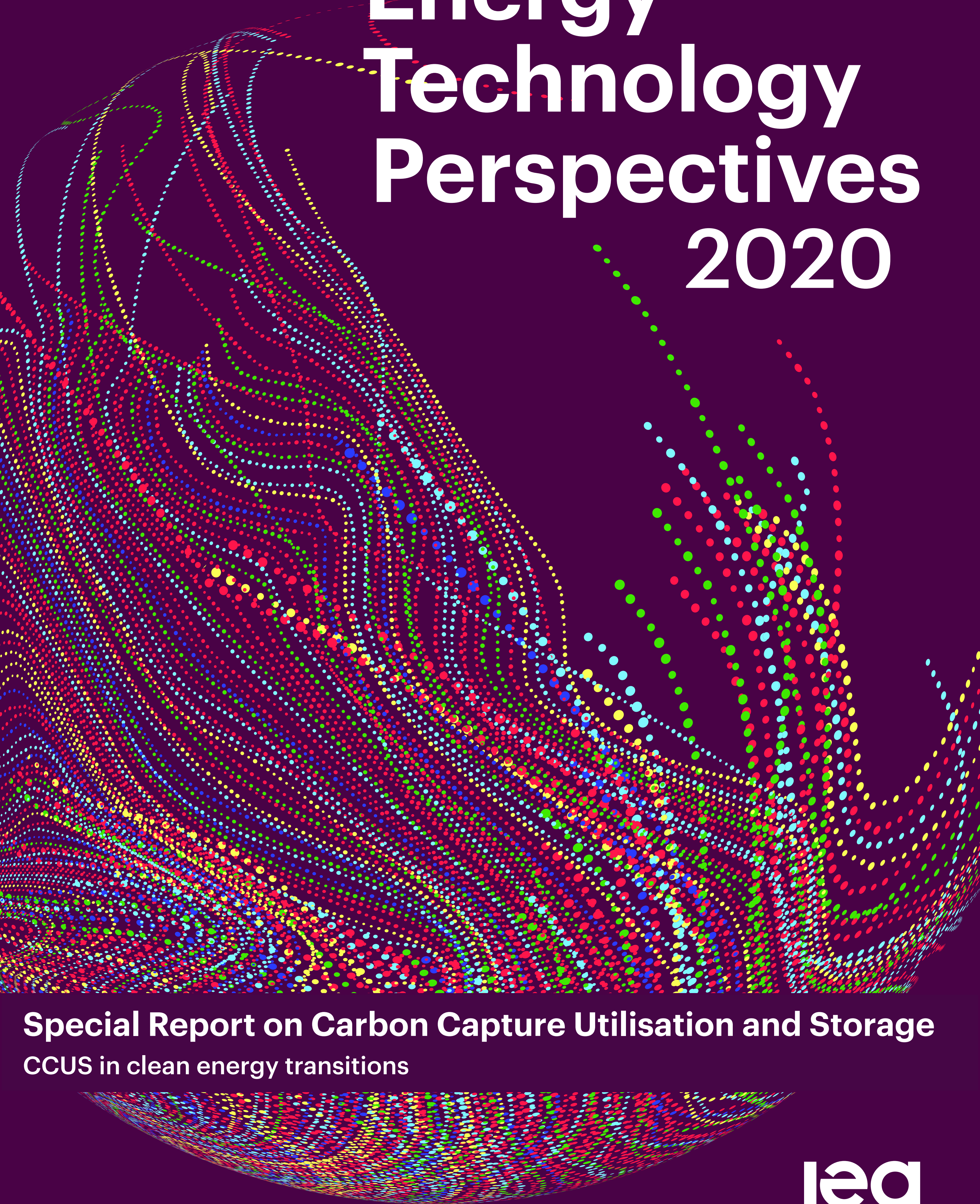
Energy Technology Perspectives 2020



Special Report on Carbon Capture Utilisation and Storage

CCUS in clean energy transitions

iea

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INTERNATIONAL ENERGY AGENCY

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Foreword

The International Energy Agency (IEA) has long highlighted that there are no single or simple solutions to reaching international energy and climate goals. Doing so requires a wide range of technologies, some more mature than others. Our revamped *Energy Technology Perspectives* series, of which this special report is a key part, has done important work in illuminating the contours of the major energy technology challenges we face today – and how to overcome them. The analysis shows that one of the key technology areas for putting energy systems around the world on a sustainable trajectory will be carbon capture, utilisation and storage (CCUS).

In a path towards meeting international goals, CCUS is the only group of technologies that contributes both to reducing emissions in key sectors directly and to removing CO_2 to balance emissions that cannot be avoided. This is a critical part of reaching "net" zero targets.

Today, there are only around 20 commercial CCUS operations worldwide – nowhere near the amount required to put global emissions on a sustainable path. But momentum is growing – and through smart policies, investments and international co-operation, governments and companies across the globe can give CCUS the boost it needs.

The United States has helped spur the development of CCUS facilities in its energy system through its innovative 45Q tax credits. And just before the launch of this special report in September 2020, Norway showed its leadership in Europe by making a major funding commitment to the Longship project. Longship will connect two different plants capturing CO_2 in Norway with the Northern Lights storage facility deep under the North Sea. Northern Lights will be able to receive CO_2 captured in neighbouring European countries, as well, thereby playing an important role in meeting not just Norway's ambitious climate goals but those of the entire region.

Plans for more than 30 commercial CCUS facilities have been announced in the last three years – mainly in Europe and the United States, but also in Australia, the People's Republic of China, Korea, the Middle East and New Zealand. Projects now nearing a final investment decision represent an estimated potential investment of around USD 27 billion – more than double the investment planned in 2017.

Co-operation – across borders, and between government and industry – is critical if CCUS is to grow at the pace needed to meet energy and climate goals. The IEA is committed to playing a leading role in those efforts, as demonstrated by this special report and the ongoing work of the Agency's team of CCUS analysts.

Markets alone will not turn CCUS into the clean energy success story it must become. But governments and industry today have the chance to combine their forces to realise the environmental and economic benefits that CCUS offers. Without it, our energy and climate goals will become virtually impossible to reach.

Dr. Fatih Birol
Executive Director
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Executive summary

A new dawn for a vital technology area

Carbon capture, utilisation and storage (CCUS) will need to form a key pillar of efforts to put the world on the path to net-zero emissions. A net-zero energy system requires a profound transformation in how we produce and use energy that can only be achieved with a broad suite of technologies. Alongside electrification, hydrogen and sustainable bioenergy, CCUS will need to play a major role. It is the only group of technologies that contributes both to reducing emissions in key sectors directly and to removing CO_2 to balance emissions that cannot be avoided – a critical part of "net" zero goals.

Stronger investment incentives and climate targets are building new momentum behind CCUS. After years of slow progress and insufficient investment, interest in CCUS is starting to grow. Plans for more than 30 commercial facilities have been announced in the last three years. And projects now nearing a final investment decision represent an estimated potential investment of around USD 27 billion – more than double the investment planned in 2017. This portfolio of projects is increasingly diverse – including power generation, cement and hydrogen facilities, and industrial hubs – and would double the level of CO_2 captured globally, from around 40 million tonnes today.

Support for CCUS in economic recovery plans can ensure the Covid-19 crisis does not derail recent progress. Despite almost USD 4 billion in government and industry commitments to CCUS so far in 2020, the economic downturn is set to undermine future investment plans. CCUS is in a much stronger position to contribute to sustainable recoveries than it was after the 2008-09 global financial crisis. Since then, deployment has tripled (albeit from a small base), the range of demonstrated applications has expanded, costs have declined, and new business models have emerged.

Reaching net zero will be virtually impossible without CCUS

CCUS technologies contribute to clean energy transitions in several ways:

- **Tackling emissions from existing energy infrastructure.** CCUS can be retrofitted to existing power and industrial plants that could otherwise emit 600 billion tonnes of CO_2 over the next five decades – almost 17 years' worth of current annual emissions.

- **A solution for some of the most challenging emissions.** Heavy industries account for almost 20% of global CO_2 emissions today. CCUS is virtually the only technology solution for deep emissions reductions from cement production. It is also the most cost-effective approach in many regions to curb emissions in iron and steel and chemicals manufacturing. Captured CO_2 is a critical part of the supply chain for synthetic fuels from CO_2 and hydrogen – one of a limited number of low-carbon options for long-distance transport, particularly aviation.
- **A cost-effective pathway for low-carbon hydrogen production.** CCUS can support a rapid scaling up of low-carbon hydrogen production to meet current and future demand from new applications in transport, industry and buildings.
- **Removing carbon from the atmosphere**. For emissions that cannot be avoided or reduced directly, CCUS underpins an important technological approach for removing carbon and delivering a net-zero energy system.

CCUS grows and evolves on the path to net zero

In a transition to net-zero emissions, the role of CCUS evolves and extends to almost all parts of the global energy system. In the IEA's Sustainable Development Scenario – in which global CO_2 emissions from the energy sector decline to net zero by 2070 – the initial focus of CCUS is on retrofitting fossil fuel-based power and industrial plants and supporting low-carbon hydrogen production. By 2030, more than half of the CO_2 captured is from retrofitted existing assets. Over time, the focus shifts to CO_2 capture from bioenergy and the air for carbon removal – and as a source of climate-neutral CO_2 for synthetic aviation fuels. In this scenario, around 60% of CO_2 capture is linked to fossil fuels, and the rest is from industrial processes, bioenergy and the air.

CCUS is one of the two main ways to produce low-carbon hydrogen. Global hydrogen use in the Sustainable Development Scenario increases sevenfold to 520 megatonnes (Mt) by 2070. The majority of the growth in low-carbon hydrogen production is from water electrolysis using clean electricity, supported by 3 300 gigawatts (GW) of electrolysers (from less than 0.2 GW today). The remaining 40% of low-carbon hydrogen comes from fossil-based production that is equipped with CCUS, particularly in regions with access to low-cost fossil fuels and CO_2 storage. CCUS-equipped hydrogen facilities are already operating in seven locations today, producing 0.4 Mt of hydrogen – three times as much hydrogen as is produced from electrolysers.

A faster transition to net zero increases the need for CCUS. CCUS accounts for nearly 15% of the cumulative reduction in emissions in the Sustainable Development Scenario. Moving the net-zero goalposts from 2070 to 2050 would require almost 50% more CCUS deployment.

Carbon removal is part of the net-zero equation

Underpinned by CCUS, carbon removal plays an important role in the net-zero transition. Technology-based carbon removal approaches are needed to balance emissions that are technically difficult or prohibitively expensive to eliminate. When net-zero emissions is reached in the Sustainable Development Scenario, 2.9 gigatonnes (Gt) of emissions remain, notably in the transport and industry sectors. These lingering emissions are offset by capturing CO_2 from bioenergy and the air and storing it.

Direct air capture technologies have significant potential to accelerate the transition to net zero, but costs need to come down. Capturing carbon directly from the air and storing is an alternative to capturing it from bioenergy. Direct air capture plants are already operating on a small scale, but their costs are currently high. With further innovation, the availability of direct air capture technologies could offer an important backstop or hedge in the event that other technologies fail to materialise or have slower-than-anticipated pathways to becoming commercially viable.

CCUS is up and running in some sectors – but lagging in the most critical ones

CCUS facilities have been operating for decades in certain industries, but they are still a work in progress in the areas that need them most. CCUS has primarily been used in areas such as natural gas processing or fertiliser production, where the CO_2 can be captured at relatively low cost. But in other areas, including cement and steel, CCUS remains at an early stage of development. These are the sectors where CCUS technologies are critical for tackling emissions because of a lack of alternatives.

With ample storage available, success will hinge on getting the infrastructure right

Infrastructure to transport and store CO_2 safely and reliably is essential for rolling out CCUS technologies. The development of CCUS hubs – industrial centres that make use of shared CO_2 transport and storage infrastructure – could help accelerate deployment by reducing costs. At least 12 CCUS hubs are in development globally – including in Australia, Europe and the United States – and many of them are linked to low-carbon hydrogen production. Norway's Northern Lights project, a large offshore CO_2 storage facility in the North Sea, could provide a solution for emissions from neighbouring countries.

Major CO_2 emissions sources are within reach of potential storage. Our detailed analysis in this report of CO_2 emissions from power and industrial facilities in the

People's Republic of China, Europe and the United States finds that 70% of the emissions are within 100 km of potential storage, a relatively practical and cost-effective range for transporting the captured CO_2. In the United States, CO_2 captured at existing facilities is transported an average of 180 km. But shorter distances can reduce costs and decrease infrastructure development times. The overall technical capacity for storing CO_2 worldwide is vast, but detailed site-specific assessment is needed.

