The role of CCUS in low-carbon power systems

Table of contents

List of figures

List of tables

Abstract

Meeting climate and energy goals requires a fundamental and accelerated transformation of power systems globally. Decision makers collectively must support a rapid shift to low-carbon generation while meeting strong growth in power demand, driven by increased energy access in developing economies and electrification of end-use sectors. Carbon capture, utilisation and storage (or "CCUS") technologies can play an important role in this transformation in three ways:

First, retrofitting carbon capture technologies is an important solution to avoid the "lock-in" of emissions from the vast fleet of existing fossil-fuelled power plants while also providing plant owners with an asset protection strategy for recent investments. This is of particular relevance in Asia, where the average age of coal-fired power plants is just 12 years.

Second, increasing variable renewable generation requires dispatchable energy for flexibility and resource adequacy. Batteries and other forms of energy storage are being further developed and deployed, but carbon capture, utilisation and storage technologies are also part of the portfolio of low-carbon technologies able to meet the growing need for flexibility (to manage both short-term and seasonal variations). These strategies offer a technological hedge against innovation uncertainty in the power system transformation.

Third, through its combination with bioenergy, carbon capture technologies can enable negative-emission power plants, which may be critical for offsetting emissions in harder-to-abate sectors and to support "net-zero" climate goals.

Today, only two large-scale CCUS facilities are operating in the power sector. But experience from these first-of-a-kind plants highlights the potential to reduce costs significantly and improve technology with further research, development and deployment. Policy makers are urged to provide targeted policy support, including capital grants, public procurement and tax credits, to kick-start near-term investment in CCUS-equipped power plants.

Highlights

- Carbon capture, utilisation and storage technologies have important roles to play in decarbonising global power systems, which today are dominated by fossil fuels, and in supporting the transition to net-zero emissions.
- Owners of existing plants as well as those under construction can retrofit carbon capture technologies to protect their assets and avoid the potential "lock in" of emissions, in particular in Asia with a large and relatively young fleet of existing fossil-fuelled plants.
- System operators can benefit from CCUS-equipped power plants, which help integrate growing shares of renewables into the power system by providing short- and long-term flexibility.
- Combining these technologies with bioenergy enables negative-emission power plants that can offset emissions in harder-to-abate sectors and support "net-zero" climate goals.
- Significant cost reductions and technology improvements have already been achieved for these technologies, with further improvements anticipated through research, development and deployment.
- Targeted policy measures, like the 45Q and 48A tax credits in the United States, will be critical to realise the potential of carbon capture technologies in power generation.

Actions for policy makers

Policy makers can accelerate the low-carbon transition by supporting policies that promote carbon capture technologies in power generation

Carbon capture, utilisation and storage, one element in an array of technologies enabling countries to achieve the Paris Agreement goals, has an important role to play in the least-cost transformation of power generation systems for a low-carbon future.

However, its deployment will rely on policy makers taking action to give direction to utilities and investors. Policy actions will need to take into account local and regional power market characteristics and the anticipated role of CCUS-equipped plants in the market, which may evolve over time as flexibility requirements increase. The availability of CO_2 transport and storage infrastructure or demand for CO_2 from users will be critical to underpin investment in CO_2 capture facilities at power plants.

Policy makers are likely to need a range of approaches to support successful business cases and accelerate deployment of carbon capture technologies in power generation, including:

- **Capital support,** including grants and provisions from government or state-owned enterprises. Grant funding was instrumental in early deployment of carbon capture technologies in power, with Boundary Dam receiving CAD 250 million (USD 170 million) from the Canadian government and Petra Nova benefiting from almost USD 200 million from the United States Department of Energy.
- **Public procurement,** where the government is involved directly or indirectly in the project, including through contracts to purchase power from CCUS-equipped plants. This approach may be particularly relevant in countries or regions with state-owned energy utilities, including in Asia.
- **Tax credits**, such as the Section 45Q tax credits in the United States, which provide USD 50 t/CO2 for dedicated geological storage or USD 35 t/CO2 for use of CO2 in enhanced oil recovery; or the Section 48A credit, which applies to a percentage of capital expenditure for retrofitting carbon capture technologies to a coal-fired power plant.
- **Regulatory standards and obligations,** such as a regulated asset base model where costs are passed on to consumers or tradable carbon capture certificates

associated with a CO2 storage obligation. In the case of tradable certificates, the government would issue them to project operators based on the amount of CO2 stored, while other parties (emitters) would be obliged to purchase them.

- **Operational subsidies**, such as contract for difference mechanisms that can cover the cost differential between the higher generation costs and the market price.

Investors will not commit to carbon capture technologies in power generation unless they are sure of government support in a shifting market

Depending on the region and electricity mix, power plants equipped for carbon capture, utilisation and storage can be designed to operate in a baseload capacity (e.g. with high utilisation factors) or to be highly flexible with a reduced number of operating hours but providing high-value dispatchable power. Operators may need to transition their plants from baseload generation to more flexible operation over time as the penetration of variable renewable generation increases.

The utilisation rate of CCUS-equipped power facilities will typically have significant cost and policy implications. Early, first-of-a-kind carbon capture projects based on currently available technologies will have high capital and operating costs. Plants running at high capacity factors will be able to generate greater revenues from electricity sales but with higher operating costs relative to plants with lower utilisation rates. Plants operating in a flexible manner will require higher compensation for the power delivered during limited operating hours if they are to be (or remain) commercially viable.

The extent to which the higher costs associated with carbon capture technologies can be passed to electricity consumers will depend on the region and market design. Many markets are "captive," with limited competition within each region or country, enabling cost pass-through, while, in others, regulated pricing could facilitate the pass-through.

Policies therefore need to be designed to account for a range of characteristics to provide an effective incentive for investment in power plants equipped with carbon capture technologies. These characteristics include:

- The high capital cost of retrofits and first-of-a-kind new-build CCUS power stations.
- The high degree of variation in power markets across regions and countries.
- The changes in load factors that may occur over time at CCUS power plants.

- These factors call for policies that provide capital support and/or guaranteed operational revenue, and policies that incorporate sufficient flexibility to accommodate a potential transition from baseload to flexible generation.

Support for CO_2 infrastructure will be an essential element of policy incentives for CCUS

Government leadership will be important to facilitate the development of CO_2 transport and storage infrastructure.[1] CCUS-equipped power plants have potential to act as "anchor projects" for the construction of shared infrastructure, including for establishing industrial carbon capture hubs, with large quantities of CO_2 enabling economies of scale for infrastructure development. In the United Kingdom, the Drax bioenergy power plant – equipped with carbon capture and storage – could support plans for a net-zero industrial cluster in the Humber region, while proposals for a gas-fired power plant with carbon capture technologies would support the development of an industrial cluster for carbon capture and storage in the Tees Valley.[2]

[1] Element Energy (2018), Policy Mechanisms to Support the Large-Scale Deployment of Carbon Capture and Storage (CCS).

[2] Zero Carbon Humber (2019), Zero Carbon Humber Infographic; Net Zero Teesside (2019), Partners: Net Zero Teesside.

Why carbon capture technologies are important

Fossil fuels still provide the majority of the world's electricity, and power generation is the largest emitter of carbon in the entire energy sector

Power plants fuelled by coal and gas continue to dominate the global electricity sector – they account for almost two-thirds of power generation, a share that has remained relatively unchanged since 2000 despite the advent of low-cost variable renewable sources. In absolute terms, power generated from fossil fuels has increased by 70% since 2000, reflecting the steady rise in global demand for power.

Coal remains by far the largest fuel source for power generation, at 38%, followed by gas at about 20%. In the world's fastest-growing economies, such as the People's Republic of China (hereafter, "China") and India, the coal-fired share of total generation is higher than 60%. While we see a temporary dent in coal generation and higher shares for variable renewables due to the Covid-19 pandemic, these shares could return to historic trends as electricity demand recovers.

Power is the largest carbon emitter in the energy sector, creating almost 40% of global energy-related emissions. Despite the pressing need to confront the major causes of climate change, emissions in 2019 from the power sector were only slightly below their 2018 all time high at 13.6 $GtCO_2$.

The global community has committed to the goal of limiting the increase in the average temperature to well below 2°C above pre-industrial levels

The Paris Agreement's goal is to keep the increase in global average temperature to well below 2°C above pre-industrial levels and, in doing so, to pursue efforts to limit the increase to 1.5°C. This has been incorporated into the critical energy-related UN Sustainable Development Goals, which seek in addition to widen access to clean, affordable energy.

The global power sector is therefore expected to meet rising demand as access to electricity grows and to provide for a low-carbon future where end-use activities are increasingly electrified.

Despite the rapid expansion of renewable energy generation, the sheer scale of current power sector emissions and the vital role of electrification mean that countries must urgently tackle their emissions from power to meet these global climate goals. In effect, the power sector has to dramatically reduce its carbon intensity.

A low-carbon future means tackling emissions from the fossil-fuelled power fleet using every means available

To meet climate goals, policy makers need to address emissions from existing coal-fired power plants and those being built today. Yet, under current policies stated by governments, while CO_2 emissions from the existing coal-fired fleet would decline by approximately 40%, annual emissions would still amount to 6 $GtCO_2$ per year in 2040. Significant additions to coal-fired capacity were still under construction at the start of 2020, highlighting the challenge ahead.

Meeting long-term climate goals without applying carbon capture, utilisation and storage technologies at scale in the power sector requires the virtual elimination of coal-fired power generation and, eventually, that of gas-fired generation as well, with significant early retirements and potential for stranded assets.

The young age of the global fleet of fossil-fuelled power plants means that about one-quarter of the existing fleet would be retired before reaching the typical 50-year lifespan. Almost one-third of all coal-fired capacity is less than ten years old, the vast majority of which is in Asia. Those kept in operation would likely see substantially reduced operating hours.

Under the IEA Sustainable Development Scenario, carbon capture technologies play an important role in supporting modern and flexible power systems

The IEA Sustainable Development Scenario outlines a major transformation of the global energy system, showing how the world can deliver the three main energy-related Sustainable Development Goals simultaneously. Under this scenario, carbon capture technologies play an important role in providing dispatchable, low-carbon electricity – in 2040, plants with these technologies generate 5% of global power. CCUS-equipped coal and gas plants become increasingly important for secure, sustainable and affordable power systems in the IEA Sustainable Development Scenario.

Meeting climate goals also means creating an extremely flexible power system that can manage high shares of variable renewable power sources. Coal- and gas-fired power plants have been a major source of system flexibility, providing benefits essential to the operation of the electricity grid, such as inertia and frequency control. Carbon capture, storage and utilisation allows these plants to continue providing these benefits and meet long-term flexibility requirements, such as annual seasonality.

An emphasis on supporting system flexibility could see some CCUS-equipped coal and gas plants operating at relatively low load factors. However, the unique ability to achieve negative emissions through bioenergy with carbon capture and storage may mean that these plants run at high capacity factors, even in a power system with high renewable shares. This could come at the expense of a reduced contribution to system flexibility but would support economics of scale in CO_2 transport and storage infrastructure and maximise climate benefits.

