generation costs compared with the variable operating costs of a coal power plant. The impact would be fully felt due to the absence of both a wholesale electricity market and a carbon price.

To support the use of low-carbon fuels in the power sector, electricity markets should be redesigned to reward flexibility, capacity and other system service contributions provided by low-carbon thermal power plants. This could be accompanied by support measures such as carbon pricing and/or other complementary policies, as well as regulatory frameworks to further decrease the remaining cost gap with incumbent generation. Support measures should be tailored towards cost-effective system integration and maximising the value of low-carbon dispatchable generation. They should also aim at fostering competition and improving environmental performance over time.

In any case, given expectations of increased competition from other forms of low-carbon dispatchable resources and other flexibility and storage options, as well as from possible retrofitting of fossil fuel plants with CCUS, the feasibility and competitiveness of low-carbon thermal power plants will need to be continuously and carefully assessed.

Developing markets for low-carbon fuels and their supply chains by 2030 will establish significant opportunities in many countries and economic sectors

It is vital that economies with strong drivers for using low-carbon fuels successfully create demand, bring down costs and stabilise value chains by 2030. Only their success will open up opportunities to expand low-carbon fuel use in emerging and developing economies.

This is particularly relevant for countries with young fossil fuel fleets, after having implemented and utilised most of their existing flexibility resources, such as grids and interconnections, storage and demand-side response. For example, low-carbon fuels use is a possible long-term option for emerging economies in Southeast Asia. Power systems in this region already have considerable other latent flexibility that can be activated by targeted policy measures to address flexibility needs in the short term, while in the longer term there are opportunities for using low-carbon fuels in the existing thermal power plant fleet.

Displacing meaningful amounts of fossil fuels from power generation will require a major expansion of the supply infrastructure. This implies not just massive investments but also concerted and coordinated efforts across many stakeholders, including duly addressing health & safety risks related to the handling of hydrogen and ammonia.

Electrolyser and hydrogen transport capacity especially need to massively expand many times over their current size. Despite already being widely traded, transport volumes of ammonia are also small in comparison to the needs of the power sector. For example, co-firing 60% of ammonia in a coal power plant fleet of just 10 GW_e – about 10 large coal plants -- would mobilise an amount almost equivalent to the total ammonia traded worldwide today.

While the expansion of the supply infrastructure is a condition to develop markets for low-carbon hydrogen and ammonia in the power sector, it is also an important investment opportunity. Ultimately, using large volumes of low-carbon hydrogen and ammonia in the power sector will help establish supply chains and drive down costs through economies of scale and technological improvements, thereby complementing and mutually reinforcing the use of low-carbon in fuels in other hard-to-abate sectors such as long-haul transport and industry.

Chapter 1. The role of thermal generation in clean energy transition

Highlights

- **Thermal power plants have supplied the bulk of increasing electricity demand in the last two decades, particularly in China and emerging economies.** The capacity of the worldwide fleet of coal and gas plants doubled from 2000 to 2019, from 1.8 TW to 3.7 TW. More than half of these plants have been in service since 2005, and more than half of those in China have been in service since 2008. In India, plants which have been in service since 2012 comprise more than half of the fleet.
- **These plants have technical lifetimes that extend well into the future**. By 2030, 79% of the coal and gas-fired plants in the advanced economies will still have useful technical life, before declining to 43% in 2040. In the emerging economies, due to the amount of recent investments in coal and gas-fired capacity, these figures are 83% in 2030 and 61% in 2040.
- **But the emissions from coal and natural gas use must be reduced drastically in order to align with the objectives of the Paris Agreement and – where applicable – with more recent Net Zero country pledges.** Alongside using less coal and gas by operating the plants at lower utilisation rates or by retiring them early, the other pathway to reduce emissions is to retrofit the plants to generate with low-carbon fuels or to capture and store the carbon emissions. A number of factors, including the pace of cost reductions in the technologies, renewable energy resource potential and geographic location, will drive the balance between the two pathways.
- **Meanwhile, massive expansion of solar PV and wind is rapidly transforming power systems across the world, calling for a profound transformation in the way that these systems are planned and operated to maintain electricity security.** In the SDS, VRE will need to increase rapidly in the advanced economies, rising from 11% of total energy in 2019 to 50% in 2040. In the emerging economies, this share will rise even more rapidly, from 6% in 2019 to 43% in 2040. Due to their variable nature, in every region, this growth in VRE generation will entail a significant increase in the need for flexibility from other sources of supply and demand in the power system.
- **Low-carbon retrofitting of thermal power plants would allow the re-use of existing assets and their associated infrastructure in the future as low-emission sources of firm capacity**. Thermal plants can balance the variability of wind and solar generation in the power system by generating when those resources are unavailable, or by adjusting up or down based on instantaneous or hourly and daily fluctuations in VRE output. The rotational mass of thermal plants supplies inertia which helps maintain frequency for secure operation of the power system. Currently, gas and coal-fired generation accounts for over half of current flexibility capacity globally. Dispatchable power plants will likely continue to contribute to electricity security in regions with large thermal fleets, in particular those with limited other options: in the SDS in Japan and ASEAN, dispatchable capacity is almost equal to variable renewable capacity still by 2040.