Government action this decade is crucial

We need to take urgent steps to ensure CCUS is available to contribute to net-zero goals. A major ramp-up of CCUS deployment is required in the next decade to put the global energy system on track for net-zero emissions. Governments have a critical role to play through policies that establish a sustainable and viable market for CCUS. But industry must also embrace the opportunity. No sector will be unaffected by clean energy transitions – and for some, including heavy industry, the value of CCUS is inescapable. Oil and gas companies have the engineering expertise, project management capabilities and financial resources to drive CCUS development and deployment.

Four high-level priorities for governments and industry would accelerate the progress of CCUS over the next decade:

1. create the conditions for investment by placing a value on reducing emissions and direct support for early CCUS projects
2. co-ordinate and underwrite the development of industrial hubs with shared CO_2 infrastructure
3. identify and encourage the development of CO_2 storage in key regions
4. boost innovation to reduce costs and ensure that critical emerging technologies become commercial, including in sectors where emissions are hard to abate and for carbon removal.

Chapter 1: A new era for CCUS

HIGHLIGHTS

- Carbon capture, utilisation and storage (CCUS) so far has not lived up to its promise. Although its relevance for reaching climate goals has long been recognised, deployment has been slow: annual CCUS investment has consistently accounted for less than 0.5% of global investment in clean energy and efficiency technologies.

- Stronger climate targets and investment incentives are injecting new momentum into CCUS. Plans for more than 30 new integrated CCUS facilities have been announced since 2017, mostly in the United States and Europe, although projects are also planned in Australia, China, Korea, the Middle East and New Zealand. Projects at advanced stages of planning represent a total estimated investment of more than USD 27 billion, almost double the investment in projects commissioned since 2010.

- CCUS technologies offer significant strategic value in the transition to net-zero:
  - CCUS can be retrofitted to existing power and industrial plants, which could otherwise still emit 8 billion tonnes (Gt) of carbon dioxide (CO_2) in 2050.
  - CCUS can tackle emissions in sectors where other technology options are limited, such as in the production of cement, iron and steel or chemicals, and to produce synthetic fuels for long-distance transport (notably aviation).
  - CCUS is an enabler of least-cost low-carbon hydrogen production.
  - CCUS can remove CO_2 from the atmosphere by combining it with bioenergy or direct air capture to balance emissions that are unavoidable or technically difficult to abate.

- The Covid-19 crisis represents both a threat and an opportunity for CCUS: the economic downturn will almost certainly impact investment plans and lower oil prices are undermining the attractiveness of using CO_2 for enhanced oil recovery. But CCUS is in a stronger position to contribute to economic recoveries than after the global financial crisis. A decade of experience in developing projects and the recent uptick in activity means that there are a number of "shovel-ready" projects with potential to double CCUS deployment by 2025.

Introduction

The story of CCUS has largely been one of unmet expectations: its potential to mitigate climate change has been recognised for decades, but deployment has been slow and so has had only a limited impact on global CO_2 emissions. This slow progress is a major concern in view of the urgent need to reduce emissions across all regions and sectors in order to reach global net-zero emissions as quickly as possible. Yet there are clear signs that CCUS may be gaining traction in spite of the economic uncertainty created by the Covid-19 crisis, with more projects coming online, more plans to build new ones and increased policy ambition and action. The coming decade will be critical to scaling up investment in developing and deploying CCUS and realising its significant potential to contribute to the achievement of net-zero emissions.

A radical transformation of the way we produce and consume energy will be needed to bring about a rapid reduction in emissions of greenhouse gases (GHGs) consistent with the Paris Agreement goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels". The Paris Agreement also seeks to achieve a "balance between anthropogenic emissions by sources and removals by sinks" in the second half of this century: in practice, this translates to net zero emissions. Net zero requires that any CO_2 released into the atmosphere from human activity be balanced by an equivalent amount being removed, either through nature-based solutions (including afforestation, reforestation and other changes in land use) or technological solutions that permanently store CO_2 captured (directly or indirectly) from the atmosphere. The sooner net zero emissions are achieved, the greater the chances of meeting the most ambitious climate goals.

The International Energy Agency (IEA) *Energy Technology Perspectives 2020* report highlights the central role that CCUS must play as one of four key pillars of global energy transitions alongside renewables-based electrification, bioenergy and hydrogen (IEA, 2020a). CCUS can reduce emissions from large stationary sources, essentially power stations and large industrial plants, in a variety of ways, as well as generate negative emissions, by combining it with bioenergy (BECCS) or through direct air capture (DAC) (Box 1.1). Carbon removal technologies will almost certainly be required due to the practical and technical difficulties in eliminating emissions in certain sectors, including some types of industry (notably steel, chemicals and cement), aviation, road freight and maritime shipping.

Another key attraction of CO_2 capture technology is that it can be retrofitted to existing plants, many of which were built recently and could operate for decades to come. CCUS can also provide a least-cost pathway for producing low-carbon hydrogen based on natural gas or coal in countries with low-cost resources. Captured CO_2 can be used in a number of ways, including to produce clean aviation fuels (see below).

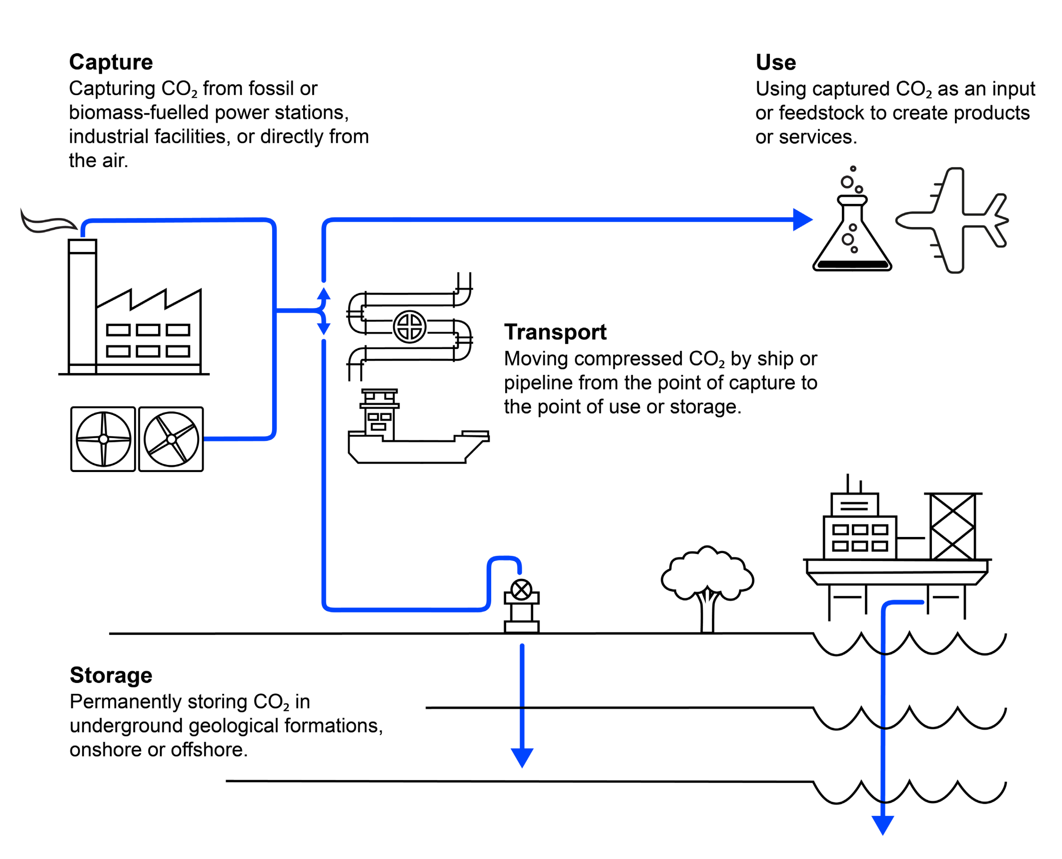
Box 1.1 What is CCUS and how does it work?

CCUS refers to a suite of technologies that involves the capture of CO_2 from large point sources, including power generation or industrial facilities that use either fossil fuels or biomass for fuel. The CO_2 can also be captured directly from the atmosphere. If not being used on-site, the captured CO_2 is compressed and transported by pipeline, ship, rail or truck to be used in a range of applications, or injected into deep geological formations (including depleted oil and gas reservoirs or saline formations) which trap the CO_2 for permanent storage. The extent to which CO_2 emissions are reduced in net terms depends on how much of the CO_2 is captured from the point source and whether and how the CO_2 is used.

The use of the CO_2 for an industrial purpose can provide a potential revenue stream for CCUS facilities. Until now, the vast majority of CCUS projects have relied on revenue from the sale of CO_2 to oil companies for enhanced oil recovery (EOR), but there are many other potential uses of the CO_2, including as a feedstock for the production of synthetic fuels, chemicals and building materials.

CCUS technologies can provide a means of removing CO_2 from the atmosphere, i.e. "negative emissions", to offset emissions from sectors where reaching zero emissions may not be not economically or technically feasible. Bioenergy with carbon capture and storage (CCS), or BECCS, involves capturing and permanently storing CO_2 from processes where biomass (which extracts CO_2 from the atmosphere as it grows) is burned to generate energy. A power station fuelled with biomass and equipped with CCUS is a type of BECCS technology. DAC involves the capture of CO_2 directly from ambient air (as opposed to a point source). The CO_2 can be used, for example as a CO_2 feedstock in synthetic fuels, or it can be permanently stored to achieve negative emissions. These technology-based approaches for carbon removal can complement and supplement nature-based solutions, such as afforestation and reforestation.

Schematic of CCUS



CO_2 can be captured from a range of sources, including the air, and transported by pipeline or ship for use or permanent storage.

Different terminology is often adopted when discussing CCUS technologies. In this report:

- Carbon capture and storage (CCS): includes applications where the CO_2 is captured and permanently stored
- Carbon capture and utilisation (CCU) or CO_2 use: includes where the CO_2 is used, for example in the production of fuels and chemicals
- Carbon capture, utilisation and storage (CCUS): includes CCS, CCU and also where the CO_2 is both used and stored, for example in EOR or in building materials, where the use results in some or all of the CO_2 being permanently stored.

Strategic value of CCUS

CCUS carries considerable strategic value as a climate mitigation option. It can be applied in a number of ways and across a range of sectors, offering the potential to contribute – directly or indirectly – to emissions reductions in almost all parts of the global energy system. Consequently, progress in developing and deploying CCUS technologies in one sector could have significant spillover benefits for other sectors or applications, including for technological learning, cost reductions and infrastructure development. The four main ways in which CCUS can contribute to the transition of the global energy system to net-zero emissions – tackling emissions from existing energy assets, providing a platform for low-carbon hydrogen production, a solution for sectors with hard-to-abate emissions, and removing carbon from the atmosphere – are detailed below.

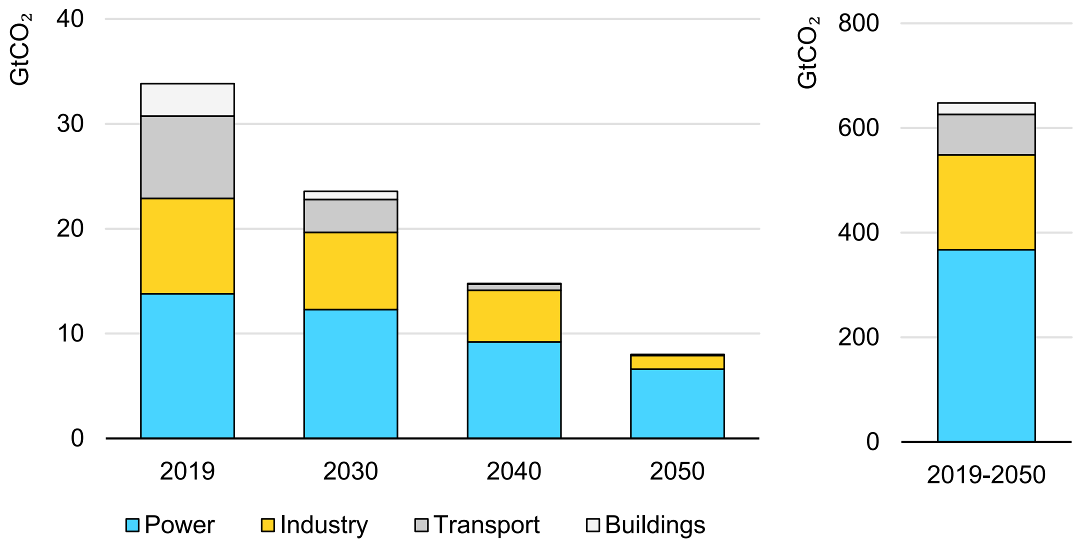
Tackling emissions from existing energy assets

Tackling emissions from today's power stations and industrial plants will need to be central to the global clean energy transition. Those assets could generate more than 600 $GtCO_2$ – almost two decades' worth of current annual emissions – if they were to operate as they currently do until the end of their technical lives. Together with the committed emissions from other sectors, this would leave virtually no room for any emissions-generating assets in any sector to meet climate goals – an inconceivable prospect as populations and economies around the world continue to grow.