Including carbon capture, utilisation and storage in the portfolio of technology options can reduce the total cost of power system transformation. Carbon capture technologies become more competitive in the power system when their flexibility, reliability and carbon intensity are fully valued.

How carbon capture technologies support the power transition

This analysis identifies and discusses the three greatest contributions that carbon capture, utilisation and storage can make to power system transformation:

- **Tackling emissions from existing plants.** In the near and medium term, retrofitting the power sector with carbon capture technologies addresses emissions from the existing fossil-fuelled fleet of power plants. These retrofits enable owners of existing power plants to recover their investment and, in doing so, to reduce the cost of power system transformation. CCUS retrofits are particularly important in Asia, with its young fleet of fossil-based power plants.
- **Flexibility for stable power.** Carbon capture technologies further help power networks achieve electricity security goals. Many regions have growing shares of power from variable renewables, driving a greater need for flexibility to ensure the stable operation of their power systems. CCUS-equipped power plants can provide this extra flexibility across broad timescales, ranging from the very short term (e.g. grid services, inertia and frequency ancillary services) to the very long term (e.g. seasonal variations).[3]
- In addition, **carbon capture provides a technological hedge** as the power system undergoes transition. Networks face uncertainty in operating with very high shares of renewables (Phases 5 and 6 of renewables integration according to IEA classification), and they will need technological innovations. This concerns, in particular, the balancing of longer-term seasonal variations, and to a lesser extent very short-term flexibility provision (e.g. inertia, frequency control, dispatchability). Our expectations for these innovations are positive (e.g. for advances in battery technology or synthetic inertia), in particular for short-term flexibility, but the full portfolio of technologies will need to be developed and deployed to support a rapid transformation.
- **Net-zero and negative emissions.** The long-term value of carbon capture technologies to the power system (and the energy system as a whole) may further increase in line with more ambitious climate goals due to its ability to enable negative emissions from power generation when combined with bioenergy. Negative emissions can counterbalance residual emissions in other sectors that are harder-to-abate (i.e. they are costlier or have limited technology solutions), thereby reducing the cost of energy sector decarbonisation.

[3] IEA (2018), Status of Power System Transformation 2018.

These are discussed in turn after we have established the rationale for including carbon capture technologies in power systems that are undergoing a low-carbon transformation.

Carbon capture technologies are important for achieving climate objectives, widening the portfolio of low-carbon power sources

Carbon capture has consistently been identified as an integral part of a least-cost portfolio of technologies needed to support the transformation of power systems globally.[4] These technologies play an important role in supporting energy security and climate objectives by enlarging the portfolio of low-carbon supply sources. This is of particular value in countries where fossil-based power generation is likely to retain an important role, for example due to existing infrastructure or abundant domestic resources. Similarly, other options may be constrained, for example, where renewable energy potential is limited due to poor solar radiation or wind potential, or limited land availability. Wind and solar power plants occupy much larger amounts of land than CCUS-equipped power stations, which can give rise to constraints on siting.

Including carbon capture in the portfolio of technology options can reduce the total cost of power system transformation. Previous analysis by the IEA highlighted that if the availability of CO_2 storage was limited across the global energy system, the marginal abatement costs in the power sector would increase from around USD 250/tCO_2 in 2060 in a low carbon pathway to USD 450/tCO_2. A 2019 report that targeted regional studies found that the cost of decarbonising the UK power system would be about 50% higher if carbon capture was not available. In Poland it would be 2.5 times higher, and in New South Wales in Australia it would be twice as high.

Future power systems will be more distributed and diverse. In this new paradigm, future power generation assets will be valued not only for energy, but also for a diverse set of services like grid services, inertia and frequency provision, or turn down capabilities and dispatchability. All of these services are essential for a reliable and affordable power supply. This is a key reason why traditional cost metrics like the levelised cost of electricity (LCOE) are often inadequate, as they do not reflect the total cost and value of generation assets to the operation of the power system.

[4] See IEA (2019): World Energy Outlook 2019 and Exploring Clean Energy Pathways; IPCC (2014): Fifth Assessment Report; and Pratama and Mac Dowell (2019), The Role of CO_2 Capture and Utilisation in Mitigating Climate Change.

The IEA sees carbon capture technologies playing their part in a low-carbon future

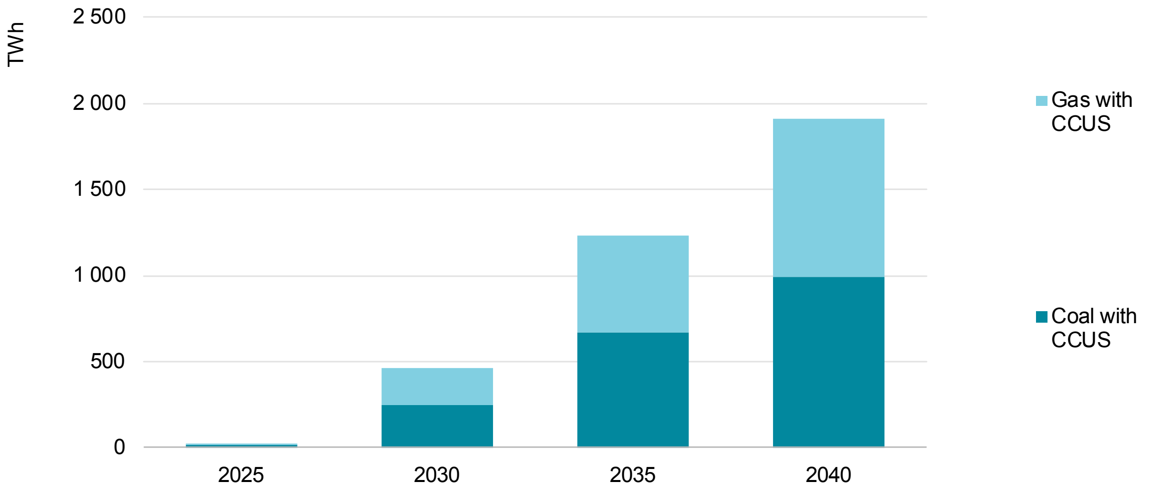
While electricity demand is increasing, the global power sector has to dramatically reduce its carbon intensity to play its part in achieving the critical energy-related Sustainable Development Goals and the Paris Agreement target.

The IEA Sustainable Development Scenario outlines a major transformation of the global energy system to achieve them. Under this Scenario, carbon capture technologies play an important role in providing dispatchable, low-carbon electricity. By 2040, 315 GW of electricity generation capacity is equipped with carbon capture, utilisation and storage. This is the equivalent of adding retrofit and new-build CCUS capacity of around 15 GW per year on average over the next two decades.[5] Annual spending on fossil-fuelled plants equipped with carbon capture technologies rises to almost USD 30 billion per year, with most of this increase coming in the second half of the outlook period.

In 2040, CCUS-equipped plants generate 1 900 TWh, or 5% of global power, up from some 470 TWh or 1.5% in 2030.

Power generation from CCUS-equipped plants grows steeply in the SDS to reach 1 900 TWh in 2040

Figure 1 **Power generation from CCUS-equipped plants in the IEA Sustainable Development Scenario**



Source: IEA (2019), World Energy Outlook 2019.

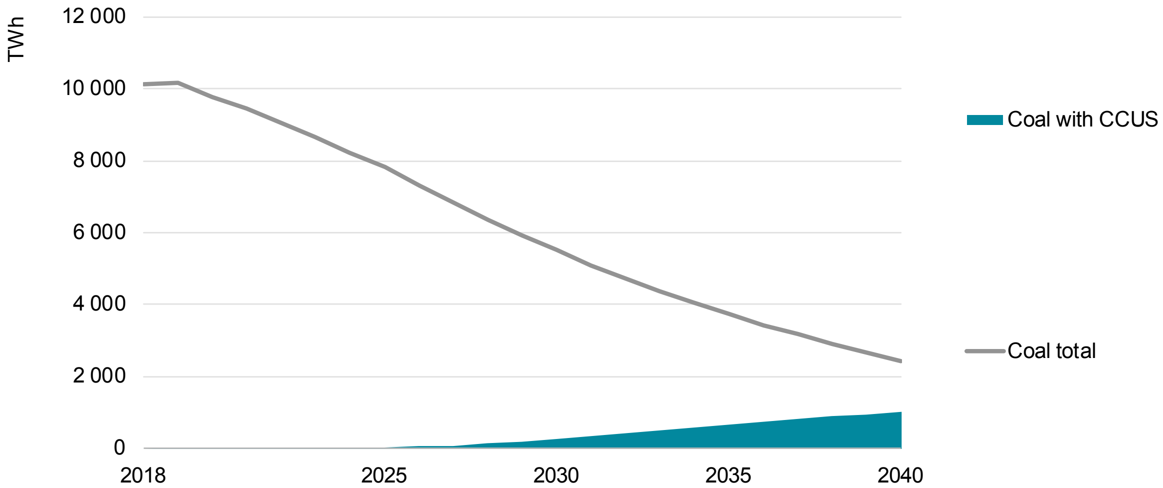
[5] IEA (2019), World Energy Outlook 2019.

Coal-fired generation falls dramatically in the Sustainable Development Scenario. The combination of CO_2 and air pollution policies in this Scenario contributes to a steep reduction in the share of coal-fired power generation, from around 38% today to around 6% in 2040.

Of the remaining coal-fired power generation, 40% comes from plants fitted with carbon capture technologies. In 2040 the 160 GW of coal-fired capacity with these technologies generates 1 000 TWh, or 2.6% of global power generation at an emissions intensity of some 90-100 gCO_2/kWh. This is based on CO_2 capture rates of 90% – recent analysis has highlighted the possibility of higher capture rates at only a small increase in capture costs. Coal plants without these technologies run at very low capacity factors, well below 20% for all but the most efficient plants, and generate about 1 400 TWh in 2040.

Carbon capture becomes increasingly important to continuing coal plant operation in the Sustainable Development Scenario

Figure 2 Evolution of coal-fired power generation in the SDS



Source: IEA (2019), World Energy Outlook 2019.

Natural gas-fired power generation increases globally until the mid-2020s, peaking at some 24% of the power mix, before falling to 14% by 2040. Natural gas plants equipped with carbon capture capabilities produce around 900 TWh of electricity in 2040, around 16% of total gas-fired power generation, with an emissions intensity of less than 40 gCO_2/kWh. In total, the use of carbon capture for gas in power generation avoids over 300 $MtCO_2$ in 2040.