The power sector is in rapid transformation

Thermal generation, fired mainly by coal and natural gas, dominates today's power systems. Fossil-based thermal generation has historically been the one of the cheapest sources of electricity, but it is also dispatchable and flexible – it can sustain its output over long periods and respond to expected and unexpected changes to demand and other generation sources. Thermal generation is therefore able to contribute a very high share of its installed capacity towards meeting peak demand, or system adequacy. Thermal generation also provides key system services in meeting flexibility needs particularly inertia, a key source of grid stability, through the rotating mass of its turbines.

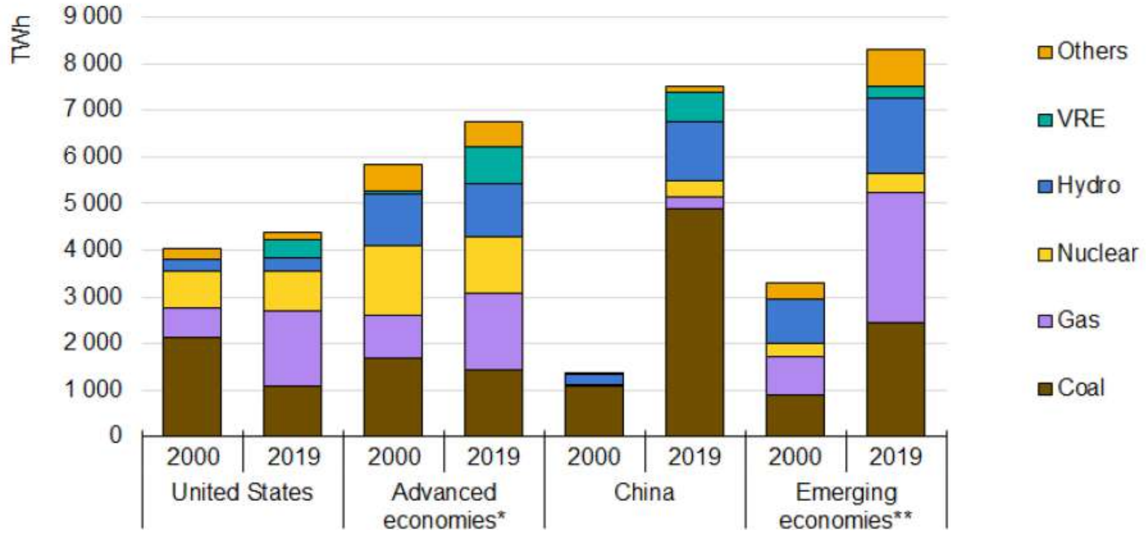
However, the resulting emissions from the unabated use of coal and natural gas in thermal generation must be reduced drastically in order to align with the objectives of the Paris Agreement and – where applicable – with more recent net zero pledges. Wind and solar generation will need to replace the bulk of emissions-producing fossil fuels during the transition to cleaner power systems, rising rapidly from 7 percent of electricity generation in 2019 to 29 percent in 2030 and 45 percent in 2040 globally in the Sustainable Development Scenario (SDS). This will require power systems to increase sources of flexibility in order to respond to variability and uncertainty of these sources. Investments in large-scale transmission network upgrades and measures to increase demand-side flexibility will be needed. Investments in technologies that provide key system services like, like battery storage and low-carbon dispatchable energy technologies, will also be required. Governments will also need to manage the transition away from coal and gas to ensure that economic and social disruption is minimised and costs are contained.