Coal-fired power generation presents a particular challenge. The global coal fleet accounted for almost one-third of global CO_2 emissions in 2019, and 60% of the fleet could still be operating in 2050. Most of the fleet is in the People's Republic of China (hereafter, "China"), where the average plant age is less than 13 years, and in other emerging Asian economies where the average plant age is less than 20 years. Similarly, 40% of current primary steel-making assets could still be operating in 2050 unless retired early (Figure 1.1).

CCUS is the only alternative to retiring existing power and industrial plants early or repurposing them to operate at lower rates of capacity utilisation or with alternative fuels. Retrofitting CO_2 capture equipment can enable the continued operation of existing plants, as well as associated infrastructure and supply chains, but with significantly reduced emissions. In the power sector, this can contribute to energy security objectives by supporting greater diversity in generation options and the integration of growing shares of variable renewables with flexible dispatchable power (see Chapter 2). Retrofitting facilities with CCUS can also help to preserve employment and economic prosperity in regions that rely on emissions-intensive industry, while avoiding the economic and social disruption of early retirements. To illustrate the potential significance, Germany's plans to retire around 40 GW of coal-fired generation capacity before 2038 is accompanied by a EUR 40 billion (USD 45 billion) package to compensate the owners of coal mines and power plants as well as support the communities that will be affected (BMWi, 2020).

Figure 1.1 Global energy sector CO_2 emissions from existing power and industrial facilities, 2019-50



Notes: Includes assets under construction in 2018. Analysis includes industrial process emissions, and emissions are accounted on a direct basis. Annual operating hours over the remaining lifetime are kept as in 2018.

Emissions from today's power and industrial assets could still be generating around 8 Gt of CO_2 in 2050, if allowed to operate until the end of their technical lives.

A solution for sectors with hard-to-abate emissions

Meeting net-zero goals requires tackling emissions across all energy sectors, including those that are sometimes labelled as "hard to abate". This includes heavy industry, which accounts for almost 20% of global CO_2 emissions,[1] as well as long-distance modes of transport, including aviation, road freight and maritime shipping. In these sectors, alternatives to fossil fuels are either prohibitively expensive, such as electricity to generate extreme heat, or impractical, such as electric-powered aircraft or tankers.

[1] Including industrial process emissions. *Heavy industry* encompasses cement, steel and chemicals production.

In practice, some sectors will simply not be able to achieve net-zero emissions without CCUS. Cement production is a prime example: it generates significant process emissions, as it involves heating limestone (calcium carbonate) to break it down into calcium oxide and CO_2. These process emissions – which are not associated with fossil fuel use – account for around two-thirds of the 2.4 Gt of emissions from global cement production and more than 4% of all energy sector emissions. With no demonstrated alternative way of producing cement, capturing and permanently storing these CO_2 emissions is effectively the only option.

In other sectors, CCUS is one of few available technologies that can yield significant emissions reductions. In the iron and steel sector, production routes based on CCUS are currently the most advanced and least-cost low-carbon options for the production of virgin steel[2] which accounts for around 70% of global steel production. In chemicals, CCUS is often the cheapest option for reducing emissions from the production of fertiliser (ammonia) and methanol.

CCUS is also the only solution to address CO_2 emissions from natural gas processing, which is important given the continued use of natural gas across the energy system over the next decades (IEA, 2020a). Natural gas deposits can contain large amounts of CO_2 – even up to 90% – which, for technical reasons, must be removed before the gas is sold or processed for liquefied natural gas (LNG) production. This CO_2 is typically vented to the atmosphere but can instead be reinjected into geological formations or used for EOR.

CCUS is also among a limited number of options that can decarbonise long-distance transport, including aviation. A supply of CO_2 is needed to produce synthetic hydrocarbon fuels, which alongside biofuels are the only practical alternative to fossil fuels for long-haul flights due to energy density requirements. Limitations on the availability of sustainable biomass mean that these synthetic fuels will be needed for net-zero emissions; the CO_2 would need to come from bioenergy production or the air to be carbon-neutral (see Chapter 2).

A platform for low-carbon hydrogen production

Hydrogen is a versatile energy carrier that can support the decarbonisation of a range of sectors, including transport, industry, power and buildings (IEA, 2019a). CCUS can facilitate the production of clean hydrogen from natural gas or coal, which are the

[2] Steel that is not made from recycled material.

sources of practically all hydrogen production today, and provide an opportunity to bring low-carbon hydrogen into new markets in the near term at least cost.

Today, the cost of CCUS-equipped hydrogen production can be around half that of producing hydrogen through electrolysis powered by renewables-based electricity (which splits water into hydrogen and oxygen). The costs of electrolytic hydrogen will certainly decline over time, with cheaper electrolysers and renewable electricity, but CCUS-equipped hydrogen will most likely remain a competitive option in regions with low-cost fossil fuels and CO_2 storage resources. CCUS also offers an opportunity to address emissions from existing hydrogen production that almost exclusively relies on natural gas and coal and is associated with more than 800 $MtCO_2$ each year.

Removing carbon from the atmosphere

Meeting international climate goals, including net-zero emissions, will almost certainly require some form of carbon removal. There are multiple approaches to removing carbon from the atmosphere, including nature-based solutions such as afforestation and reforestation or enhanced natural processes such as the addition of biochar (charcoal produced from biomass) to soils. Technology-based carbon removal solutions are underpinned by CCUS, namely BECCS and DACS.

The role for carbon removal in meeting ambitious climate goals was emphasised by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on 1.5°C. Out of 90 scenarios considered by the IPCC, 88 assumed some level of net-negative emissions to limit future temperature increases to 1.5°C (IEA, 2019b). Carbon removal can neutralise or offset emissions where direct mitigation is currently technically challenging or prohibitively expensive, such as some industrial processes and long-distance transport. Carbon removal is also a hedge – although not a substitute – against the risk of slower-than-expected innovation or commercialisation of other technologies. BECCS and DACS are an energy sector contribution to carbon removal and, if successfully deployed, can also mitigate slower progress in emissions reductions outside the energy sector. Unlike BECCS, DACS is not limited by the availability of sustainable biomass but rather the availability of low-cost energy (see Chapter 2).

CCUS deployment today

Today, there are 21 CCUS facilities around the world with capacity to capture up to 40 $MtCO_2$ each year (Table 1.1).[3] Some of these facilities have been operating since the 1970s and 1980s, when natural gas processing plants in the Val Verde area of Texas began capturing CO_2 and supplying it to local oil producers for EOR operations.[4]

Since these early projects, CCUS deployment has expanded to more regions and more applications. The first large-scale CO_2 capture and injection project with dedicated CO_2 storage and monitoring was commissioned at the Sleipner offshore gas field in Norway in 1996, which has now stored more than 20 $MtCO_2$ in a deep saline aquifer. For technical and commercial reasons, the CO_2 needs to be removed from the gas before it can be sold; a CO_2 tax on offshore oil and gas activities introduced by the Norwegian government in 1991 made the project commercially viable (IEA, 2016).

Table 1.1 Large-scale commercial CCUS projects in operation in 2020

Country	Project	Operation date	Source of CO_2	CO_2 capture capacity (Mt/year)	Primary storage type
United States (US)	Terrell natural gas plants (formerly Val Verde)	1972	Natural gas processing	0.5	EOR
US	Enid fertiliser	1982	Fertiliser production	0.7	EOR
US	Shute Creek gas processing facility	1986	Natural gas processing	7.0	EOR
Norway	Sleipner CO_2 storage project	1996	Natural gas processing	1.0	Dedicated
US/Canada	Great Plains Synfuels (Weyburn/Midale)	2000	Synthetic natural gas	3.0	EOR

[3] One facility, the Petra Nova coal-fired power generation plant in the United States, has temporarily suspended CO_2 capture operations in response to low oil prices (see below).

[4] CO_2-EOR is a proven technology for rejuvenating the production of oil at mature oilfields but can also provide a means of storing CO_2 permanently, as much of the gas injected is ultimately retained in the reservoir over the life of the project. For a CO_2-EOR/CCUS project to be considered a genuine climate mitigation measure, the CO_2 has to come from an anthropogenic source, such as a power station or natural gas processing plant. In practice, about 70% of the CO_2 used in United States EOR projects today comes from naturally occurring underground reservoirs (not included here as CCUS). Several additional activities would also need to be undertaken before, during and following CO_2 injection, including additional measurement, reporting and verification of stored volumes.

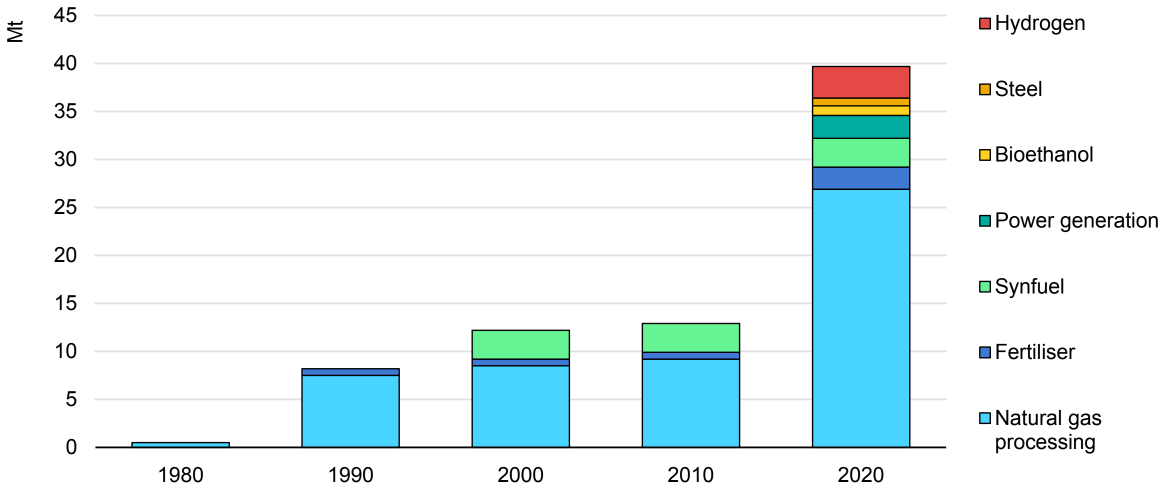
Country	Project	Operation date	Source of CO_2	CO_2 capture capacity (Mt/year)	Primary storage type
Norway	Snohvit CO_2 storage project	2008	Natural gas processing	0.7	Dedicated
US	Century plant	2010	Natural gas processing	8.4	EOR
US	Air Products steam methane reformer	2013	Hydrogen production	1.0	EOR
US	Lost Cabin Gas Plant	2013	Natural gas processing	0.9	EOR
US	Coffeyville Gasification	2013	Fertiliser production	1.0	EOR
Brazil	Petrobras Santos Basin pre-salt oilfield CCS	2013	Natural gas processing	3.0	EOR
Canada	Boundary Dam CCS	2014	Power generation (coal)	1.0	EOR
Saudi Arabia	Uthmaniyah CO_2-EOR demonstration	2015	Natural gas processing	0.8	EOR
Canada	Quest	2015	Hydrogen production	1.0	Dedicated
United Arab Emirates	Abu Dhabi CCS	2016	Iron and steel production	0.8	EOR
US	Petra Nova	2017	Power generation (coal)	1.4	EOR
US	Illinois Industrial	2017	Ethanol production	1.0	Dedicated
China	Jilin oilfield CO_2-EOR	2018	Natural gas processing	0.6	EOR
Australia	Gorgon Carbon Dioxide Injection	2019	Natural gas processing	3.4-4.0	Dedicated
Canada	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 stream	2020	Fertiliser production	0.3-0.6	EOR
Canada	ACTL with North West Sturgeon Refinery CO_2 stream	2020	Hydrogen production	1.2-1.4	EOR

Note: Large-scale is defined as involving the capture of at least 0.8 Mt/year of CO_2 for a coal-based power plant and 0.4 Mt/year for other emissions-intensive industrial facilities (including natural gas-based power generation).
Source: GCCSI (2019), The Global Status of CCS 2019: Targeting Climate Change.

The deployment of carbon capture to date has been concentrated in the United States, which is home to almost half of all operating facilities. This is due in large part to the availability of an extensive CO_2 pipeline network and demand for CO_2 for EOR, as well as public funding programmes, including those introduced after the global financial crisis of 2008-09. In the last decade, CCUS facilities have been commissioned in Australia, Brazil, Canada, China, Saudi Arabia and the United Arab Emirates.