In 20 years CCUS-equipped plants capture the same amount as a decade's worth of aviation emissions

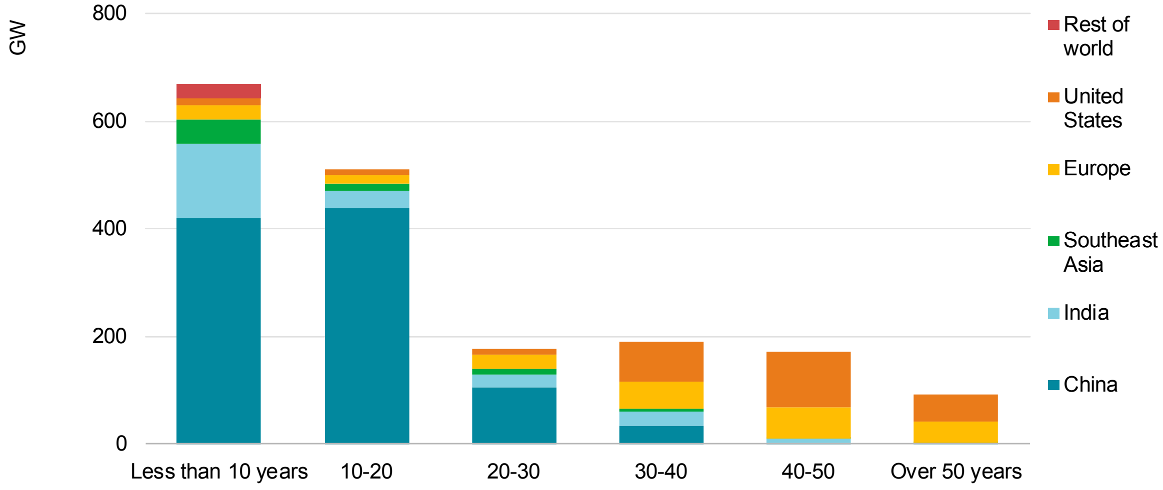
Some 9.7 $GtCO_2$ are captured cumulatively from power generation to 2040 in the Sustainable Development Scenario, an amount equivalent to more than a decade of emissions from the global aviation industry (based on 2019 emissions). While the share of generation from plants equipped with carbon capture is split almost equally 50:50 coal-fired and gas-fired, the vast majority of the CO_2 captured in the power sector is from coal-fired power plants due to their higher carbon intensity. Coal-fired power plants account for 7.0 $GtCO_2$ or more than 70% of total CO_2 captured in the sector through to 2040. In addition to CO_2 captured from coal and gas, the Scenario also identifies some 400 $MtCO_2$ captured from bioenergy for power in the period to 2040.

Tackling emissions from existing plants

Owners of fossil-fuelled power plants can use carbon capture to cut emissions and protect their assets

CCUS retrofits provide a solution to emissions from existing (and planned) fossil-fuelled power generation, recognising that much of the global fossil fuel power fleet is unlikely to be shut down within a timeframe that meets climate targets. The global fleet of fossil-fuelled power plants is surprisingly young. For example, almost one-third of all coal-fired power capacity is less than ten years old, the vast majority of which is in Asia.

Figure 3 Global coal-fired power capacity by plant age, 2018



Source: IEA (2019), World Energy Outlook 2019.

In light of the young age of the fossil-fuelled power fleet and increasingly strict emission regulations in several countries, CCUS retrofits provide plant owners with an important asset protection strategy that allows them to continue operations at existing plants while meeting carbon reduction targets and thereby recover some of the remaining capital at risk. Owners and investors have yet to recover more than USD 1 trillion of capital expenditure in the existing coal fleet alone, most of it in Asia.

A large share of these assets is state-owned (e.g. in China), and governments will take into consideration a multitude of factors when deciding on the future of existing infrastructure, including electricity price impacts, implications for employment and the financial health of state-owned enterprises.

Retrofitting carbon capture technologies makes most sense for power plants that are well-located, young and efficient

Carbon capture retrofits are most attractive for young and efficient 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.

Certain technical features of existing power plants have to be considered when assessing whether a retrofit is likely to make commercial sense in conjunction with the policy environment. These factors include age, capacity, availability of on-site space for carbon capture equipment, load factor and type, and location of fuel source. Attributes such as cooling type and the steam cycle design of coal plants will have a critical impact on the cost of retrofitting.

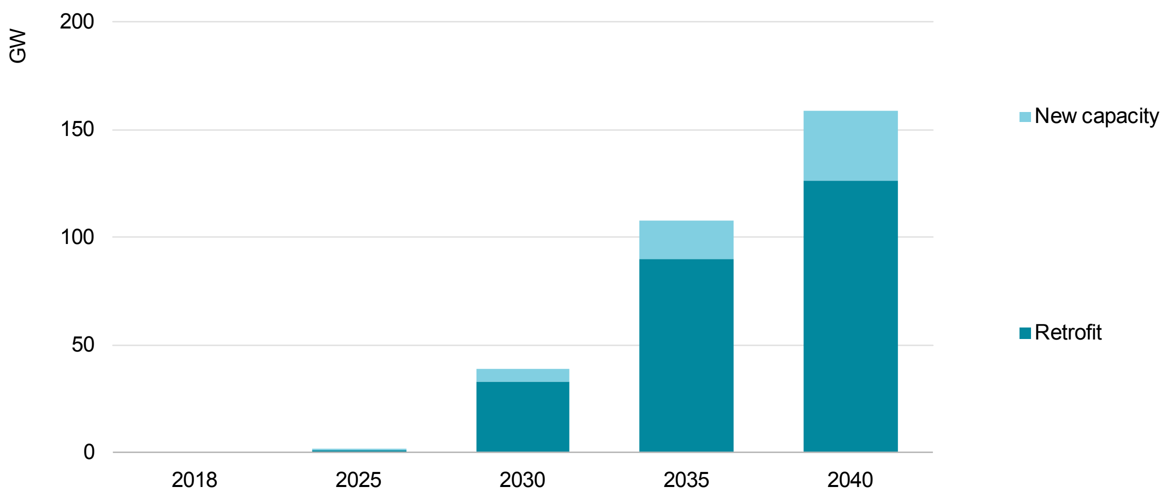
Further, carbon capture retrofits require high confidence in the availability of CO_2 storage or demand for use. IEA analysis of the existing coal power plant fleet in China concluded that over 300 GW could be suitable for retrofit when taking into account these considerations.

Addressing the emissions of existing coal-fired power plants or those being built today will be critical to reach climate goals. The IEA has outlined options to address the emissions of the existing coal-fired power plant fleet featuring three pillars: a) the retrofit of plants with carbon capture technologies, b) the repurposing of coal plants to provide flexibility, and c) the gradual phase-out of plants where carbon capture is not possible.

Without carbon capture, meeting climate goals would ultimately mean almost eliminating the use of fossil fuels for power.

In the Sustainable Development Scenario, 120 GW of existing coal-fired capacity is retrofitted with carbon capture by 2040, accounting for some 80% of the coal plants equipped with these technologies. More than 110 GW of these retrofits are in China, representing a capital investment of around USD 160 billion. A further 10 GW are in the United States. Without carbon capture available at scale in power, coal-fired power generation, and eventually also gas-fired generation, would need to be virtually eliminated to meet long-term climate goals, with significant early retirements and potential stranding of assets.

Figure 4 Coal-fired power plants equipped with carbon capture in the Sustainable Development Scenario

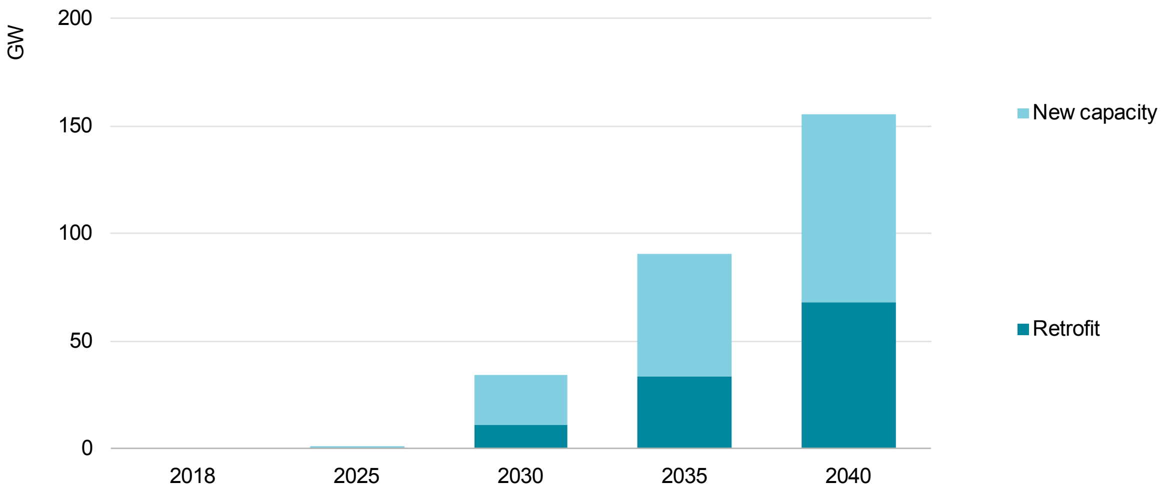


Source: IEA (2019), World Energy Outlook 2019.

Over 750 GW of existing coal plants reduce operations to cut emissions in this Scenario, limiting electricity production but still providing system adequacy and flexibility. About one-quarter of the existing fleet would be retired before reaching the typical 50-year lifespan. Shutdowns and reduced operating hours are likely to lead to balance sheet write-downs for some owners of existing facilities. Coal plant retirements also imply greater investment in other low-carbon sources of electricity and associated network infrastructure.

Carbon capture retrofits also play an important role for the gas-fired power plant fleet, which currently has an average age of only around 19 years. In the SDS 155 GW of natural gas-fired power plants are equipped with carbon capture, utilisation and storage by 2040, almost half of them in the United States. Of the CCUS-equipped capacity, about 55% relates to new plants and 45% to retrofitted, providing a total of around 900 TWh in 2040.

Figure 5 Natural gas-fired power plants equipped with carbon capture in the Sustainable Development Scenario



Source: IEA (2019), World Energy Outlook 2019.