Given the constraints of affordability, security and decarbonisation driving clean energy transitions across the globe, low-carbon fuels have the potential to play a significant role, particularly in regions where the potential to integrate more variable renewable energy (VRE) is low. In addition to the cost-saving potential of the use of existing assets and transmission networks, thermal generation using low-carbon fuels is uniquely positioned as a resource that is clean, dispatchable and flexible.

Electricity demand has increased dramatically over the past 20 years

Electricity demand, driven by increasing energy access and industrialisation in the emerging economies and the People's Republic of China (hereafter 'China') has increased rapidly over the past 20 years, by over 150% and 400%, respectively. By contrast, total electricity demand has increased by only 13% in the advanced economies, mainly by improving end-use energy efficiency and switching to less energy-intensive industries.

Electricity generation (TWh), 2000-2019

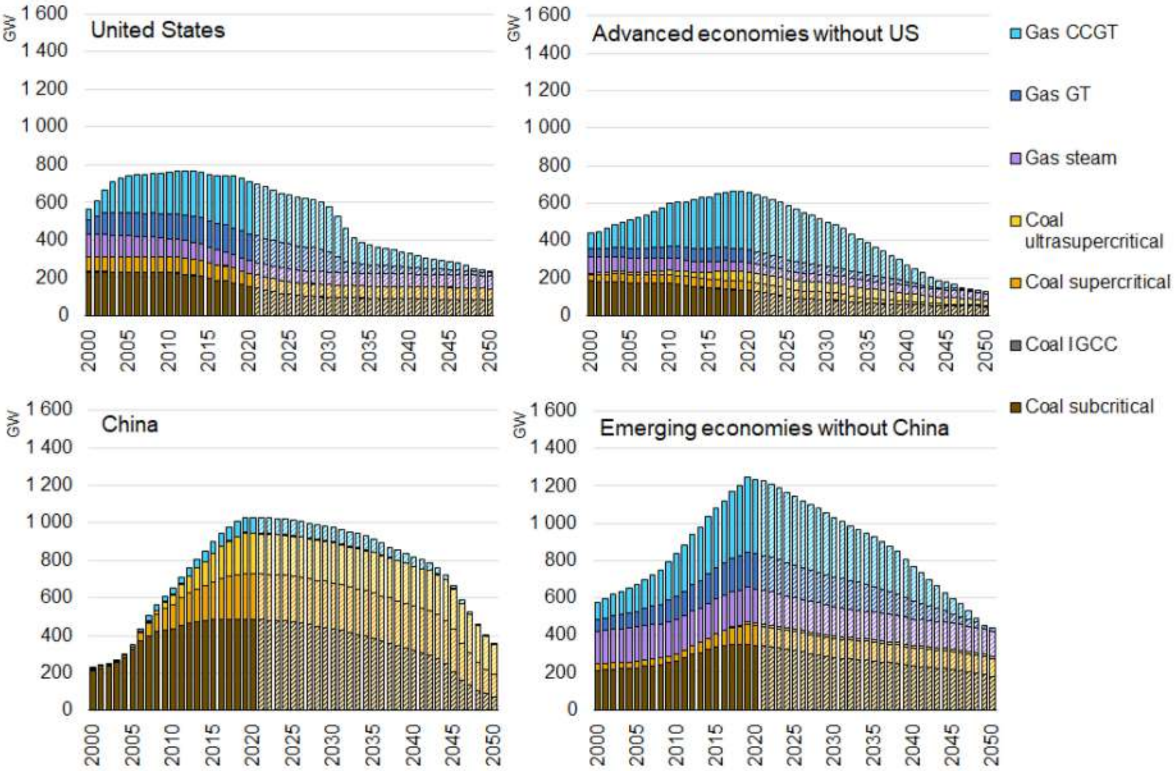


*Does not include United States. **Does not include China.
Note: IEA definitions of advanced and emerging economies from the World Energy Outlook.
Source: Data from IEA World Energy Outlook (2020).

Increasing demand has been satisfied mostly by thermal power plants