Many of the early CCUS projects focused on industrial applications where CO_2 can be captured at relatively low additional cost, from around USD 15/tCO_2. For example, in natural gas processing, any CO_2 contained in the gas usually needs to be separated out to meet market requirements or prior to liquefaction for LNG production to avoid the CO_2 freezing and damaging the production facilities. In other applications, such as bioethanol production (the Illinois Industrial project in the United States) or steam methane reformers to produce hydrogen (such as Quest in Canada), the CO_2 stream is relatively concentrated, which reduces the cost and the amount of energy required in the capture process. Until the 2000s, virtually all the CO_2 captured globally at large-scale facilities came from gas processing plants, but other sources now make up about one-third of the total (Figure 1.2)[5].

Figure 1.2 Global CO_2 capture capacity at large-scale facilities by source



Source: IEA analysis based on GCCSI (2020), Facilities Database, https://co2re.co/FacilityData.

Carbon capture facilities have been operating since the 1970s, with the number and type of applications expanding in the last decade.

[5] This includes CO_2 capture at integrated CCUS facilities where the CO_2 is capture and used in EOR or permanently stored. It does not include CO_2 generated in ammonia production and used on-site to manufacture urea (as this use of CO_2 is not associated with a climate benefit).

CCUS deployment tripled over the last decade, albeit from a low base – but it has fallen well short of expectations. In 2009, the IEA roadmap for CCUS set a target of developing 100 large-scale CCUS projects between 2010 and 2020 to meet global climate goals, storing around 300 $MtCO_2$ per year (IEA, 2009). Actual capacity is only around 40 Mt – just 13% of the target.

Investment in CCUS has also fallen well behind that of other clean energy technologies. Annual investment in CCUS has consistently accounted for less than 0.5% of global investment in clean energy and efficiency technologies (IEA, 2020b). Since 2010, around USD 15 billion in capital has been invested in the 15 large-scale CCUS projects that have been commissioned as well as the Kemper County CCUS facility, which was abandoned in 2017 (IEA, 2017). The investment in these facilities was supported by around USD 2.8 billion in public grant funding (see Chapter 5).[6]

There are several reasons CCUS has not advanced as fast as needed; many planned projects have not progressed due to commercial considerations and a lack of consistent policy support. In the absence of an incentive or emissions penalty, CCUS may simply not make any commercial sense, especially where the CO_2 has no significant value as an industrial input. The high cost of installing the infrastructure and difficulties in integrating the different elements of the CO_2 supply chain, technical risks associated with installing or scaling up CCUS facilities in some applications, difficulties in allocating commercial risk among project partners, and problems securing financing have also impeded investment. Public resistance to storage, particularly onshore storage, has also played a role in some cases, notably in Europe. CCUS is also often viewed as a fossil fuel technology that competes with renewable energy for public and private investment, although in practice it has substantial synergies with renewables (see Chapter 2).

Growing CCUS momentum

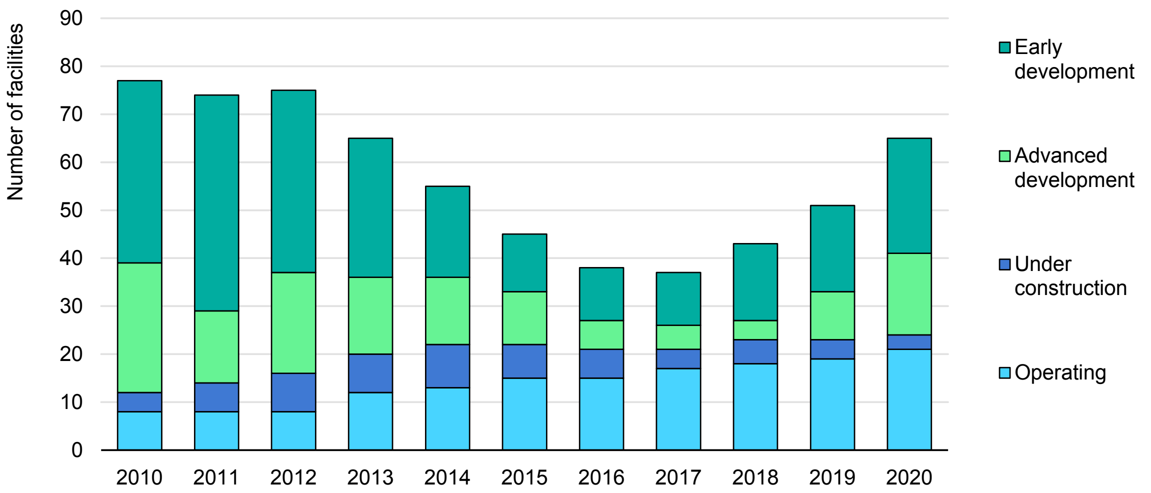
CCUS may not be a new technology or concept, but it has been the subject of renewed global interest and attention in recent years, holding out the promise of a rapid scaling-up of investment, wider deployment and accelerated innovation. The pipeline of new CCUS projects has been growing, underpinned by strengthened national climate targets and new policy incentives. CCUS costs have been declining, new business models that can improve the financial viability of CCUS have emerged,

[6] An estimated USD 6.2 billion was invested in developing a new integrated gas combined cycle technology at the Kemper County CCUS facility, which was abandoned in 2017 after significant cost overruns.

and technologies associated with CO_2 use and carbon removal are advancing and attracting interest from policy makers and investors.

After years of a declining investment pipeline, plans for more than 30 new integrated CCUS facilities have been announced since 2017 (Figure 1.3). The vast majority are in the United States and Europe, but projects are also planned in Australia, China, Korea, the Middle East and New Zealand. If all these projects were to proceed, the amount of global CO_2 capture capacity would more than triple, to around 130 Mt/year. The 16 projects at advanced stages of planning, including several facing a final investment decision (FID) within the next 12 months, represent a total estimated investment of more than USD 27 billion. This is almost double the investment in projects commissioned since 2010 and around 2.5 times the planned investment in projects at a similar stage of development in 2017.

Figure 1.3 Global large-scale CCUS facilities operating and in development

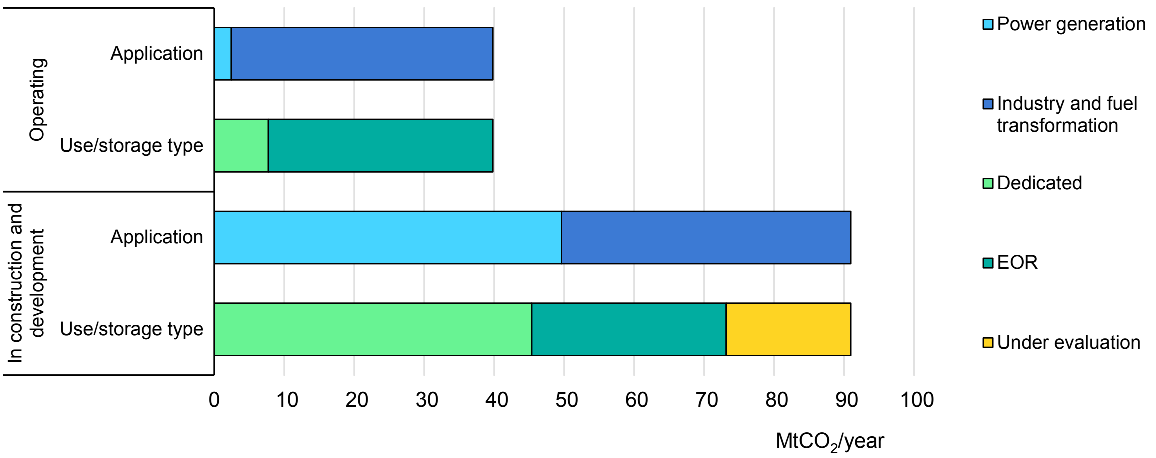


Notes: Includes the Petra Nova coal-fired power plant, which temporarily suspended CO_2 capture operations in May 2020 in response to low oil prices.
Source: IEA analysis based on GCCSI (2020), Facilities Database, https://co2re.co/FacilityData,

Plans for more than 30 new large-scale integrated CCUS facilities have been announced since 2017.

Although some projects might fall by the wayside, the new investment plans for CCUS, if realised, will push the technology further along the learning curve, contribute to infrastructure development and further reduce unit costs. Importantly, several of the planned projects go beyond the "low-hanging fruit" opportunities associated with natural gas processing to include less developed applications, including coal- and gas-fired power generation and cement production. There is also less reliance on EOR, which has been a major driver of CCUS investment to date (16 of the 21 capture facilities in operation sell or use the CO_2 for EOR). Less than half of the planned facilities are linked to EOR, with a shift towards dedicated CO_2 storage options (Figure 1.4). Almost one-third of planned projects involve the development of industrial CCUS hubs with shared CO_2 transport and storage infrastructure.

Figure 1.4 Large-scale CCUS projects in development worldwide by application and storage type



Notes: Includes the Petra Nova coal-fired power plant, which temporarily suspended CO_2 capture operations in May 2020 in response to low oil prices.
Source: IEA analysis based on GCCSI (2020), Facilities Database, https://co2re.co/FacilityData.

The completion of large-scale CCUS facilities in the pipeline would make power generation the leading application and expand by a factor of five the amount of dedicated CO_2 storage.

The large-scale deployment of CCUS provides an important indicator of the state of technology development, but does not convey the entire CCUS story. In addition to major commercial projects, there are a large number of pilot and demonstration-scale CCUS facilities operating around the world, as well as numerous CCUS technology test centres (GCCSI, 2020). There are also a growing number of facilities making use of CO_2 (see Chapter 3).

What is driving renewed momentum?

Strengthened climate commitments

The more stringent climate targets triggered by the greater ambition of the 2015 Paris Agreement and the 2018 IPCC Special Report on 1.5°C have spurred greater interest in mitigation options that go beyond renewables or power generation, including

CCUS. There is also increased focus on technology opportunities to reduce emissions where they are hard to abate, given the need to fully decarbonise the entire energy sector to reach net zero.

An increasing number of countries and organisations have adopted net-zero emissions targets, drawing attention to the need for CCUS. By August 2020, 14 countries and the European Union (EU) – representing around 10% of energy-related global CO_2 emissions – had adopted formal net-zero emissions targets in national law or proposed legislation to that effect, with a target date of 2045, 2050 or beyond (IEA, 2020a). Similar targets are under discussion in about 100 other countries.

CCUS also features in the mid-century climate strategies that parties to the Paris Agreement are invited to submit this year. Of the 16 country strategies submitted by August 2020, nine referenced a role for CCUS: Canada, France, Germany, Japan, Mexico, Portugal, Singapore, the United Kingdom (UK) and the United States (UNFCCC, 2020). Together, these countries account for 96% of the total energy-related CO_2 emissions of those countries that have submitted mid-century strategies.

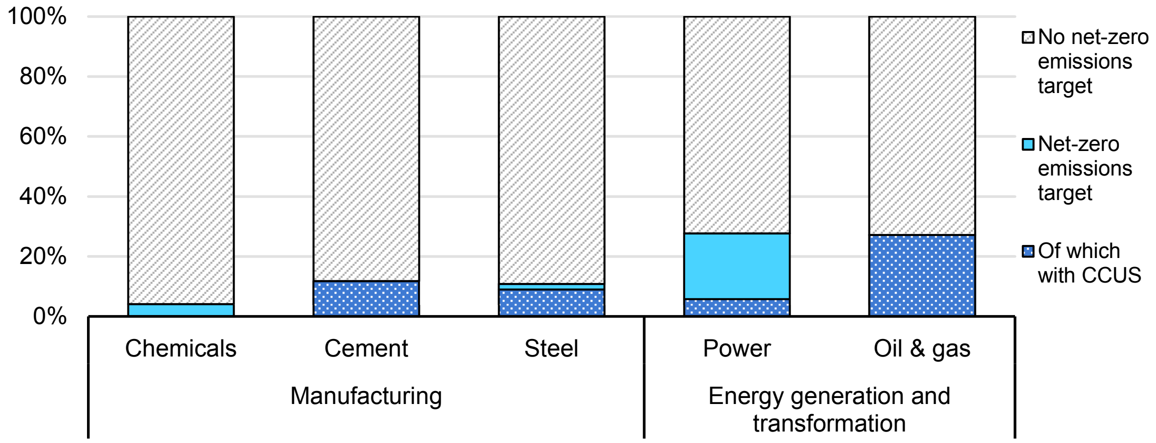
A growing number of corporations across a range of industry sectors, including oil and gas, power generation, manufacturing, transport, and technology services, are also adopting net-zero emissions targets (IEA, 2020a). The level of detail and approach to meeting these commitments varies, including in the coverage of emissions across the value chain.[7] More than 20% of global oil and gas production is covered by 2050 net-zero commitments, with CCUS expected to play a role in every case (Figure 1.5). Companies such as Dalmia Cement and Heidelberg Cement in the cement sector and ArcelorMittal in steel are actively pursuing CCUS to meet their goals.