Flexibility for stable power

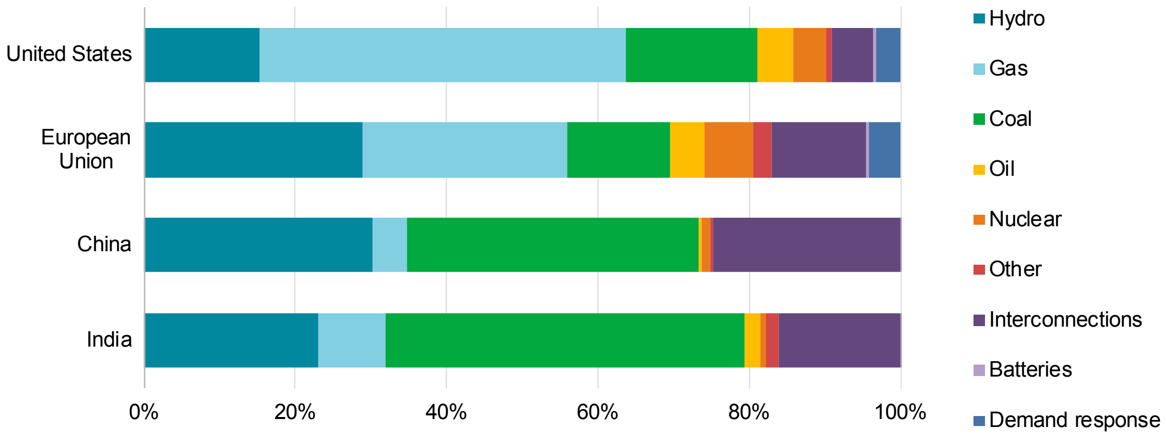
System operators will face a growing need for flexibility as the share of variable renewables rises

Flexibility and electricity security are increasingly important issues for power systems, particularly those that are integrating a growing share of variable renewable energy in daily operations. Flexibility in this context relates to the ability to respond in a timely manner to changes in electricity supply and demand in numerous timescales, from the very short term (subseconds, seconds, minutes and hours) to the balancing of weekly, monthly or seasonal demand and supply variations. For system operators, the priority timescales depend on the share of renewables in a power system, with longer-term flexibility concerns typically growing in importance as renewables expand.

Thermal power plants provide the bulk of flexibility needs today, alongside interconnection and hydropower

Flexibility can generally be provided through four main levers: demand response, grid interconnections, dispatchable power generation and energy storage. To date, conventional thermal and hydro power plants have acted as the primary source of system flexibility, maintaining the reliability of power systems around the world and helping to accommodate rising shares of variable renewable energy.

Figure 6 Sources of flexibility by region in 2018



Source: IEA (2019), World Energy Outlook 2019.

In part, thermal power plants have made this possible by retrofitting various technologies, ranging from advanced monitoring and control technologies to deeper technical interventions.[6] These have helped to improve the plants' flexibility performance (e.g. increased ramp rates, lower minimum stable loads of generation, shorter start-up times and shorter minimum up and down times). The construction of more flexible power plants, such as open-cycle gas turbines, also helps.

Meeting climate goals means creating an extremely flexible power system

The very high share of renewables generation and capacity by 2040 in the Sustainable Development Scenario requires an extremely flexible power system to ensure stable and secure operation. The Scenario sees a significant increase in the need for flexibility along all timescales. When expressed, for instance, as peak ramping requirements, flexibility needs grow even faster than electricity demand. Developing economies experience notable acceleration in the need for flexibility – it is in these countries where almost 90% of growth in global electricity demand takes place in the Scenario, and where renewables meet a significant amount of new demand. In 2040 India's power system needs six times more flexibility than today,

[6] IEA (2018), Status of Power System Transformation 2018.

and China's requires three times more. But advanced economies also need higher levels of flexibility; for example, in the United States they are 2.5 times today's level in 2040.

To address this rising need for flexibility, system operators will need new flexibility sources. Batteries, demand response and sector coupling are poised to play pivotal roles in making sure future power systems are secure and reliable, in particular for short-term flexibility.

Demand-side response has a role 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 when allied with appropriately designed markets, as is happening in several countries.

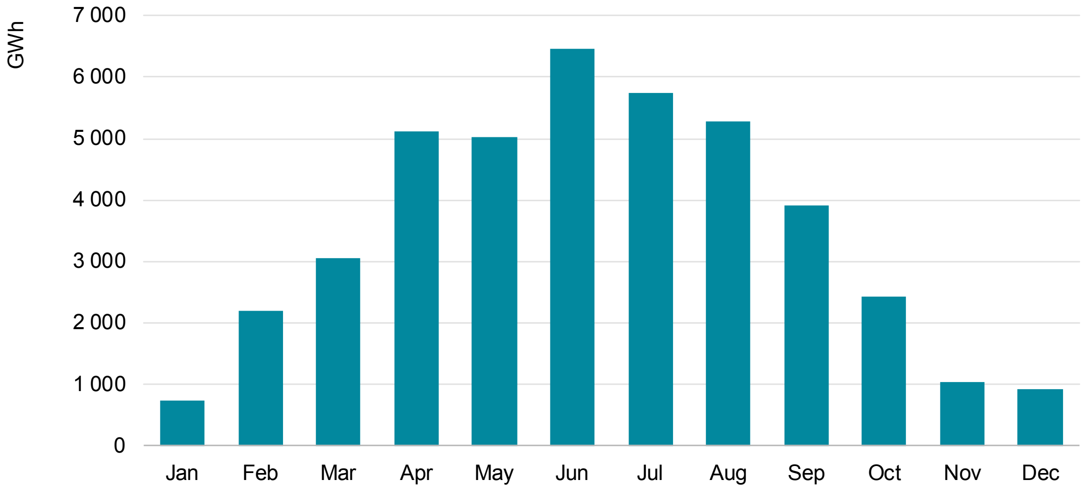
We expect CCUS-equipped thermal plants to be an important element of a fully flexible power system

Thermal plants equipped with carbon capture, utilisation and storage techologies are also expected to play an important role in providing flexibility. Plant operators can run them in a flexible manner to accommodate short-term variations, very much like unabated thermal power plants today. These technologies have various effects on plant operation. Indeed, carbon capture capabilities may even in some instances increase short-term flexibility as the operator can increase or reduce the energy used by the CO_2 capture unit to follow electricity load fluctuations. The International CCS Knowledge Centre's Shand feasibility study also identified that the CO_2 capture rate could increase from 90% at full load to 97% at the minimum power plant output level (to make way for renewable sources) at almost no additional cost.

While short-term flexibility is well understood today and technological innovations (e.g. batteries) may ultimately be able to meet these requirements without support from thermal generators,[7] seasonal or long-term fluctuations in electricity supply arguably present a more significant challenge. They underscore the value of dispatchable forms of generation, including CCUS-equipped plants. Many regions experience pronounced seasonality of renewables generation, presenting power system operators with significant fluctuations across the year; for example, in Germany, part of the temperate climate zone, solar power generation in January 2019 was only around 10% of summer generation in the peak month of June.

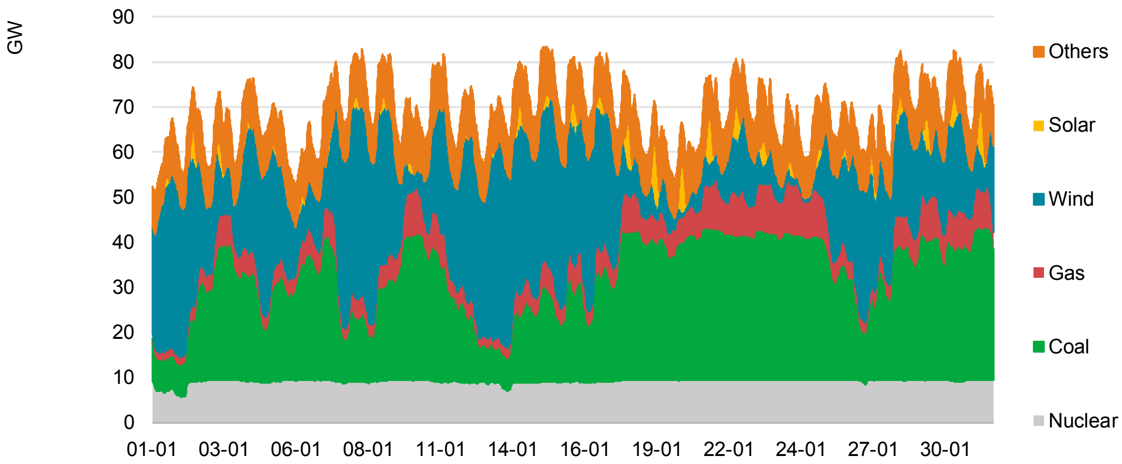
[7] IEA (2018), Status of Power System Transformation 2018.

Figure 7 Solar power generation in Germany (2019)



To date, thermal generators have played an important role in balancing this kind of seasonality, as well as meeting unexpected shortfalls in renewable generation over extended periods of time (e.g. several days to weeks). The graphic representation of the German electricity system in January 2019 demonstrates this. Wind and solar generation was very limited at a time of high winter heating demand and coal generators ramped up over an extended period to cover for the generation shortfall.

Figure 8 Power generation mix in Germany in January 2019



Cost-effective alternatives to manage these seasonal variations are currently limited and there is no "one size fits all" solution. Improved regional integration or interconnectors could play an important role in some regions – and indeed are a feature of many systems with a high penetration of variable renewables today. But they require co-ordination across jurisdictions and may be limited by national energy security considerations and/or the presence of similar weather patterns across regions.

Nuclear power could fill the shortfall in renewables generation at comparable economics to carbon capture, but a reduction in nuclear capacity is expected in many advanced economies, such as Belgium, Germany, Korea, Spain and Switzerland, due to economic and political headwinds.

Given today's technology characteristics, battery solutions are generally better suited to cost-effectively balance shorter-term supply–demand imbalances (up to several hours), but face challenging economics to bridge longer-term imbalances.

Hydro storage as a backup for an entire power system for an extended period of time is, for most countries, impractical due to limited hydro expansion potential. This highlights the value of having a full portfolio of technology solutions available to support energy security and emissions reductions objectives.

An alternative flexibility route is the generation of low-carbon hydrogen or ammonia (e.g. through electrolysis or steam methane reforming with carbon capture) and their use in, for instance, combined-cycle gas turbines.

Carbon capture in the power system becomes more competitive when its flexibility, reliability and carbon intensity are fully valued

When comparing renewables and thermal generators, a one-to-one replacement of renewables with thermal generators on a pure capacity or generation basis is typically not feasible. CCUS-equipped plants offer higher load factors than variable renewable energy sources. On average, thermal carbon capture capacity of 1 GW would require some 2-5 GW of wind or solar capacity to achieve similar power generation levels.

This 2-5 GW, however, does not translate into a similar level of security of supply due to their intermittent nature. Power system planners therefore typically do not consider the entire rated capacity of variable renewables to be guaranteed available should it be needed. The fraction that is considered guaranteed and, hence, the value to the system of any additional unit of variable renewable capacity may further decrease with the amount of variable renewable capacity already in the system, a feature that has been exhibited in capacity auction markets like the PJM market in the United States.

The competitiveness of carbon capture in the power system relative to other generation sources increases when the full value of this power as a flexible, secure and low-carbon source of electricity is taken into account.

The levelised cost of electricity is the most common metric for comparing the competitiveness of power generation technologies, but considers only the costs of generation. It does not take into account the value that each technology may provide to the overall electricity system in ensuring flexibility and reliability. This, however, is becoming increasingly important given the unprecedented changes power systems are undergoing, including rising shares of variable renewables and an increasing need to source power system flexibility. A more complete picture of competitiveness requires system planners to consider these values. The value-adjusted LCOE, a new metric presented in World Energy Outlook 2018, combines a technology's costs with estimates of these values.

Using the value-adjusted LCOE measure, plants equipped with carbon capture (retrofits, in particular) perform more competitively than when simply using the LCOE. This is mainly due to the increasing system value associated with enhancing system reliability and flexibility services as the share of variable renewables in total generation increases.

