is set to rise faster in India than in any other region to 2040 as a result of population growth and economic development. Increasing wealth drives demand for cooling, which expands eightfold and accounts for about 30% of the country's total electricity demand growth.

**Renewables expand:** Massive deployment of solar PV is projected in India thanks to a strong policy push. Its solar PV capacity is projected to reach 620 GW by 2040. Flexibility needs increase dramatically as demand peaks get higher, and the share of solar PV and wind in total electricity generation increases from 6% in 2018 to 34% in 2040.

**Coal continues to grow:** Total coal-fired power capacity is set to increase with 40 GW under construction in India at the start of 2019 and more in the pipeline. Uncertainty remains over whether new coal-fired power plants will continue to be built after 2030.

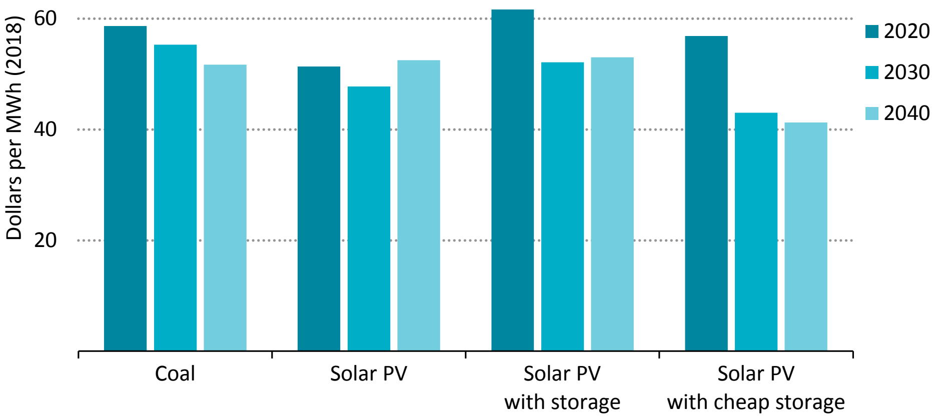
**Battery opportunity:** Battery storage is one of the technologies best suited to provide the flexibility that power systems in India need. The combination of solar PV and battery storage is emerging as a potentially potent combination that could drive significant new growth in storage capacity. Moreover, electric vehicle use is poised to increase significantly encouraged by policies to combat air pollution, thereby expanding demand for batteries exponentially. Boosting deployment could cultivate domestic battery manufacturing, potentially driving down their costs.

**Rewarding flexibility:** India needs flexible sources of electricity to ensure grid stability in the face of very large increases in variable renewable generation. Battery storage capacity could thrive in an ancillary services market that remunerates flexible options depending on their response speed (Central Electricity Authority, 2017). There is already an increasing need for energy storage to facilitate the integration of solar PV and wind generation as these technologies begin to affect the economics and technical operation power systems.

Battery storage coupled with variable renewables can both provide flexibility for power system operation as well as improve the competitiveness of variable renewables, especially solar PV. The rapidly falling costs of both battery storage and solar PV help to make combined facilities competitive with coal-fired power plants in India by 2030. As such, coupling battery storage with solar PV would offer an affordable option for displacing the need for some coal-fired capacity.

*Cheap Battery case: India*

**Figure 6.24 ▷ Value-adjusted LCOE for select power technologies in India in the Stated Policies Scenario**




***Compared with new coal-fired power plants, solar PV alone is already more competitive and solar PV with storage is rapidly closing the gap, especially if batteries are cheap***

Notes: LCOE = levelised cost of electricity. Assumed $CO_2$ prices in India are zero.

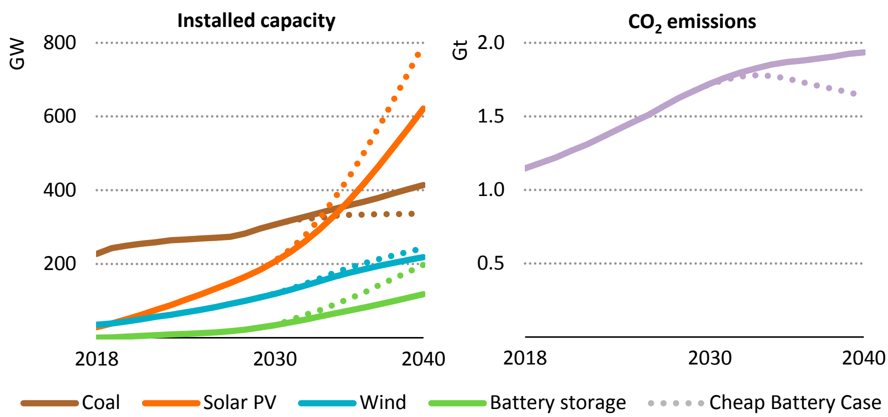
The cost of battery storage in the future is uncertain. Here we consider a case in which further cost reductions are achieved through improved chemistry; economies of scale in manufacturing and learning from experience. Battery system costs, which include the battery pack and the remaining balance-of-system costs, for a four-hour storage system go below $200/kWh by 2040 in the Stated Policies Scenario. In the Cheap Battery case, they are further reduced by 40% reaching $120 /kWh, making solar PV paired with batteries far more competitive with coal-fired power plants (Figure 6.24).

The Cheap Battery case projects 200 GW of installed battery storage capacity in India by 2040, around 80 GW higher than in the Stated Policies Scenario. This would have a direct impact on the need for new coal-fired power plants: once the existing coal project pipeline is completed, additions after 2030 would be cut by almost three-quarters, avoiding the construction of almost 80 GW of new coal-fired capacity. Adding battery capacity could bring additional benefits:

- **Tackle local pollution:** With a larger amount of power system flexibility from battery storage, higher shares of variable renewables can be accommodated, helping to reduce local air pollution. In the Cheap Battery case, the share of renewables in India's power sector would exceed 50% by 2040 without additional curtailment. Solar PV capacity would increase by almost 30%, reaching 800 GW, and an additional 25 GW of wind capacity would be added, bringing the total close to 250 GW.

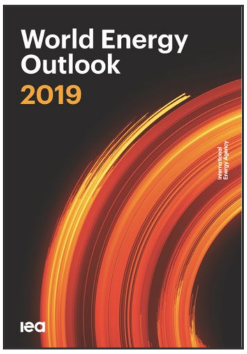
- **Reduce $CO_2$ emissions**: In the Cheap Battery case, $CO_2$ emissions from electricity generation in India would peak just after 2030 (Figure 6.25). This would help the transition from the Stated Policies Scenario to a more sustainable path in which more renewables are deployed, although further changes would be needed to follow the pathway in the Sustainable Development Scenario.

**Figure 6.25 ▷ Installed capacity by source and $CO_2$ emissions from electricity generation in India in the Stated Policies Scenario and Cheap Battery Case**




*Increased battery use in the Cheap Battery Case enables more solar PV and wind installations and cuts coal use so that $CO_2$ emissions peak just after 2030*

- **Provide alternatives to grid upgrades:** Total power systems costs would be unchanged from the Stated Policies Scenario as battery storage could reduce network requirements and displace some investment in transmission and distribution grids.
- **Improved operation of conventional plants:** Enhanced use of battery storage in India could improve the economic performance of the thermal power plant fleet because they would be able to operate at higher annual capacity factors. This could also provide cost savings for distribution companies by reducing overcapacity needs.

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