Extensive investments in new coal and gas capacity have been made to support this increase in demand. The worldwide fleet of coal and gas plants doubled from 2000 to 2019, from 1.8 to 3.7 TW. More than half of these plants have entered service since 2005, and in China more than half have entered service since 2008. In India, plants built since 2012 comprise more than half of the fleet. These plants have technical lifetimes that ensure that the bulk of this capacity will still be capable of operation well into the future. By 2030, 79% of the coal and gas-fired plants in the advanced economies will still have useful technical life, before declining to 43% in 2040. In the emerging economies, due to the amount of recent investments in coal and gas-fired capacity, these figures are 83% in 2030 and 61% in 2040. In China and India in 2030, the figures are 95% and 86%, before declining to 79% and 73% in 2040.

Cumulative capacity by 2019 and expected retirement of the existing fleet by 2050 based on technical lifetime (GW)



Source: Data from IEA World Energy Outlook (2020).

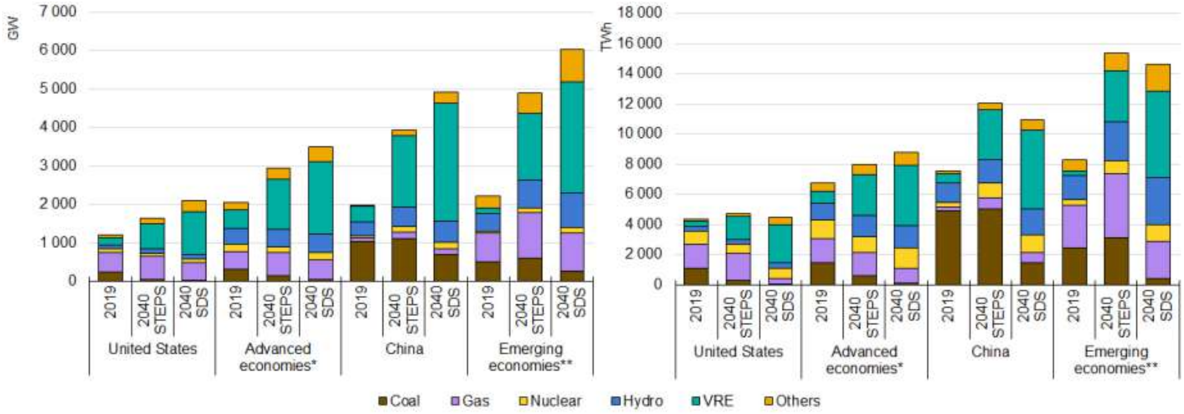
Globally, coal and gas-fired generation accounted for almost two-thirds of the increase in global demand between 2000 and 2019. The emerging economies account for almost all of the additional coal and gas generation, with coal plants in China alone making up half of the total increase. Coal-fired generation actually declined over 30% in the advanced economies, due either to lower natural gas prices, as in the United States, or policy-driven phase-outs of coal-fired generation, as in Europe, or a combination of the two as in Canada.