IEA analysis shows that the value-adjusted LCOE for thermal power plants is up to 15% lower than the corresponding LCOE measure, depending on the characteristics of the power system and given moderate renewables penetration of some 20-30% in the system. Likewise, the value-adjusted LCOE of renewables can increase by up to 5% compared to the LCOE measure, thereby making thermal operators (with carbon capture) more competitive if we adequately account for the flexibility and capacity value of plants. In systems with higher shares of renewables, these effects are likely to be more pronounced as the value of flexibility and secure capacity increases.

Net-zero and negative emissions

Combining bioenergy-fuelled power production with carbon capture and storage can offset carbon emissions elsewhere

When combined with bioenergy, carbon capture and storage can support net-zero or even negative emission power plants. Bioenergy with carbon capture and storage plays a uniquely important role in meeting ambitious climate goals due to the potential for negative emissions.[8] Negative emissions from bioenergy with carbon capture arise due to the fact that biomass absorbs CO_2 as it grows, and, when combusted for energy, the CO_2 is released back into the atmosphere, creating a full cycle with a neutral impact on atmospheric volumes of CO_2. When combined with the CO_2 capture and storage process, much or all of the CO_2 absorbed by the biomass may be permanently removed from the atmosphere.

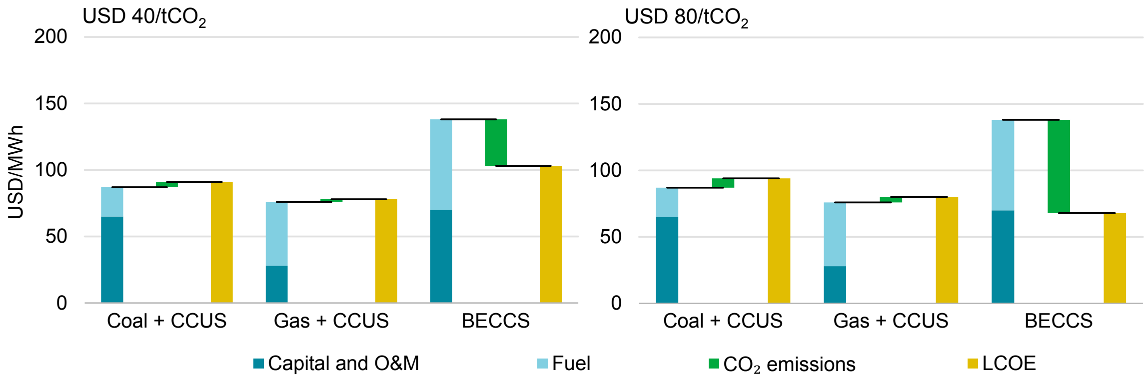
These negative emissions can play an important role in offsetting emissions from other sectors where direct abatement is either technologically difficult or prohibitively expensive, including long-distance transport and some industrial processes. Within the power sector, generators that utilise bioenergy with carbon capture have the potential to offset emissions from the use of (for example) gas-fired peaking power plants, which play a key role in supporting the cost-effective integration of renewables but are incompatible with a net-zero power system.

Carbon capture with bioenergy becomes increasingly cost-competitive with fossil fuel-based CCUS at higher carbon prices

Dedicated plants using bioenergy with carbon capture technologies typically feature higher investment costs, lower efficiencies and higher cost of fuel (biomass) compared with coal- or gas-fired plants with carbon capture. With stronger climate ambition and higher carbon prices, bioenergy with carbon capture and storage becomes increasingly competitive when monetisation of negative emissions is permitted in a carbon trading system. The LCOE analysis in the graph is used for illustrative purpose only, but the more complex calculations underlying a value-adjusted LCOE computation would show similar effects.

[8] IEA (2017), Energy Technology Perspectives 2017.

Figure 9 Impact of carbon prices on the LCOE of power generation with carbon capture



Note: The graph on the left depicts the LCOE at a carbon price of USD 40/tCO_2, while the graph on the right depicts the LCOE at a carbon price of USD 80/tCO_2. Calculations for coal and natural gas with carbon capture are based on cost and technology assumptions for an ultra-supercritical coal plant and a natural gas combined-cycle plant equipped with post-combustion capture in North America in 2040; bioenergy with carbon capture calculations are based on assumptions for a biomass integrated gasification combined-cycle plant equipped with carbon capture technologies.

Biomass co-firing in combination with carbon capture at very high rates (e.g. exceeding 99%) may be one of the most cost-effective ways to decarbonise existing fossil power infrastructure. Co-firing can lower the costs of bioenergy in power by taking advantage of the economies of scale associated with fossil-based power plants. Analysis by IEA Greenhouse Gas R&D Programme highlights that the most economical option to achieve carbon-neutral ultra-supercritical coal plants may be the co-combustion of 10% biomass at a 90% CO_2 capture rate. This would increase the CO_2 avoided cost by only 1.5% relative to a CCUS-equipped coal plant without biomass co-firing, to around 62 USD/tCO_2. Further increasing the share of bioenergy or higher capture rate may result in negative emission power plants.

The unique ability to achieve negative emissions through carbon capture technologies may also open up the possibility of allowing these plants to run at high capacity factors even in a power system with high renewable shares. This would potentially come at the expense of a reduced contribution to system flexibility, but would improve the economics of CO_2 transport and storage infrastructure through higher utilisation factors and economies of scale.

For CCUS-equipped plants to be economic, power markets must reward flexibility services appropriately

In some countries, thermal power plants operate at comparably low capacity factors today to help integrate growing shares of low-marginal-cost renewables. The business model for CCUS-equipped plants to operate flexibly will rely crucially on decision makers designing the electricity market so that it adequately remunerates flexibility services. Currently, CCUS plants are capital intensive and it is questionable whether owners of newly built or retrofitted plants would be able to recover their costs if required to operate at very low capacity factors. Similarly, the associated CO_2 transport and storage infrastructure would, in the absence of other users, face lower utilisation rates and challenging economics.

However, in an energy system with strong climate ambition, the ability of bioenergy with carbon capture and storage to provide negative emissions to help offset emissions from other sectors may prove more valuable than its capability for flexibility provision. In this case there might be better options for flexibility, for example gas peaking plants.

Timely advances in carbon capture, utilisation and storage

Current status

Progress with carbon capture in power generation has not met expectations, but new projects are emerging in key regions

Currently, two large-scale CCUS facilities operate in the power sector, the Petra Nova Carbon Capture project and the Boundary Dam Carbon Capture project, which are both CCUS retrofits to existing coal-fired power plants. At 240 MW, the Petra Nova project in Texas, which has been operating successfully since 2017, is the largest post-combustion carbon capture system installed on a coal-fired power plant. It captures up to 1.4 $MtCO_2$ annually for use in enhanced oil recovery, which uses injected CO_2 to reverse the decline in production of mature oil fields and to increase overall extraction.

In December 2019 J-Power began testing at its Osaki CoolGen Capture demonstration project in Japan, capturing CO_2 from a 166 MW integrated gasification combined-cycle plant, enlarging the portfolio of capture technologies at operational coal-fired power plants.

Progress on bioenergy in combination with carbon capture has accelerated with Drax's BECCS pilot project in the United Kingdom, a world-first demonstration capturing CO_2 from a power plant fuelled by 100% biomass feedstock. The first pilot commenced capture operations in early 2019 (1 tCO_2/day) and a second pilot project was announced in June 2020, set to capture 0.3 t CO_2/day from Q3 2020. If the project proceeds to a full-scale operation, it could become the world's first negative-emissions power station.[9]

While there are currently no large-scale CCUS gas-fired plants operating, the Oil and Gas Climate Initiative recently announced that a partnership involving several of its

[9] Drax (2019), Carbon dioxide now being captured in first of its kind BECCS pilot; Drax (2020), Negative emissions pioneer Drax and leading global carbon capture company – Mitsubishi Heavy Industries Group – announce new BECCS pilot.

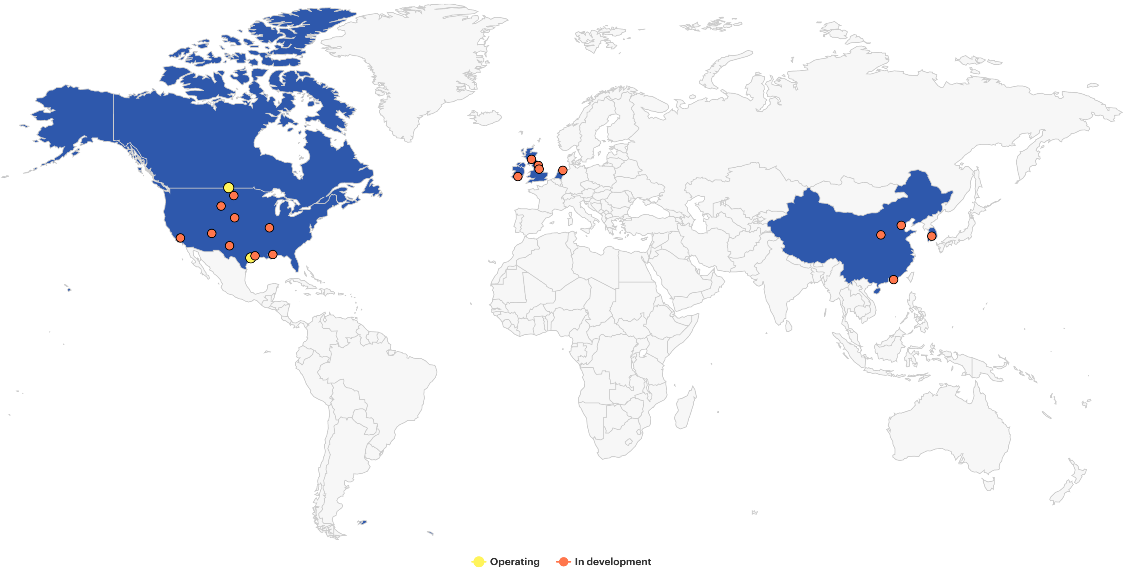
member companies will undertake a front-end engineering and design (FEED) study on a gas-fired power plant in the United Kingdom.

Separately, the NET Power 50 MW_{th} clean energy plant in Texas is a first-of-its-kind natural gas-fired power plant employing Allam cycle technology, which aims to use CO_2 as a working fluid in an oxyfuel supercritical CO_2 power cycle. The NET Power demonstration project started operations in 2018. According to the developers, NET Power could make zero-emissions natural gas-fired power generation competitive with existing power generation technologies. It is also developing the application of Allam cycle technology to coal using coal gasification.

Twenty CCUS power generation projects are currently under development. Eleven of the twenty projects are in the United States; three are in China and the United Kingdom, respectively, as well as one each in Ireland, Korea and the Netherlands. Seven of the projects in development relate to gas-fired power: one involves converting a gas-fired plant to hydrogen, two relate to biomass and waste based power generation, and the remainder plan to apply CCUS to existing or new coal-fired power plants.