Carbon removal approaches are to the fore in meeting commitments in other sectors, notably aviation. To date, all airline companies that have adopted net-zero goals have identified the need for offsets from other sectors, primarily relying on nature-based solutions such as reforestation (IEA, 2020a). Microsoft announced in January 2020 that it aims to become carbon negative by 2030, and by 2050 it plans to have removed from the atmosphere all the carbon that it has emitted since it was founded in 1975 (Microsoft, 2020). This would be achieved through a portfolio of solutions, potentially including afforestation and reforestation, soil carbon sequestration,

[7] For example, some companies include the use of the commodity or product being sold while others include only the company's operations.

BECCS, and DACS. Microsoft is establishing a USD 1 billion climate innovation fund to accelerate the global development of carbon reduction, capture and removal technologies.

Figure 1.5 Share of activity covered by corporate carbon-neutral targets in select sectors, with an identified role for CCUS



CCUS is seen as an important measure for meeting corporate climate commitments, particularly in the oil and gas and manufacturing sectors.

Improved investment environment

The growing pipeline of CCUS facilities also reflects a considerably improved investment environment, underpinned by new policy incentives.[8] In the United States, the expansion of the 45Q tax credit alongside complementary policies – such as the California Low Carbon Fuel Standard (LCFS) – has spurred a large number of new investment plans. The expanded tax credit, introduced in 2018, provides a credit of USD 50/t for CO_2 that is permanently stored and USD 35/t for CO_2 used in EOR or other beneficial uses, for 12 years from the commencement of operation of the project (see Chapter 4).

In Europe, the EU Innovation Fund for demonstrating innovative low-carbon technologies and funded by revenues from the Emissions Trading System (ETS) – valued at EUR 10 billion at current CO_2 prices – will be able to support CCUS projects among other clean energy technologies from 2020 (European Commission, 2020). Norway is also funding the development of a full-chain CCUS project – Longship – , involving CO_2 capture at a cement factory and a waste-to-energy plant and its storage

[8] See Chapter 5 for a discussion of existing and potential policy measures for CCUS.

in a large facility in the North Sea – Northern Lights – being developed by a consortium of oil and gas companies. The Netherlands is expanding its SDE+ support scheme to a wider set of clean energy technologies, including CCUS and low-carbon hydrogen (SDE++). The UK government has also announced significant public funding for new CCUS projects.

Deployment strategies that shift the focus from large, stand-alone CCUS facilities to the development of industrial "hubs" with shared CO_2 transport and storage infrastructure are also opening up new investment opportunities. This approach can improve the economics of CCUS by reducing unit costs through economies of scale as well as reducing commercial risk and financing costs by separating out the capture, transport and storage components of the CCUS chain (Box 1.2). The development of shared infrastructure can also be a major trigger for new investments. For example, the development of the Northern Lights CO_2 storage project – the central component of Norway's Longship project – is linked to the potential development of at least nine capture facilities across Europe, including four cement factories and a steel plant (Northern Lights PCI, 2020). Plans to equip these facilities with CO_2 capture would probably not have materialised in the absence of a potential CO_2 storage solution.

Box 1.2 The role of hubs in accelerating deployment of CCUS

The development of CCUS hubs – industrial centres with shared CO_2 transport and storage infrastructure – could play a critical role in accelerating the deployment of CCUS. Efforts to develop CCUS hubs have commenced in at least 12 locations around the world. These hubs have an initial CO_2 capture capacity of around 25 Mt/year, but could be expanded to more than 50 Mt/year. A major legal barrier to the development of CCUS was resolved in 2019 when Norway and the Netherlands secured an amendment to the London Protocol to permit cross-border transportation of CO_2 (see Chapter 4).

The principal benefit of a "hub" approach to CCUS deployment is the possibility of sharing CO_2 transport and storage infrastructure. This can support economies of scale and reduce unit costs, including through greater efficiencies and reduced duplication in the infrastructure planning and development phases. The initial oversizing of infrastructure increases the capital cost of the project and so can make it harder to raise financing, but it can reduce unit transport and storage costs substantially in the longer term. For example, the Zero Emissions Platform estimates that the cost of transporting CO_2 through a 180 km onshore pipeline in Europe would equate to around EUR 5.4/t with a capacity of 2.5 Mt/year of CO_2 – 70% higher than the cost of

EUR 1.5/t for the same length pipeline but with a capacity of 20 Mt/year (ZEP, 2011). For an average cement plant capturing around 0.5 Mt/year of CO_2, this would represent an annual cost saving of almost EUR 2 million.

Developing CCUS hubs with shared infrastructure can also make it feasible to capture CO_2 at smaller industrial facilities, for which dedicated CO_2 transport and storage infrastructure may be both impractical and uneconomic. It can allow continued operation of existing infrastructure and supply chains in industrial regions, maintaining employment and making it easier to attract new investment, including in energy-intensive industries or low-carbon hydrogen production, while respecting emissions reduction targets.

Government leadership and co-ordination are vitally important to the early development of CCUS hubs in most regions, notably in supporting or underwriting investment in new CO_2 transport and storage infrastructure (see Chapter 5). This can help to overcome the initial "chicken and egg" problem with CCUS – there is no point in capturing the CO_2 if there is nowhere to store it and there is no point in developing storage if there is no CO_2. In Canada, the Alberta Carbon Trunk Line (ACTL), which came online in June 2020, is an example of strong government support for CO_2 transport infrastructure to enable the future expansion of CCUS. The 240 km pipeline has been oversized with almost 90% of its capacity available to accommodate future CO_2 sources (ACTL, 2020).

Technological advances

Experience with building and operating CCUS facilities has contributed to progressive improvements in CCUS technologies as well as significant cost reductions. At around USD 65/t of CO_2, the cost of capture at the Petra Nova coal-fired power plant in Houston (commissioned in 2017) is more than 30% lower than the Boundary Dam facility in Canada – the only other commercial coal plant with capture facilities – which started operations in 2014. Detailed engineering studies show that retrofitting a coal-fired power plant today could cost around USD 45/t (International CCS Knowledge Centre, 2018). There are now plans to retrofit as many as ten coal power plants with capture equipment (in China, Korea and the United States). With further research, development and demonstration (RD&D) and growing practical experience, there is considerable potential to further reduce energy needs and costs (see Chapter 3).

New technologies and ways for using or recycling CO_2 other than EOR, such as to produce synthetic fuels or building materials, are emerging, potentially boosting demand for CO_2. The growing interest in these technologies is reflected in increasing support from governments, industry and investors, with global private funding for CO_2 use start-ups reaching nearly USD 1 billion over the last decade (IEA, 2019c). Several governments and agencies have been supporting innovation related to CO_2 conversion technologies. For example, in June 2019, Japan released a Carbon Recycling Roadmap highlighting opportunities to commercialise CO_2 use technologies over the next decade (METI, 2019). Additionally, several prize initiatives have been held with the aim of promoting the development of CO_2 conversion technologies, awarding a prize to the most innovative CO_2 use applications. A notable example is the NRG COSIA Carbon XPrize (NRG COSIA XPRIZE, 2019).

DAC technologies are also making significant progress and attracting investment from a range of stakeholders. Since 2019, around USD 180 million in private investment has been raised by leading developers alongside more than USD 170 million in public funding for research and development. A number of small-scale DAC facilities are operating commercially today, and a planned large-scale facility in the United States, with capacity to capture 1 $MtCO_2$ per year, could be operational by the mid-2020s.

Will the Covid-19 crisis derail momentum?

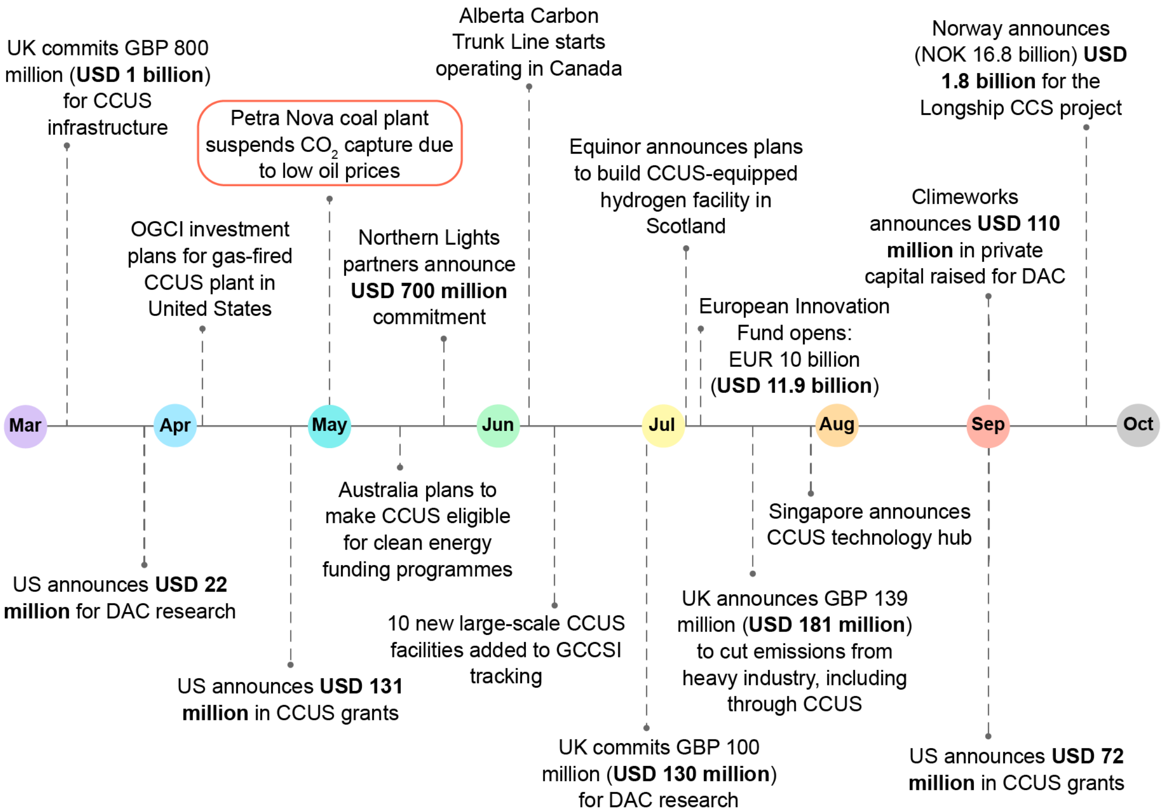
The response to the Covid-19 crisis has driven the world into a deep recession, which will almost certainly affect investment plans for CCUS. The slump in economic activity is likely to curb interest in new CCUS projects, at least in the near term, but this could be partially or wholly offset by fresh government incentives for CCUS and other clean energy technologies as part of economic recovery programmes currently under development.

With the global economy set to shrink by several percentage points in 2020 and gross domestic product (GDP) expected to contract in nearly every country, investment in clean energy technologies could plunge by as much as 20% (IEA, 2020b). This has prompted governments around the world to draw up plans to invest massively to stimulate economic recovery. The IEA has called for governments to put clean energy at the heart of stimulus packages and, in July 2020, released the Sustainable Recovery Plan – a set of actions that can be taken over the next three years to promote economic growth through investment in clean energy. The IEA estimates that implementing this plan could boost global economic growth by 1.1% per year and save or create 9 million jobs while avoiding a rebound in emissions (IEA, 2020c).

CCUS developments in 2020

Despite the economic and investment uncertainty created by the Covid-19 crisis, the prospects for CCUS have been boosted by a number of new funding announcements and project developments since the beginning of 2020 (Figure 1.6). In March, the UK government confirmed its pledge to invest GBP 800 million (USD 995 million) in CCUS infrastructure, involving establishing CCUS in at least two industrial locations and equipping a gas-fired power plant with CCUS. In July, it announced additional investment of GBP 139 million (USD 178 million) to cut emissions from heavy industry, including through CCUS. In April, the US government awarded USD 85 million in grants and announced a further USD 46 million in new grants for CCUS development and deployment, followed by an additional USD 72 million in funding in September (DOE, 2020a, 2020b). In May, the Australian government announced plans to make CCUS eligible for existing funding programmes for clean technologies, including via the Clean Energy Finance Corporation's AUD 10 billion (USD 7.1 million) investment fund (Australian Government, 2020). In September 2020, the Norwegian government announced it would provide NOK 16.8 billion (USD 1.8 billion) in funding for the Longship CCS project (formerly called the "Full-Scale CCS Project), including ten years of operating support. The total cost of the Longship project is estimated at NOK 25.1 billion (USD 2.7 billion).