Electricity demand will continue to increase in the future in all scenarios

In both the Stated Policies Scenario ("STEPS") and the SDS, the two central scenarios considered in the IEA's World Energy Outlook 2020, further significant increases in electricity demand are foreseen by 2040. In the STEPS, which includes all stated commitments to reduce emissions by governments, electricity demand will increase by 49% globally, with demand in China increasing by 60% and demand in the emerging economies (excluding China) increasing by 85%. In the emerging economies in particular, reaching universal energy access, including secure round-the-clock electricity availability, as well as the replacement of traditional biomass for heating and cooking, will drive growth in electricity consumption. In the advanced economies, increases in energy efficiency will offset increased electrification of end-uses, resulting in relatively stable electricity consumption.

In the SDS, VRE will need to increase rapidly in the advanced economies, rising from 11% of total energy in 2019 to 50% in 2040. In the emerging economies, this share will rise even more rapidly, from 6% in 2019 to 43% in 2040. In every region, this increase in VRE generation will entail an increase in the need for flexibility from other sources of supply and demand in the power system.

Installed capacity and generation by source in the Stated Policies and Sustainable Development Scenarios (2019 and 2040)

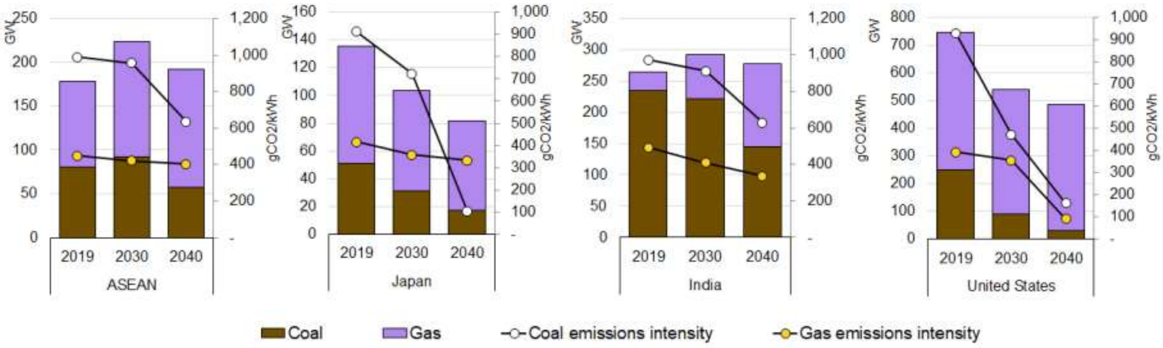


*Does not include United States. **Does not include China.
Source: Data from IEA World Energy Outlook (2020).

Emissions reductions from fossil-based thermal generation sources are necessary

Reducing the emissions from the coal and gas fleet will need to be a key focus of the global clean energy transition. In the SDS, the global coal and gas fleet must reduce its emissions by a factor of seven in the period between now and 2040. This is particularly true for coal, where the emissions intensity must drop about six fold in the US and nine fold (912 g CO_2/kWh in 2019 to 105 g CO_2/kWh in 2040) in Japan (see Figure below).

Dispatchable fossil fuel-based capacity and emissions intensity in the SDS, 2019-2040



Source: Data from IEA World Energy Outlook (2020).

In the SDS, the two available options to accomplish this reduction are retiring the most emissions-intensive coal generation technology and retrofitting some amount of capacity with carbon capture use and storage (CCUS) technology. This report introduces another option, one that is not contemplated in the SDS – retrofitting thermal power plants for use with low-carbon fuels.

Lower utilisation and early retirement of thermal generation

In the SDS, global installed capacity of coal-fired generation is 20% below the level in the STEPS in 2030 (2 v 1.6 TW) and 40% lower in 2040 (1.9 v 1.1 TW). The capacity factors of the coal-fired plants are reduced from 53% in the STEPS in 2030 and 2040, to 35% in 2030 and 21% in 2040 in the SDS. As a result, the global share of total energy provided by coal-fired generation is reduced from 22% in the STEPS to 5% in the SDS. Gas-fired generation follows a similar course, but the reductions occur at a slower pace, reflecting its lower emissions intensity. VRE replaces the vast majority of the coal- and gas-fired generation, with smaller contributions from additional nuclear power and energy efficiency in the SDS.