The two large-scale CCUS power projects operational today and the 20 in development have a potential combined capture capacity of more than 50 $MtCO_2$ per year.This compares to around 310 $MtCO_2$ captured from power generation in 2030 in the IEA Sustainable Development Scenario, reflecting that carbon capture, utilisation and storage in power is not currently on course.

Figure 10 Power sector CCUS facilities



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.
Source: IEA analysis based on Global CCS Institute's CO2RE database, accessed 20 June 2020.

Cost reductions

A broad range of studies identify significant potential to reduce the cost of equipping power plants with carbon capture technologies

A series of studies have highlighted significant potential to reduce the cost of equipping power plants with carbon capture technologies.[10] These studies highlight that significant cost reductions can be achieved from one generation of plants to the next through technology refinement and efficiency improvements, as well as capital and operating cost reductions, based on the lessons learned from the plants already in operation.

The operators of the Boundary Dam CCS Facility identified that cost savings of at least 30% are possible for the construction and operation of a similarly scaled CCUS facility, based on the early experiences and lessons learned from the plant's commissioning and early operation. The subsequent Shand CCS feasibility study (undertaken by the operators of the Boundary Dam CCUS retrofit project) found that a second-generation capture facility could be built with 67% lower capital costs (per tonne CO_2), achieving an overall cost of capture of USD 45/tCO_2 and a CO_2 capture rate of more than 90%.

In a study for the IEA Coal Industry Advisory Board, the International CCS Knowledge Centre (2019) identified a series of opportunities to reduce the cost of retrofitting post-combustion capture at plant level. Their findings are based on the learnings from the two large-scale CCUS power plants in operation and the 2018 Shand CCS feasibility study. Reductions can be achieved in capital costs, operating costs and CO_2 transport and storage costs.

Table 1 Cost reduction potential for next-generation CCUS projects by cost type

Cost component	Cost reduction measure
Capital costs	Scaling up the CCUS plant
	Improved site layout and modularisation
	Increasing capture capacity
	Increased efficiency of the host power unit
	Optimising CCUS operating envelope
	Development of a CCUS supply chain

[10] For example: UK CCS, 2013; UK CCUS, 2018; Mac Dowell et al., 2017; and International CCS Knowledge Centre 2019.

Cost component	Cost reduction measure
Operating costs	Reduced amine degradation
	Lower maintenance costs
	Optimisation of thermal energy
	Optimised water consumption
	Increased compression efficiency
	Digitalisation
Transport and storage costs	Siting with complementary partners in industrial CCUS hubs, allowing for shared infrastructure

Source: Based on International CCS Knowledge Centre (2019), Learning by doing: The cost reduction potential for CCUS at coal-fired power plants.

Capital costs are an important component of CCUS projects and account for more than half of the total cost of capture at the first-generation CCUS retrofit plants in operation. Operating costs for CCUS-equipped plants are typically higher than for unabated plants due to the additional energy required to operate the capture facility. Further operating expenses relate to the consumption of solvents, chemical reagents, catalysts, the disposal of waste products and additional staff needed to run the CCUS facilities. CO_2 transport and storage costs form an important cost component of a CCUS project if it requires new CO_2 storage or transport infrastructure.

Emerging technologies

CO_2 capture is benefiting from numerous research initiatives

New technologies and improvements are under development for post-combustion, pre-combustion and oxy-fuel combustion capture systems. It is currently unclear which CO_2 capture technologies will be the most effective in delivering cost reductions and performance improvements as several are still in the early stages of development and demonstration. IEAGHG conducted a comprehensive assessment of emerging CO_2 capture technologies for the power sector. Here is a high-level summary of the main technological developments by capture route:

Post-combustion capture. This capture route separates CO_2 from the combustion flue gas. Chemical absorption using amine-based solvents is the most technologically mature CO_2 separation technique for power plants and is applied in the two large-scale projects in operation today (Boundary Dam and Petra Nova).

Scope exists for cost reductions, mainly due to the use of innovative solvents, standardisation of capture units and large-scale deployment leading to economies of scale and learning-by-doing benefits.

Several technological approaches are on the horizon with the potential to improve post-combustion capture, covering the full range of technological maturity, including sorbents and membranes. Some of these technologies may be able to outperform solvents over time, but each has its own challenges and requires further R&D and demonstration at scale.

Pre-combustion capture. In this capture route, the fuel is processed with steam and/or oxygen to produce a gaseous mixture called syngas, consisting of carbon monoxide and hydrogen (a process referred to as reforming or gasification). Reacting the carbon monoxide with more steam (water-gas shift reaction, [WGS]) yields additional hydrogen and converts the carbon monoxide to CO_2. Separating the CO_2 from the high-pressure gas mixture provides a gas for the generation of electricity (in a combined-cycle gas turbine or fuel cell).

Coal gasification and gas reforming are both mature technologies. Research focuses on novel technologies that aim to separate the CO_2 and hydrogen from the gas mixture during the WGS reaction, including membranes and absorbents. Other research areas include technologies related to coal gasification, such as improved turbines, and fuel cell technology.

Oxy-fuel combustion capture. This capture route uses (nearly) pure oxygen instead of air to combust fuel, resulting in a flue gas composed of CO_2 and water vapour . Dehydrating the flue gas results in a high-purity CO_2 stream. The oxygen for combustion is commonly produced by separating it from air, often using an air separation unit (ASU). Research efforts focus mainly on improving the efficiency and cost-effectiveness of ASUs as well as those of novel oxygen production technologies, such as oxygen membranes. Chemical looping is another advanced oxy-fuel technology under development; it shows large energy reduction potentials but is still in its infancy.

Supercritical CO_2 (sCO_2) cycles promise substantial cost and emissions reductions, and have gained particular interest in recent years. While in conventional power plants flue gas or steam is used to drive one or multiple turbines, in sCO_2 cycles supercritical CO_2 is used, that is CO_2 at or above its critical temperature and pressure. Supercritical CO_2 cycles offer many potential advantages, including higher plant efficiencies, lower air pollutant emissions, lower investment costs and high CO_2 capture rates. Two sCO_2 technologies are currently being progressed to an industrial scale by US-based companies:

- NET Power's 50 MW_{th} clean energy plant in Texas employs Allam cycle technology. The company reports a net efficiency of 59% (lower heating value, natural gas) and electricity costs have been estimated to be around USD 75/MWh. To put this into perspective, the generation cost of a conventional gas-fired combined-cycle power plant is estimated to be around USD 60/MWh (without carbon capture technologies) and USD 85/MWh (with conventional carbon capture technologies) based on a natural gas price of USD 6/MWh.

  The Allam cycle is a specialised sCO_2 system in which sCO_2 produced from natural or synthetic gas (from coal gasification) is fired with pure oxygen under pressure. There is interest in demonstrating the coal-based route in the United States too. While this route involves roughly double the CO_2 emissions per unit of electricity produced and requires more energy, it has potential in regions of the world where coal is cheap and abundant but gas rarer.

- Clean Energy Systems' 150 MW_e energy plant is at the Kimberlina power plant in Bakersfield, California. Estimations show a net efficiency of around 49% (lower heating value, natural gas) and a cost of electricity of around USD 100/MWh.

Supercritical CO_2 cycles are among the technologies supported by the US Coal FIRST programme aimed at developing a new generation of near-zero carbon emissions coal power plants.

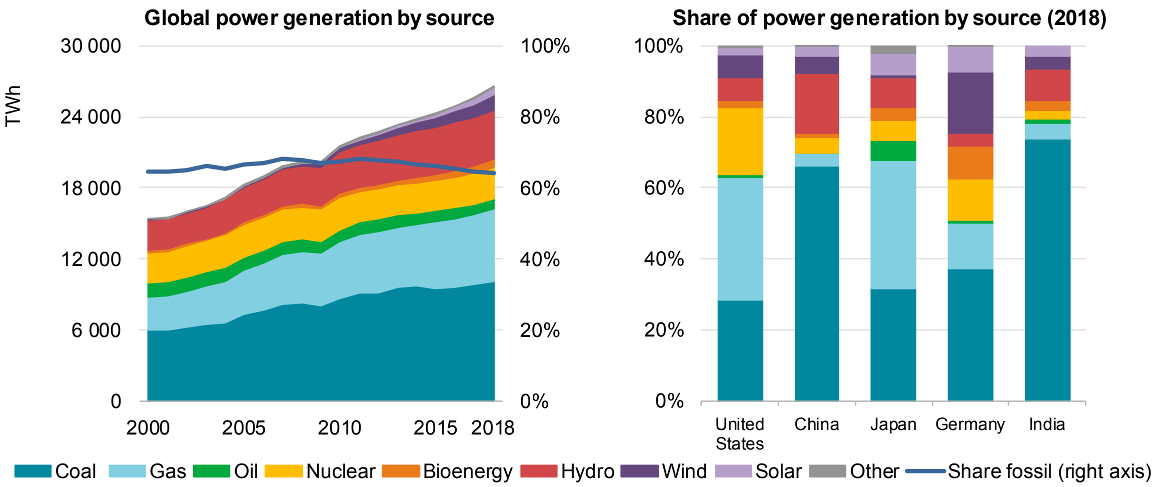
The CO_2 emissions challenge

Fossil fuels dominate power generation today

Coal and gas continue to provide the majority of power generation in a growing global market

Fossil fuels remain the backbone of global power systems, with their 64% share of power generation relatively unchanged since 2000. In absolute terms, fossil fuel generation has increased by 70% since 2000, reaching a new high of around 17 000 TWh in 2018.

Figure 11 Power generation by source globally (left) and in selected major economies (right)



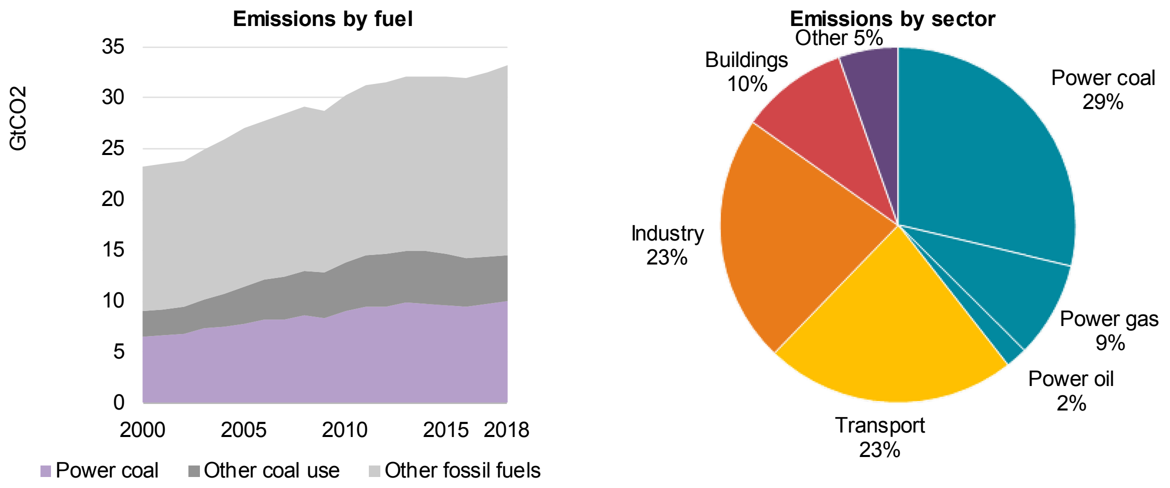
Coal, by far the largest fuel source, accounts for 38% of global electricity generation, followed by gas at around 20%. In major emerging economies such as China and India, the share of coal-fired power exceeds 60%. In many advanced economies, including the United States, Germany and Japan, coal and gas continue to provide the bulk of electricity.