Figure 1.6 Timeline of CCUS developments, March-September 2020



A number of new CCUS projects and investment incentives have been announced in 2020, but momentum is threatened by the economic downturn.

The private sector has also announced several new CCUS investments. In April 2020, the Oil and Gas Climate Initiative (OGCI) – a group of 13 international oil and gas companies – announced it would invest in equipping a natural gas power plant in the United States with CCUS (OGCI, 2020). A month later, Equinor, Shell and Total announced plans to invest more than USD 700 million in the Northern Lights offshore CO_2 storage project, subject to government support (Equinor, 2020a). In July, Equinor announced it would lead a project – H2H Saltend – to produce hydrogen from natural gas with CCUS in the Humber region of the United Kingdom (Equinor, 2020b).

Spending on DAC research has also expanded since the start of 2020. In March, the US Department of Energy announced USD 22 million in funding for DAC. In June, the UK government allocated GBP 100 million (USD 128 million) to the technology. In addition, Climeworks – one of the leading DAC technology developers – announced in September 2020 that it had raised 100 million Swiss francs (USD 110 million), the largest private investment for DAC (Climeworks, 2020).

The impact of the economic downturn and lower oil prices

Notwithstanding these positive developments in 2020, CCUS investments will almost certainly be vulnerable to delays and cancellations due to the global economic downturn. In particular, oil and gas companies, which are involved in more than half of planned CCUS projects, have announced significant capital spending cuts for 2020.

In the United States, the attractiveness of the 45Q tax credit – a major driver of new investments – is likely to diminish as profits slump and corporate tax liabilities fall. Any delays to projects would also have a significant impact on their eligibility for credits, as facilities must be in construction before 1 January 2024 to qualify under current arrangements. Projects unable to meet this deadline are far less likely to proceed.

Another important consideration is the impact of low oil prices on the demand and price for CO_2 used in EOR. Two-thirds of operating CCUS facilities rely on revenue from sales of CO_2 for EOR, and more than one-third of planned projects are linked to EOR (GCCSI, 2020). The price paid for CO_2 for EOR is typically indexed to the oil price in commercial contracts, so the recent slump in oil demand and prices will have substantially reduced revenues for CCUS facilities.

Low oil prices led NRG, the operator of the Petra Nova coal-fired power plant in Texas, to suspend CO_2 capture operations at the plant in May 2020. The plant has a CO_2 capture capacity of 1.4 Mt/year, with the CO_2 transported by a 132 km pipeline to the West Ranch oilfield southwest of Houston for EOR. According to NRG, crude oil prices in excess of USD 60/bbl to USD 65/bbl are required to cover the operating costs of the capture facilities, while the price of West Texas Intermediate has averaged less than USD 40/barrel between January and August 2020 and USD 17/barrel in April (NRG, 2020a). Petra Nova is the only CCUS facility in the United States capturing CO_2 from a relatively dilute source, which is associated with higher capture costs.[9] This highlights the risks of business models linked to EOR revenue – especially for these higher-cost CCUS applications. NRG has stated that it will bring the facility back online "when economic conditions improve" (NRG, 2020b).

An extended period of low oil prices and demand would undoubtedly undermine planned investment in CCUS projects linked to EOR. The risk of project delays or cancellations is generally higher for CCUS projects at early stages of development, or in regions where the use of CO_2 for EOR is still relatively limited and where expansions require significant new injections of capital for EOR infrastructure.

In the United States, demand for CO_2 for EOR may be more resilient. Around 80 $MtCO_2$ is used for EOR today, with around 70% of this extracted from declining natural CO_2 deposits. An increase in the availability of CO_2 captured from power or industrial CCUS facilities could displace the use of this naturally occurring CO_2, without requiring an expansion in demand or significant new EOR infrastructure. Further, the availability of the 45Q tax credits could act as a commercial buffer during periods of low CO_2 prices. However, capture projects may opt for dedicated geological storage, which attracts a higher tax credit, as a more financially attractive and stable alternative, especially if oil prices remain low for a long time.

CCUS in economic recovery plans

The inclusion of CCUS in economic recovery plans and programmes could help ensure that the Covid-related economic downturn does not derail recent progress in deploying the technology. A collective push by all stakeholders is needed to exploit recent progress and drive a major leap forward in deployment. Governments have a key role to play in incentivising investment, as well as co-ordinating and underwriting new transport and storage infrastructure. The development of economic stimulus packages presents a critical window of opportunity for governments to support investment in a technology that will be needed to meet their climate goals. The IEA Sustainable Recovery Plan identified boosting innovation in CCUS and other crucial

[9] The other nine large-scale CCUS facilities in the United States capture CO_2 from more concentrated sources; see Chapter 3 for discussion on the impact of this on costs.

technologies, including hydrogen, batteries and small modular nuclear reactors, as one of six key objectives for economic stimulus packages.

CCUS is in a stronger position to contribute to sustainable economic recovery plans than after the global financial crisis in 2008-09 (see Box 1.3). A decade of experience in developing projects and the recent uptick in activity means that there are a number of advanced "shovel-ready" projects with potential to double CCUS deployment and create thousands of jobs worldwide by 2025. As discussed above, the pipeline of at least 16 advanced projects could represent a potential investment of more than USD 27 billion and an additional 50 Mt/year of CO_2 capture capacity. For several of these projects, a FID is imminent, and construction could begin as early as 2021. These projects are well aligned with government goals of boosting economic activity in the near term while providing the foundation to meet long-term energy and climate goals. However, almost all will rely on some form of government support to overcome the commercial barriers associated with early deployment.

Box 1.3 Economic stimulus funding for CCUS after the global financial crisis of 2008-09

Government efforts to boost the deployment of CCUS after the global financial crisis were met with relatively limited success. Initially, more than USD 8.5 billion was made available to support as many as 27 integrated projects around the world. This included funding through the American Recovery and Reinvestment Act 2009 and the European Energy Programme for Recovery, as well as measures in Australia, Canada and the United Kingdom. Ultimately, however, less than 30% of this funding was spent, and only five projects are today operating as a direct result of these stimulus measures, all of them in North America.*

A number of factors explain this lack of success, including the relatively limited experience in CCUS deployment at the time as well as the way the programmes were designed:

- Many projects were not sufficiently advanced to be able to meet near-term stimulus spending milestones. It can take several years to plan and build CCUS facilities, particularly for newer applications (such as power generation or in heavy industry). For example, the US government aimed to spend USD 1 billion in grants on the FutureGen project in less than five years under the American Recovery and Reinvestment Act, but it took almost four years to obtain the approvals for what was the country's very first CO_2 injection permit for dedicated storage (Congressional Research Service, 2016).

- The focus of policy makers in many regions, including Europe, was on coal-fired power, which is an important but also a more expensive and complex application for CCUS. Where industrial facilities with high-concentration CO_2 streams (and therefore lower-cost capture) were targeted, stimulus measures met with greater success.
- Support was generally limited to capital grants for one-off projects rather than establishing a framework for broader investment. In some cases, the absence of measures to address the higher operating costs for CCUS facilities, for example through feed-in tariffs or tax credits, was cited as a reason for cancelling projects.

Despite these difficulties, the five stimulus projects that did go ahead have made an important contribution to CCUS technology development and cost reductions. Collectively, they have captured more than 15 $MtCO_2$ to August 2020. The developers of Petra Nova (coal-fired power) and Quest (hydrogen) claim that capital costs would be around 30% lower if they were to rebuild these facilities today.

* These projects are the Petra Nova CCUS retrofit project (coal power, United States); the Illinois Industrial CCS project (bioethanol production, United States); Air Products steam methane reformer (hydrogen, United States); Quest (hydrogen, Canada); and the ACTL (fertiliser and oil refining, Canada).

A number of planned projects could benefit quickly from economic stimulus packages, bringing major economic, social and environmental benefits. In Europe, the Norway Longship CCS project (including Northern Lights) is expected to generate as many as 4 000 jobs during the investment and construction phase, and 170 permanent jobs (Northern Lights PCI, 2020). In July, the European Free Trade Association (EFTA) Surveillance Authority cleared the way for the Norwegian government's support for the project under EU market rules, recognising it as "a ground-breaking step towards tackling climate change" (ESA, 2020).

A number of advanced CCUS projects are based on the development of industrial hubs, benefiting from economies of scale and reducing integration risk through shared CO_2 transport and storage infrastructure (see Box 1.2). This includes the Port of Rotterdam (Porthos) project in the Netherlands, the Net Zero Teesside project in the United Kingdom, the Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Integrated Midcontinent Stacked Carbon Storage Hub in the United States, and CarbonNet in Australia. Several of these CCUS hubs involve the production of low-carbon hydrogen.

The employment benefits of encouraging these projects – a major objective of stimulus packages – could be significant. At least 1 200 direct construction jobs could be created at each new large-scale capture facility, rising to 4 000 or more depending on location, application and size. CCUS investments would also secure existing jobs and minimise social and economic disruption by enabling the continued operation of power and industrial facilities under tighter emissions constraints. For example, the developers of the Net Zero Teesside industrial hub claim that CCUS infrastructure could safeguard between 35% and 70% of existing manufacturing jobs in the region (Net Zero Teesside, 2020).

Many of the job opportunities that will arise in the CCUS sector will also be able to make use of the subsurface skills and experience of personnel in the oil and gas sector, which has seen thousands of job losses already in 2020. These opportunities include the near-term employment needs associated with CO_2 storage exploration, as well as the more intensive phase of characterisation and development of new storage facilities.

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Chapter 2. CCUS in the transition to net-zero emissions

HIGHLIGHTS

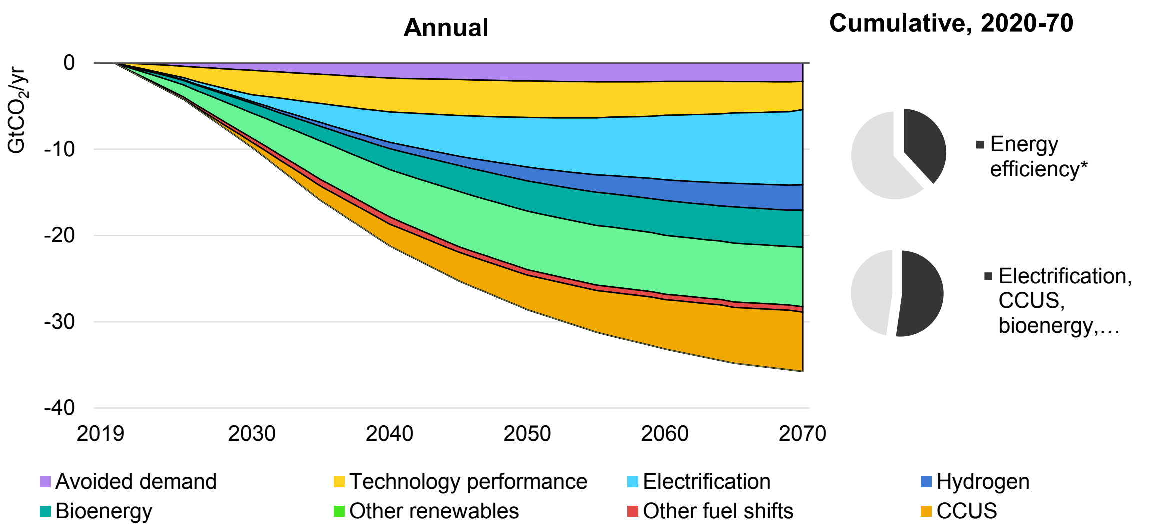
- In the IEA Sustainable Development Scenario, in which global CO_2 emissions from the energy sector fall to zero on a net basis by 2070, CCUS accounts for nearly 15% of the cumulative reduction in emissions compared with the Stated Policies Scenario. The contribution of CCUS grows over time as the technology improves, costs fall and cheaper abatement options in some sectors are exhausted. In 2070, 10.4 Gt of CO_2 is captured from across the energy sector.
- The initial focus of CCUS is on retrofitting existing fossil fuel-based power and industrial plants as well as lower-cost CO_2 capture opportunities such as hydrogen production. Over time, the focus shifts to bioenergy with CCS (BECCS) and direct air capture (DAC) for carbon removal and as a source of climate-neutral CO_2 for use in various applications, particularly synthetic fuels.
- By 2070, the power sector accounts for around 40% of the captured CO_2, almost half of it linked to bioenergy. Around one-quarter of the CO_2 captured in 2070 is in heavy industry, where emissions are hard or – in the case of process emissions in cement – currently impossible to abate in other ways. Another 30% is in the production of hydrogen, ammonia and biofuels. A further 7% comes from DAC.
- Global hydrogen use increases seven-fold to 520 Mt by 2070 and contributes to the decarbonisation of transport, industry, buildings and power. Around 6% of the cumulative emissions reductions in the Sustainable Development Scenario are from low-carbon hydrogen, with 40% of hydrogen demand met by fossil-based production equipped with CCUS in 2070.
- Carbon removal is required to balance emissions across the energy system that are technically difficult or prohibitively expensive to abate. It can also help offset emissions from outside the energy sector, should progress there be lacking. DAC technologies can play an important role alongside BECCS: the challenge will be to lower the cost of DAC, which today is very high due mainly to the large amounts of energy needed.