A transformation of this type will have vast implications for the power sector. From an operational perspective, it will require managing the variability of renewables with flexible resources, including dispatchable power plants, energy storage, demand response and transmission expansion on a much larger scale than currently exists today.

From a social and economic perspective, the transformation will have consequences for regions that rely on energy-intensive industries to support economic activity and employment. Early retirement of coal- and gas-fired generation will require additional investment in those affected regions to ensure a just transition and avoid economic and social disruption. Financial pressure will also increase on the owners of the assets that would become stranded as a result of policy decisions.

Local conditions will dictate the suitability of additional wind and solar investments, and some systems suffer from a lack of sites with high potential to exploit wind and solar generation. This will lead to lower output than global averages, and much lower output than systems with high potential for development. For example, the average capacity factor of wind generation in the Association of Southeast Asian Nation (ASEAN) region in the SDS is 25.3% in 2030 and 26.5% in 2040, compared to 38.4% and 42.0% respectively in the United States, and 29.5% and 32.4% globally. In Japan, the average solar capacity factor will reach only 9.3% in the SDS in 2040, compared to 17.1% globally and 22.8% in the Middle East. Lower capacity factors increase the average cost of energy provided by these assets, making alternatives sources of generation more attractive.

Integrating power systems through enhanced cross-border trading is one way to solve the issue of local resource constraints when attempting to increase the use of low-carbon energy sources. Large power systems are able to integrate higher shares of VRE. The benefits of integration also extend beyond the integration of renewables, including increased electricity security by allowing the pooling of reserves and decreasing the variability of both supply and demand. However, integrating power systems requires a new set of rules to manage unexpected power flows and avoid cascading outages that can cause major blackouts. The cost of interconnection can also be prohibitive to regions where physical barriers like bodies of water, mountains and long distances complicate the routing of new infrastructure. Geopolitical constraints can also limit the potential for collaboration.

Retrofit to use low-carbon fuels or CCUS

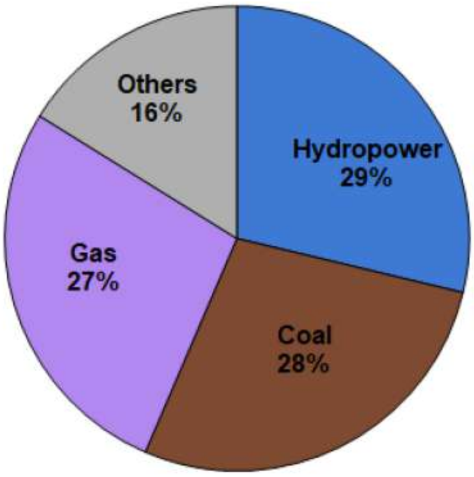
The second major pathway to decarbonise the power sector is to retrofit plants to enable the use of low-carbon fuels or to capture and store carbon using CCUS technology (see Chapter 2). This approach would allow these thermal plants to operate into the future as low-emission sources of firm capacity, while reusing existing assets and their associated infrastructure (transmission networks) and supply chains. It would also reduce costs, while reducing the economic and social dislocations associated with the large-scale transformation of the power sector. Retrofits for use of low-carbon fuels and CCUS also provide a hedge against the risk that cost reductions in newer generating technologies like offshore wind, enhanced geothermal or advanced nuclear do not materialise.

Decoupling the generation technology from the fuel allows these plants to accept feed from a variety of sources. This opens a wide set of decarbonisation opportunities for the power sector while keeping security of supply, depending on the pathways that look the most promising. In particular, co-firing would allow a gradual transition away from fossil fuels, while continuously expanding the production and transport infrastructure for low-carbon fuels.

The role of thermal generation in providing electricity security

Currently, gas and coal-fired generation accounts for over half of current flexibility capacity globally (see figure below). Thermal plants can balance the variability of wind and solar generation in the power system by generating when those resources are unavailable, or by adjusting up or down based on instantaneous or hourly and daily fluctuations in VRE output. The rotational mass of thermal plants supplies inertia, which helps maintain frequency for secure operation of the power system.