Coal- and gas-fired power plants have been providing reliable, flexible and affordable electricity for many decades. The fossil-based power plant fleet is also crucial to the operation of the electricity grid, for example by providing inertia and frequency control ancillary services. Coal-fired power plants, in particular, have helped to bring access to electricity to hundreds of millions of people across China, India and Southeast Asia, and have enabled economic development.

The power sector accounts for nearly 40% of CO_2 emissions across the energy sector, dominated by emissions from burning coal

As a result of this high reliance on fossil fuels, power is the largest carbon emitter in the energy sector, accounting for nearly 40% of global energy-related emissions. Emissions from the power sector reached a new high in 2018, at 13.8 $GtCO_2$. Coal-fired power generation is the single largest source of emissions from energy, accounting for 10 $GtCO_2$ or 29% of energy-related CO_2 emissions in 2018. It also accounts for nearly 75% of power sector emissions. Notably, CO_2 emissions from coal-fired power in China alone are more than 30% larger than the CO_2 emissions from all passenger vehicles globally.

Figure 12 Global energy-related CO_2 emissions by fuel (left) and sector (right)



In the Paris Agreement, countries agreed to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. The scale of current power sector emissions and the vital role of electrification in decarbonising end-use sectors (buildings, industry and transport) mean that countries must tackle their emissions from power to meet these global climate goals.

Continuing to operate the world's existing fossil power fleet as it is would "lock in" a vast amount of CO_2 emissions. The scale of this potential lock-in of emissions is worsened by the relatively young age of the existing fossil fuel power plant fleet.

Currently 2 080 GW of coal-fired power plants are operating worldwide, almost 60% of which are 20 years old or younger. This compares to a typical operational life of around 50 years. Similarly, gas-fired power plant capacity today stands at 1 700 GW, with an average age of just 19 years.

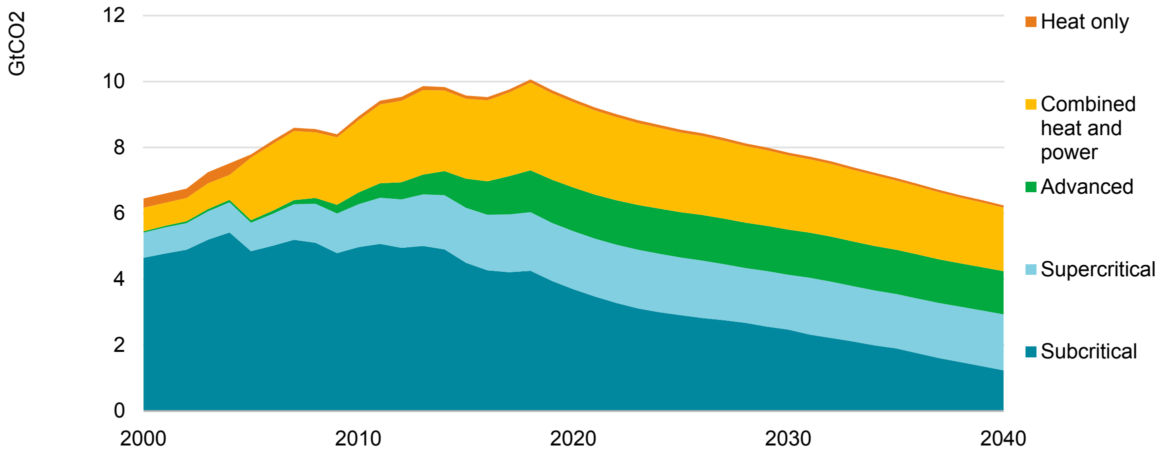
Asia is home to 90% of coal-fired power plants under 20 years of age, with decades of operational lifetime to come

The average age of the coal-fired fleet in Asia is only 12 years, and hence owners are likely to want to operate these plants for decades to come. Asia accounted for 90% of all coal-fired capacity built worldwide over the past 20 years. China built by far the most new coal-fired plants in that period, about 880 GW, followed by India (173 GW) and Southeast Asia (63 GW). There were also some additions of coal-fired capacity in Europe (45 GW), Korea (28 GW), United States (25 GW), Japan (20.5 GW) and Africa (10 GW).

With a 50-year lifetime, existing coal-fired power plants would produce 175 $GtCO_2$ in the period to 2040

The existing global coal-fired fleet is set to produce electricity and release CO_2 emissions for many years to come. On the basis that plant operations and economics are in line with stated policies, CO_2 emissions from the existing coal fleet would emit a cumulative 175 $GtCO_2$ over the period to 2040 – equivalent to 5 times total energy sector emissions in 2018 – despite annual emissions steadily declining to about 60% of today’s levels. If we assume a 40-year plant lifetime, rather than 50, the cumulative emissions lock-in from coal plants would be about 25 $GtCO_2$ lower.

Figure 13 **Global CO_2 emissions from existing coal-fired power plants by technology with a 50-year lifetime and stated policies**



Note: "Advanced" refers mainly to ultra-supercritical plant designs.
Source: IEA (2019), World Energy Outlook 2019.

Subcritical coal-fired power plants (particularly without combined heat generation) are the least efficient designs when producing only electricity and produce significantly higher emissions per unit of power generated than more modern coal plants. The emissions savings from ultra-supercritical or advanced ultra-supercritical plant designs compared to subcritical plants amount to some 15-30%. With a capacity of over 900 GW, subcritical plants produced around 4 300 TWh in 2018, and accounted for more than 40% of global CO_2 emissions from the coal fleet. Close to half of subcritical plants in operation are under 20 years of age and could emit more than 60 $GtCO_2$ over the next two decades.

More efficient supercritical and advanced designs, at an overall 660 GW capacity, produced around 3 500 TWh in 2018 and accounted for about 30% of coal plant CO_2 emissions. The remainder comes from combined heat and power plants. Over the next two decades, CO_2 emissions from efficient coal-fired power plants are set to remain largely unchanged under stated policies. However, emissions from subcritical plants are projected to fall by two-thirds.

In addition to the existing fleet, over 170 GW of coal-fired capacity was under construction at the start of 2019, mostly in China and India. The completion of these facilities will expand the global coal fleet by some 10% and risk locking-in another 15 $GtCO_2$ of emissions over the period to 2040.

Meeting the Paris Agreement goals

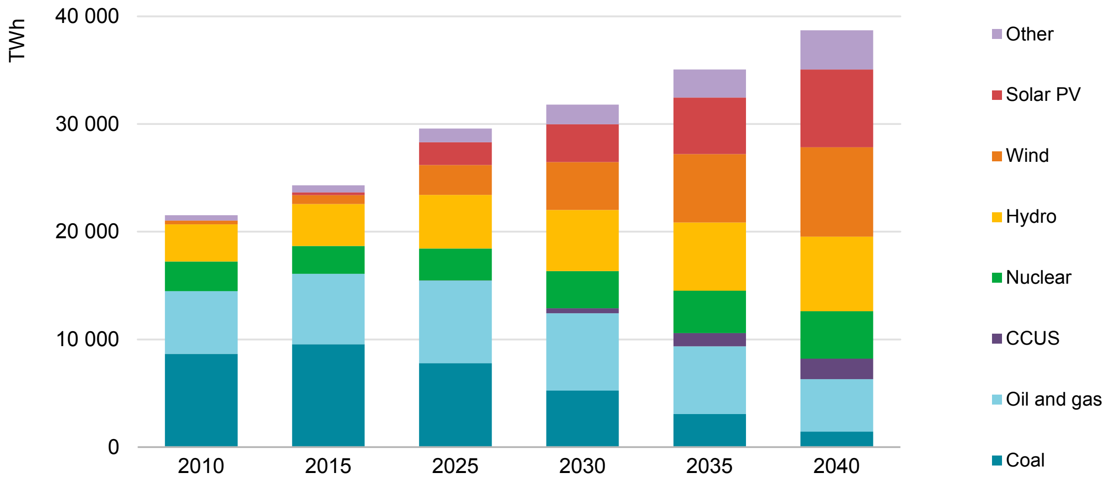
The power sector evolves rapidly in a scenario to meet the Paris Agreement, with low-carbon sources meeting 85% of power generation by 2040

The IEA *World Energy Outlook* Sustainable Development Scenario (SDS) puts forward an integrated approach to achieving the three key energy-related Sustainable Development Goals: achieving universal energy access, reducing CO_2 emissions in line with the Paris Agreement, and reducing the health impacts of air pollution. Underlying the SDS is a profound transformation of both electricity demand and supply.

Electricity demand rises by some 60% over the period to 2040 in the SDS, despite strong energy efficiency measures, driven by economic growth, electrification of end uses and increased access to electricity in developing economies. As a result, electricity meets around 30% of final energy use in 2040, up from some 19% today.

The electrification of end-uses increases both the urgency and the challenge for the power generation sector to decarbonise in parallel with rapid expansion to meet the growing demand. In the SDS, power generation is all but decarbonised by 2040: 85% of global generation comes from low-carbon sources, compared to only 35% today. This causes CO_2 emissions to fall sharply. Generation from renewables rises to around four times today's level by 2040, led by wind and solar PV, which account for almost 40% of total generation in 2040.

Figure 14 Power generation and carbon intensity in the SDS



Note: "Other" includes mainly bioenergy, but also geothermal and concentrated solar power.
Source: IEA (2019), World Energy Outlook 2019.

As discussed in detail in the other sections, the very high share of renewables generation and capacity by 2040 in the SDS requires an extremely flexible power system to ensure stable and secure operation.

The expansion of renewables capacity speeds up substantially in the SDS compared to current build rates. Solar PV additions average 180 GW per year in the period to 2040 compared to 97 GW in 2018. China and India alone make up about half of all solar PV additions. Wind also grows rapidly, with 120 GW additions per year on average, more than double the additions of some 50 GW seen in 2018. China drives this expansion with more than 35 GW of additions each year compared to 20.6 GW in 2018.