CCUS in the Sustainable Development Scenario

Overview

CCUS is an important technological option for reducing CO_2 emissions in the energy sector and will be essential to achieving the goal of net-zero emissions. As discussed in Chapter 1, CCUS can play four critical roles in the transition to net zero: tackling emissions from existing energy assets; as a solution for sectors where emissions are hard to abate; as a platform for clean hydrogen production; and removing carbon from the atmosphere to balance emissions that cannot be directly abated or avoided. These roles are evident in the IEA Sustainable Development Scenario, in which global CO_2 emissions from the energy sector fall to zero on a net basis by 2070 (Box 2.1). In total, CCUS contributes nearly 15% of the cumulative reduction in CO_2 emissions worldwide compared with the Stated Policies Scenario, which takes into account current national energy- and climate-related policy commitments. The contribution of CCUS to emissions reductions grows over time as the technology progresses, costs fall and other cheaper abatement options are exhausted (Figure 2.1).

Figure 2.1 Global energy sector CO_2 emissions reductions by measure in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2019-70



* Energy efficiency includes enhanced technology performance as well as shifts in end-use sectors from more energy-intensive to less energy-intensive products (including through fuel shifts).

Notes: CCUS = carbon capture, utilisation and storage. See IEA (2020a) and the ETP model documentation for the definition of each abatement measure. Hydrogen includes low-carbon hydrogen and hydrogen-derived fuels such as ammonia.

The contribution of CCUS to the transition to net-zero emissions grows over time, accounting for nearly one-sixth of cumulative emissions reductions to 2070.

Box 2.1 Analytical approach and IEA scenarios

The analysis in this report is underpinned by global projections of clean energy technologies from the IEA *Energy Technology Perspectives (ETP)* Model – a large-scale energy systems model that comprises optimisation or simulation models covering energy supply and energy use in the buildings, industry and transport sectors, representing current and future technology options across all sectors. The ETP Model has been developed over many years, using the latest data for energy demand and supply, costs, and prices.* It incorporates more than 800 technologies that are modelled individually, 230 of which are today not yet commercially deployed. The projections currently cover the period to 2070.

In line with other ETP publications, this report adopts a scenario approach to exploring the outlook for CCUS technologies and its role in the energy transition that would be required to achieve climate and broader energy sustainability goals. Projections for two main scenarios, which are also employed in the IEA flagship publication, the *World Energy Outlook*, are presented here, differentiated primarily by the assumptions they make about government policies:

- *Sustainable Development Scenario:* This scenario, which lies at the heart of *ETP 2020* and this *Special Report*, is used to illustrate the technology needs for reaching net-zero emissions from the energy sector. It describes the broad evolution of the energy sector that would be required to reach the United Nations Sustainable Development Goals (SDGs) most closely related to energy: achieving universal access to energy (SDG 7), reducing the impacts of air pollution (SDG 3.9) and tackling climate change (SDG 13). It is designed to assess what is needed to meet these goals, including the Paris Agreement, in a realistic and cost-effective way. The trajectory for energy- and industry-related CO_2 emissions is consistent with reaching global net-zero CO_2 emissions from the energy sector in 2070.
- *Stated Policies Scenario:* This scenario, which serves as a benchmark for the projections of the Sustainable Development Scenario, takes into account government policies and commitments that have already been adopted or announced with respect to energy and the environment, including commitments made in the nationally determined contributions under the Paris Agreement.

The projections for both scenarios build on those of the *World Energy Outlook 2019* (IEA, 2019a), which run to 2040. They have, however, been updated with new GDP and energy price assumptions to take into account the macroeconomic impacts of the Covid-19 pandemic.

Neither scenario should be considered a prediction or forecast, but rather an assessment of the impact of different policy approaches and technology choices on energy and emissions trends. They provide a quantitative framework to support decision and policy making in the energy sector, and to improve understanding of the need for technological innovation in energy supply and use. Any projection of energy supply or use 50 years ahead is bound to be speculative to some degree as it is impossible to know with certainty how technology will evolve. The further into the future one looks, the greater the uncertainty about how technology will change, the types of new technology that will emerge and how quickly they will be deployed.

* Full descriptions of the model and key assumptions can be found on line at: www.iea.org/reports/energy-technology-perspectives-2020/etp-model. Emerging near- and medium-term energy and emissions trends will be discussed in the forthcoming *World Energy Outlook 2020*.

Around 60% of the CO_2 captured in the period to 2070 in the Sustainable Development Scenario is from fossil fuel use; the rest is from industrial processes, bioenergy and DAC. This reflects difficulties in eliminating CO_2 emissions in certain industry sectors (and hence the need for carbon removal options), the high share of process emissions in some industries (in particular cement), the scope for capturing CO_2 in the production of biofuels for transport; and the increasing role for DAC in providing CO_2 as feedstock for producing synthetic aviation fuels as well as for removing CO_2 from the atmosphere. Fossil fuels are still the source of about half of CO_2 captured in 2070, with around one-third of this from low-carbon hydrogen production from natural gas.

When net-zero emissions are reached in 2070 in the Sustainable Development Scenario, 9.5 $GtCO_2$ is captured and stored and another 0.9 Gt is captured and used (Table 2.1 and Figure 2.2). The power sector accounts for around 40% of the captured CO_2 in 2070, with almost half of it linked to bioenergy. Around one-quarter of the CO_2 captured is in heavy industries, where emissions are hard to abate in other ways. Almost 30% is in the fuel transformation sector to produce hydrogen and ammonia from fossil fuels as well as CO_2 captured from biofuel plants, which is used to make synthetic fuels or stored for carbon removal. A further 7% comes from DAC, again, as a carbon-neutral source of CO_2 for fuel and feedstock production or to create negative emissions (DAC with CO_2 storage, or DACS). While only around 8% of total captured CO_2 is used or "recycled", it plays an important role in supporting the decarbonisation of the transport and industry sectors through the production of transport fuels and as a feedstock for the chemical industry (see below).[1]

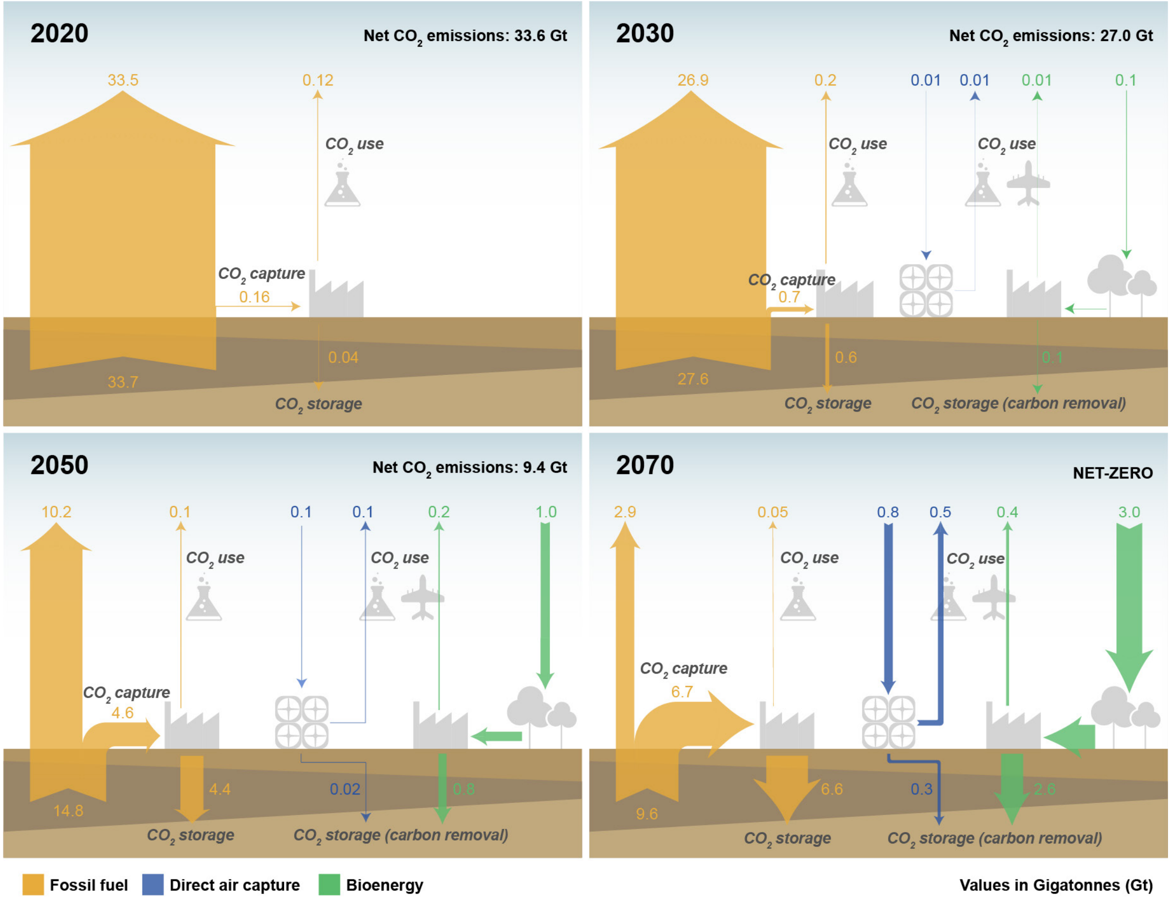
Table 2.1 Key global CCUS indicators in the Sustainable Development Scenario

	2030	2050	2070	Cumulative
Total CO_2 capture (Mt)	840	5 635	10 409	240 255
of which from coal	320	1 709	2 145	64 399
of which from oil	21	141	230	5 301
of which from natural gas	96	1 733	3 209	72 948
of which from biomass	81	955	3 010	52 257
of which from industrial processes	312	979	1 073	36 562
of which direct air capture	11	117	741	8 788
of which stored	650	5 266	9 533	220 845
of which used	189	369	877	19 409
CO_2 capture by sector (Mt)				
Industry	453	2 038	2 724	77 092
Iron & Steel	16	394	723	15 772
Chemicals	178	461	571	18 363
Cement	258	1 174	1 411	42 614
Pulp & Paper	0	8	18	343
Power generation	223	1 877	4 050	87 529
from coal	201	895	1 031	34 378
from natural gas	21	605	1 175	26 942
from biomass	0	377	1 844	26 209
Other fuel transformation	153	1 603	2 895	66 846
CO_2 removal (Mt)	76	821	2 920	47 739
Bioenergy with CO_2 capture and storage (BECCS)	75	802	2 649	45 000
Direct air capture with CO_2 storage (DACS)	1	19	271	2 739
CCUS contribution to sector CO_2 emissions reductions				
Iron & Steel	4%	25%	31%	25%
Cement	47%	63%	61%	61%
Chemicals	10%	31%	33%	28%
Fuel transformation	86%	86%	92%	90%
Power generation	3%	13%	25%	15%

Notes: Mt = million tonnes; CCUS = carbon capture, utilisation and storage; SDS = Sustainable Development Scenario; STEPS = Stated Policies Scenario. The sum of CO_2 capture by sector does not equal total CO_2 capture because it omits DAC; CO_2 removal includes only those emissions that are captured from biomass and DAC and that are permanently stored. *Industry* refers to industrial production of materials while *other fuel transformation* covers sectors such as refining, biofuels, and merchant hydrogen and ammonia production; Biomass includes waste used for energy, which makes up a minor share of the total. Capture includes internal use of CO_2 captured in the chemicals sector.

[1] The analysis considers CO_2 use only for the production of urea, methanol, liquid fuels and methane, and excludes non-energy applications (such as building materials). Early-stage CO_2 conversion technologies such as photochemical processes are excluded due to the considerable uncertainty attached to their technical performance and costs.