Global dispatchable capacity by fuel, 2019



Source: Net Zero by 2050: A Roadmap for the Global Energy Sector.

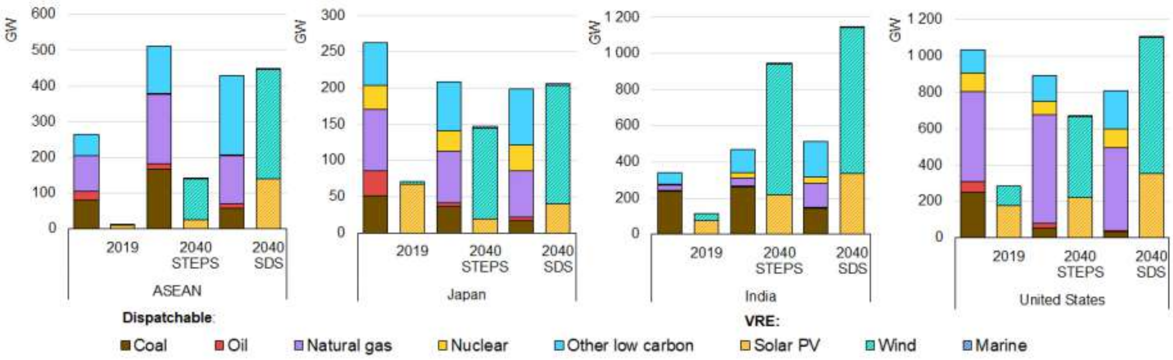
Thermal generation will remain relevant in future decarbonised power systems, even is producing lower quantities of energy, because they provide these key services that contribute to the security of supply. The outlook for other technologies that can replicate these services is uncertain. Batteries have the ability to respond to the variability of wind and solar over short time periods but do not yet possess the capability to provide long-duration or seasonal energy economically. Hydropower, nuclear, geothermal and fossil fuel thermal power plants with CCUS are other technologies that are capable of providing many of the services needed for a stable grid. However, these technologies are dependent on local conditions and resources that are not universally available to meet anticipated demand or, in the case of nuclear, are strongly dependent on policies. For hydropower, there are some constraints that could limit their use including hydrological conditions and other priority applications including irrigation, flood control and recreation. Thermal power plants are therefore the most likely source of providing dispatchable generation, but reducing emissions from these sources must be a priority in order to reach decarbonisation goals while maintaining electricity security.

Four selected regions with large thermal fleets

To demonstrate the role of thermal power plants in providing electricity security, we present four regions, each with large current fleets of thermal generation. They have otherwise varied economic and industrial characteristics and natural resource endowments. The STEPS and SDS for each of these regions show that they each expect to add substantial wind and solar capacity over the next 20 years (see Figure below). While this is sensitive to the policy environment, in both scenarios, the ratio of dispatchable capacity to VRE will decline, despite the addition of new coal, gas and hydro capacity. In the ASEAN region, the ratio declines from 18.9 to 1 in 2019 to 3.6 to 1 in the STEPS and 0.96 to 1 in the SDS in 2040. In the US, the ratio declines from 3.6 to 1 in 2019 to 1.3 to 1 in the STEPS and 0.73 to 1 in the SDS in 2040. India will expect to have the lowest ratio of dispatchable sources to VRE, declining from 3.0 to 1 in 2019 to 0.49 to 1 in the STEPS and 0.45 to 1 in the SDS in 2040. In the SDS, each of these four regions will have greater VRE generation than dispatchable capacity in 2040.

To examine the role of dispatchable thermal power plants in ensuring electricity security in a low-carbon future, we conducted a detailed case study of India’s power system, which is presented in Chapter 5.

Dispatchable capacity of selected countries in the STEPS and SDS, 2040



Note: Other low-carbon includes hydro, geothermal, biomass and concentrated solar power (CSP).
Source: IEA World Energy Outlook (2020).