Additional information

US tax credits for CCUS

Tax credits alone may not be enough to make CCUS power retrofits commercially viable, but can help when applied with other public policy measures

Although a major factor in new CCUS investment plans in the United States, the Section 45Q tax credit alone is not expected to be sufficient to close the commercial gap to enable an operator to retrofit carbon capture facilities to a coal- or gas-fired power plant. However, it could be layered with complementary measures for early projects, including capital grants. Analysis by Friedmann et al. found that, while revenue enhancements may provide the lowest risk and best chance to accelerate the deployment of carbon capture, especially for gas plants, capital treatments are expected to provide better support for coal retrofits due to their capital intensity and scale.[11]

The Section 48A credit currently requires plants to have improved efficiency after retrofit, which is very challenging when incorporating carbon capture into existing plants due to the energy needs of the capture facility. Proposed amendments contained in the Carbon Capture Modernization Act would enable CCUS retrofits to coal plants to be eligible for the tax credit by addressing the requirement for plants to have greater efficiency after retrofit.

How carbon capture affects thermal power plant flexibility

Well-conceived capture systems have minor effects on power plant flexibility and can be designed to enhance it

The three main carbon capture routes – post-, pre- and oxyfuel combustion – appear to have a small to negligible impact on the operational flexibility of thermal power

[11] Friedmann, J., O. Emeka Ochu and J.D. Brown (2020), Capturing Investment: Policy Design to Finance CCUS Projects in the U.S. Power Sector.

plants, provided that the capture systems are designed properly. In fact, post- and pre-combustion capture applications could potentially increase the ramp rate and lower the minimum stable operating load if the capture system and power block are operated independently. Oxyfuel combustion applications, however, may impose additional constraints on the power plant's flexibility in the absence of oxygen storage, due to the inertia of the oxygen production plant required for the capture process.

There are several techniques to enhance flexibility. Oxyfuel power plants could temporarily switch back to conventional air-firing mode, while power plants equipped with post- or pre-combustion systems could (partly) bypass the capture units. These options can help to temporarily boost power output as less or no energy is required for the capture process, although CO_2 would be vented to the atmosphere. Other flexibility options involve storage of oxygen (oxyfuel combustion), hydrogen (pre-combustion) or solvents (post-combustion), which enable the carbon capture process to continue during transient operation. While these storage requirements may entail slightly higher capital and operational costs, enhanced flexibility capabilities can also increase electricity sale revenues by boosting power output when electricity prices are high (arbitrage).[12]

Biomass power generation technologies and carbon capture

Carbon capture and storage can be combined with various biomass power generation technologies to help achieve negative emissions

Biomass co-firing with coal: Under this process, plant operators directly or indirectly add biomass to the combustion of coal.

Direct co-firing is a commercial technology that blends, mills and burns biomass with coal, or grinds it in a biomass mill or modified coal mill and then blends it with pulverised coal. The blended substance is either fed into the burners directly or through a dedicated biomass burner, or injected directly into the boiler.

The maximum share of biomass is relatively limited for direct co-firing in existing pulverised coal boilers without modifications, typically around 10-30%, due to prohibitively high maintenance costs and operating expenditure at shares higher

[12] IEA (2018), Status of Power System Transformation 2018.

than this. For newly built plants, these costs can be reduced through appropriate design and planning.

Indirect co-firing involves converting biomass in a dedicated fluidised bed gasifier that produces a combustible gas with low calorific value, which can be injected into the boiler of an existing coal power plant.

Whether using direct or indirect biomass co-firing, the higher the ratio of biomass to coal, the lower the CO_2 emissions emitted. The possible ratios depend on the characteristics of the biomass and the power plant design. Achieving elevated co-firing ratios has proved difficult for several reasons, including the fact that biomass has lower energy density and a different inorganic composition to hard coal, is vulnerable to biodegradation and is hydrophilic in nature.

Power plant modifications are often necessary to accommodate biomass, which requires investment and incurs higher costs. Investment costs for biomass co-firing are inherently site-specific and it is difficult to find reliable cost data. We estimate them to range between USD 700 per kilowatt (kW) and USD 1 000/kW for direct co-firing and USD 3 300/kW to USD 4 400/kW for indirect co-firing. To overcome these challenges and significantly increase the biomass co-firing share, certain plants are using thermal pretreatment technologies that increase the homogeneity, brittleness and/or energy density of biomass.

Dedicated biomass firing: It is possible to operate power plants exclusively using biomass. This typically takes place in purpose-built biomass plants, in modified pulverised coal boilers or in co-generation plants previously fired with coal or lignite, often using circulating fluidised bed (CFB) combustion technology.

CFB has the advantage of being flexible with regard to the biomass feedstock. CFB plants are usually smaller than utility boilers and are typically located in close proximity to urban areas or industrial facilities in order to supply heat. The size of dedicated biomass plants is limited by the availability of biomass and the transport costs associated with the feedstock.

The cost of converting a coal plant to biomass firing varies substantially. Costs are estimated to be around USD 600/kW for plant conversion using wood pellets and about USD 1 700/kW using wood chips. A recent example of an operator converting a coal-fired power plant to biomass is the Drax bioenergy plant in the United Kingdom, where they converted four 600 MW coal boilers to use biomass. In addition, in 2019 they started a project to capture1 tCO_2/day, with a second pilot project capturing 0.3 tCO_2/day to commence in Q3 2020.

The same capture technologies that are available to coal combustion power plants are also suitable for biomass co-firing and dedicated biomass firing, i.e. post-combustion capture or oxy-fuel combustion capture. We do not anticipate co-firing biomass to have a significant impact on post-combustion capture.

Biomethane for power generation: Biomethane obtained from fermentation and upgraded by CO_2 separation (and storage) or gasification-based biosynthetic natural gas can be used as fuel in gas-fired power technologies. One of the benefits is that there are virtually no co-firing ratio limitations; however, the availability of biogas may ultimately restrict its role in power generation. Additional costs for carbon capture technologies due to the use of biomass are limited, as conventional post-combustion capture technology can be applied.

Biomass gasification: Gasifying biomass allows a wide variety of biomass feedstocks to be used. We estimate the efficiency of dedicated biomass in integrated gasification combined-cycle plants to be in the 35-44% range for plant sizes up to about 250 MW_e. There are currently no commercial integrated biomass gasification with CCUS facilities in operation. Pre-combustion capture technology is currently considered the most promising option for biomass gasification, offering the potential to benefit from experiences gained from fossil-fuelled integrated gasification combined-cycle power plants with pre-combustion capture.[13]

The potential for higher capture rates

Researchers are identifying numerous technical approaches to achieving carbon neutrality at CCUS-equipped power plants

Assuming strong climate ambition, long-term analysis of the energy system shows the CO_2 intensity of the global power sector becoming negative sometime around 2050. However, with a CO_2 capture rate of 85% (a rate commonly assumed in modelling) and an efficiency of 41%, a hard coal power plant with post-combustion CO_2 capture still emits 125 gCO_2/kWh. Oxy-fuelled CO_2 capture emits 83 gCO_2/kWh at a typically assumed capture rate of 90% and the same efficiency.

Therefore, in the long term, for fossil-fuelled power plants with carbon capture technologies to play a role in a fully decarbonised power system, the sector needs to address these residual emissions. Increasing the capture rate is one way to reduce

[13] IEA (2017), Energy Technology Perspectives 2017.

the remaining emissions and thus increase the attractiveness of fossil-fuelled power plants with carbon capture technologies.

From a technical perspective, higher capture rates are possible. Already today, the Petra Nova CCUS project captures as much as 95% of the CO_2 from the flue gas slipstream that it processes. Capture rates at post-combustion plants can be raised by increasing the CO_2 absorption capacity. This can be done by using a leaner absorber solvent, that is the regenerated solvent entering the absorber has a lower CO_2 concentration. This requires more energy for regeneration, faster solvent recirculation between the absorber and desorber columns, and higher or more absorbent columns.

Oxy-fuelled power plants could theoretically achieve a capture rate of 100%. Technically, the capture rate can be increased by removing CO_2 through an additional scrubbing step from vent streams leaving the plant. For pre-combustion capture plants, that is integrated gasification combined-cycle coal power plants, a 100% capture rate cannot be realised due to equilibrium conditions in the physical absorption process. The IEAGHG highlights that the capture rate can be raised by increasing the conversion rate of carbon monoxide to CO_2 in the shift reaction after gasification and by increasing the CO_2 absorption capacity of the CO_2 capture unit in the same way as for the post-combustion system.

The IEAGHG suggests that CO_2 capture rates as high as 99.7% can be achieved at low additional marginal cost in coal- and gas-fired power plants equipped with carbon capture technologies. More specifically, an ultra-supercritical pulverised coal plant can be made CO_2 neutral (99.7% capture) at a 7% electricity generation cost increase over the usual 90% capture rate with only a 3% increase in CO_2 avoided cost. (Note that carbon neutrality means that the power plant only emits the amount of CO_2 present in the incoming combustion air.)

The most economical option to achieve a carbon-neutral ultra-supercritical coal plant may be co-combusting 10% biomass at 90% CO_2 capture. This would increase the CO_2 avoided cost by only 1.5% to around USD 62/tCO_2.

A natural gas-fired combined-cycle plant can theoretically be made CO_2 neutral (99% capture). Compared to the usual 90% capture rate, the electricity generation cost increases by 7% and the cost of CO_2 avoided by 8%.

Table 2 **Cost and emission intensity of alternative technologies at different capture rates**

	USC PC					USC PC with 10% co-firing	CCGT			
Capture rate	0%	90%	95%	99%	99.7%	90%	0%	90%	95%	99%
LCOE (USD/MWh)	57.3	96.6	99.6	104.3	103.7	98.5	58.7	86.1	87.6	91.8
CO_2 avoided cost (USD/tCO_2)	-	61.1	61.3	64.7	63.2	61.9	-	88.0	87.2	94.9
CO_2 emission intensity (t/MWh$_e$)	0.736	0.092	0.045	0.007	0.000	0.000	0.349	0.0372	0.0176	0.000

Notes: USC = ultra-supercritical. PC = post-combustion. CCGT = combined-cycle gas turbine.

Source: Based on IEAGHG (2019), Towards zero emissions CCS in power plants using higher capture rates and biomass.

Abbreviations and acronyms

ASU	air separation unit
BECCS	bioenergy with CCS
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CFB	circulating fluidised bed
CO	carbon dioxide
FEED	Front-End Engineering and Design
IGCC	integrated gasification combined cycle
IEA	International Energy Agency
LCOE	Levelised cost of electricity
PV	photovoltaic
SCO_2	supercritical carbon dioxide
SDS	Sustainable Development Scenario
VALCOE	value-adjusted levelised cost of electricity
WGS	water-gas shift

Units of measure

gCO_2/kWh	gram of carbon dioxide per kilowatt hour
GW	gigawatt
GWh	gigawatt hour
kW	kilowatt
MW	megawatt
MW_e	megawatt electrical
MWh	megawatt hour
MW_{th}	megawatt thermal
$MtCO_2$	million tonnes of carbon dioxide
tCO_2	tonne of carbon dioxide
t/MWh_e	tonne per megawatt hour electrical
TWh	terawatt hour

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