Figure 2.2 CO_2 emissions, capture and removal in the Sustainable Development Scenario



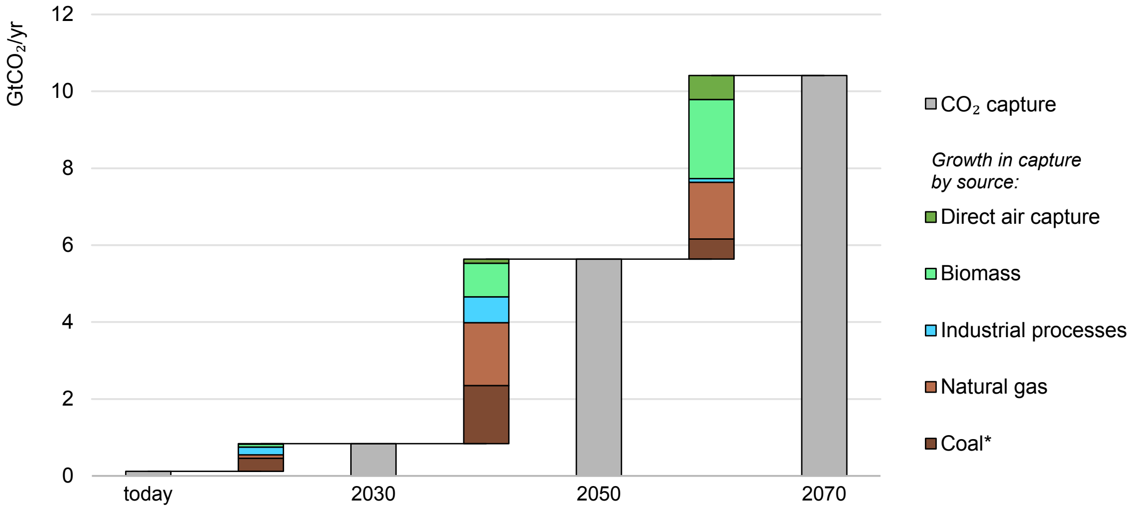
Notes: Due to rounding, some totals may not correspond with the sum. CO_2 emitted and captured from industrial processes is included with fossil fuels, a small share of which are associated with bioenergy-based processes. Bioenergy and fossil fuel flows are shown separately for simplicity, though in practice they can be applied in combination, for example in cofiring a power plant. Some emissions from CO_2 use for chemicals lead to storage, but the majority are re-released to the atmosphere. Non-energy CO_2 uses, including some that lead to storage such as use for building materials, are beyond the scope of the modelling and are not shown.

CCUS plays a critical role in achieving a balance of CO_2 emissions and removal by 2070 in the Sustainable Development Scenario.

The role of CCUS over time

The contribution of CCUS to reducing global energy sector CO_2 emissions in the Sustainable Development Scenario evolves over the projection period, with three distinct periods (Figure 2.3). In the first phase to around 2030, the focus is on capturing emissions from existing power plants and factories. In the power and industry sectors, over 85% of all CO_2 emissions captured in this decade are from plants retrofitted with CO_2 capture equipment: coal-fired power units (and, to a lesser extent, gas-fired power units); chemical plants (mainly fertilisers), cement factories, and iron- and steelworks. Some low-cost CO_2 capture opportunities in hydrogen and bioethanol production are also developed, building on the current portfolio of projects. Total capture reaches 840 Mt in 2030. Cumulatively to 2030, CCUS contributes around 4% of the overall emissions reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario.

Figure 2.3 Growth in global CO_2 capture by source and period in the Sustainable Development Scenario



* Including from the use of oil, which represents 2% of total capture to 2070.

In the Sustainable Development Scenario, the role of CO_2 capture shifts from managing emissions from existing assets towards large-scale carbon removal.

During the second phase, from 2030 to 2050, the contribution of CCUS to cumulative emissions reductions grows to 12% relative to the Stated Policies Scenario. CCUS deployment expands most rapidly in the cement, steel and chemicals sectors, which together account for around one third of the total growth in global CO_2 capture during that period. In power generation, the focus shifts to natural gas-fired stations, which help to integrate variable renewable energy sources (mainly solar and wind) in some regions by providing short-term flexibility and to balance seasonal variations in electricity demand or renewable generation, for which batteries are less well suited (Box 2.2). Hydrogen production from fossil fuels (primarily natural gas) is responsible for a fifth of the overall growth in CO_2 capture in the 2030-50 time frame, driven by increasing hydrogen demand in long-distance transport modes (such as trucks and shipping). BECCS also expands significantly, accounting for around 15% of the growth in CO_2 capture over that period. By 2050, around half of BECCS capacity is in the power sector and the remainder primarily in producing alternative low-carbon fuels, in particular biofuels. BECCS benefits from economies of scale and cost reductions through technological advances and learning-by-doing, which are generally highest at the early stages of the adoption of a technology.

Box 2.2 How CCUS can contribute to stable, zero-emissions power systems

The power sector is the largest emitter of CO_2 today, at around 40% of global energy-related CO_2 emissions. Electricity demand almost triples over the period to 2070 in the Sustainable Development Scenario (equivalent to adding the Chinese grid every eight years), driven by economic growth, electrification of end uses and increased access to electricity in developing economies. The power sector is nonetheless among the fastest to decarbonise in the Sustainable Development Scenario, reaching net-zero emissions during the 2050s and removing emissions from the atmosphere on a net basis thereafter. Although there are a wide range of low-carbon alternatives available for power generation, CCUS is projected to play an important role for three key reasons:

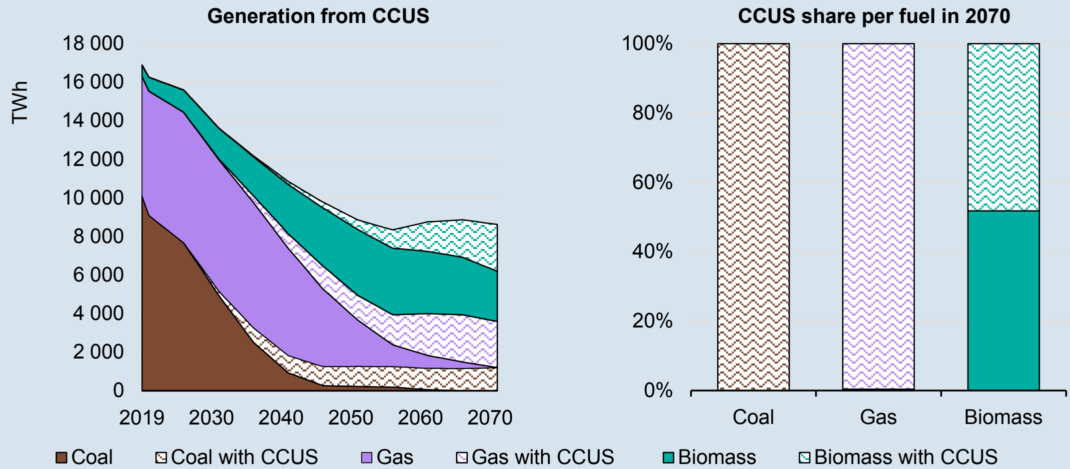
- CCUS can help to avoid the "lock-in" of emissions from the vast fleet of existing fossil-fuelled power plants through retrofits (see below).
- CCUS enables the sector to become net-negative though biomass-fuelled power plants with CCS (BECCS).
- CCUS can help to meet the growing need for system flexibility as the share of variable renewable energy technologies in generation and the need for "dispatchable" capacity increases (IEA, 2020b).

Flexibility to deal with short-term and seasonal variability of electricity demand and supply is critical to ensure the stable and reliable operation of power systems. Coal and gas-fired power plants, which can adjust their power output on demand, have traditionally been the main sources of flexibility. Demand response (whereby consumers are encouraged to shift their consumption in response to price signals or other incentives), enhanced grid interconnections with neighbouring power systems, and energy storage are expected to play an increasingly important role in providing flexibility. Technological innovations in batteries and other forms of energy storage, some of them already commercially used today, may ultimately be able to meet the need for short-term flexibility without the need for fossil-fuel based generating plants (IEA, 2018). However, batteries may not be able to sufficiently replace dispatchable forms of generation in meeting seasonal variations in demand and output from variable renewables, which can be very pronounced in many regions. Alternatives to manage these seasonal variations, such as large-scale storage of hydrogen or ammonia, are at least today more expensive.

Coal- and gas-fired power plants with CCUS could provide system balancing services and flexibility over different time-scales, from ultra-short notice to seasonal variations. Retrofitting existing coal- and gas-fired power plants with carbon capture appears to have a small to negligible impact on their operational flexibility. In fact, it could increase short-term flexibility where the capture system and power block are able to operate independently, allowing the plant to boost power output by switching off the capture system to reduce the energy required to run it, although this would increase the CO_2 emissions of the plant during those periods.

In the Sustainable Development Scenario, CCUS contributes some 15% of the cumulative emissions reduction of the power sector globally over the period to 2070. The amount of CO_2 captured from fossil fuel power plants worldwide increases continuously over the projection horizon, reaching 220 Mt in 2030 and 4.0 Gt in 2070. Coal plants dominate in the period to 2040, mainly due to retrofits. After 2040, plants fuelled by gas and biomass play an increasing role. By 2070, a total of 1 100 GW of generating capacity is equipped with CCUS, producing around 6 000 TWh of electricity (or 8% of global power generation). At that time, all remaining coal- and gas-fired electricity generation and half of biomass-fired generation (all of which are dedicated BECCS plants) is associated with CCUS.

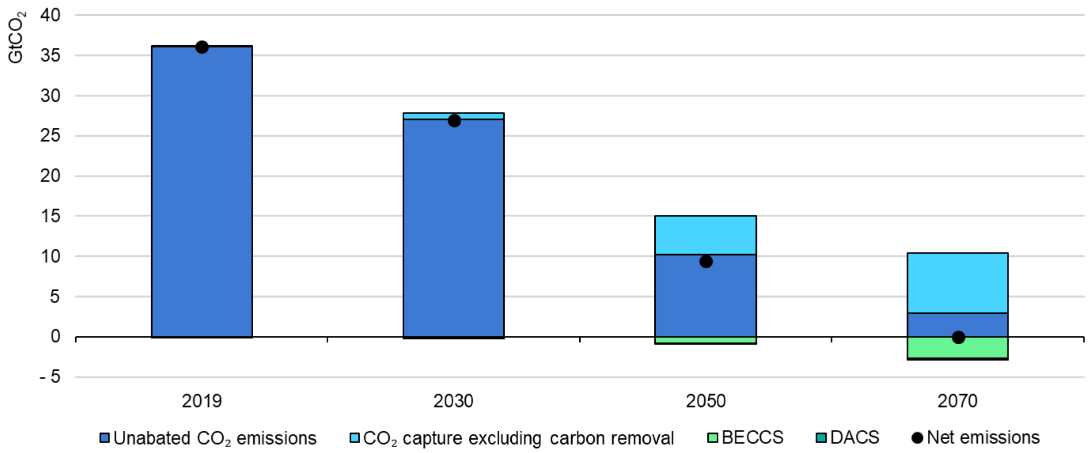
Global electricity generation from plants equipped with carbon capture by fuel in the Sustainable Development Scenario, 2019-70



In the last phase from 2050 to 2070, the amount of CO_2 captured jumps by 85%, as carbon removal and the use of CO_2 accelerate. Around 45% of the growth during this period comes from BECCS and 15% from DAC, while capture from natural gas dominates the increase in CO_2 capture from fossil fuels, driven by the production of hydrogen and electricity in regions with low-cost gas resources. In 2070, about 35%

of all CO_2 emissions captured are from bioenergy or DAC, most of which are stored, generating negative emissions to balance all remaining emissions from transport, industry and buildings so as to achieve a net-zero emissions energy system (Figure 2.4). Around one fifth of all the CO_2 captured from bioenergy or directly from the air is used in combination with clean hydrogen to produce synthetic hydrocarbon fuels, notably for use in aviation, where synthetic fuels meet 40% of aviation fuel demand. The scale-up of carbon removal in the Sustainable Development Scenario implies an average of around 50 BECCS and 5 DACS plants of 1 Mt/year being added each year from 2020 to 2070. By 2070, 800 Mtoe (33 EJ), or more than a quarter of global primary bioenergy use, is linked to BECCS, with almost half of the bioenergy in the power and fuel transformation sectors being used in plants equipped with capture facilities. The deployment of these carbon removal technologies is constrained by their cost-competitiveness with other mitigation measures and (potentially) access to suitable storage, with BECCS also constrained by the availability of sustainable bioenergy and DAC by the availability of low-cost electricity and heat (see the section on carbon removal below).

Figure 2.4 Global CO_2 emissions and capture across the energy system in the Sustainable Development Scenario, 2019-70



Note: CO_2 emissions include both energy-related and process emissions.

BECCS and DACS enable the global energy system to reach net-zero emissions by 2070 in the Sustainable Development Scenario.

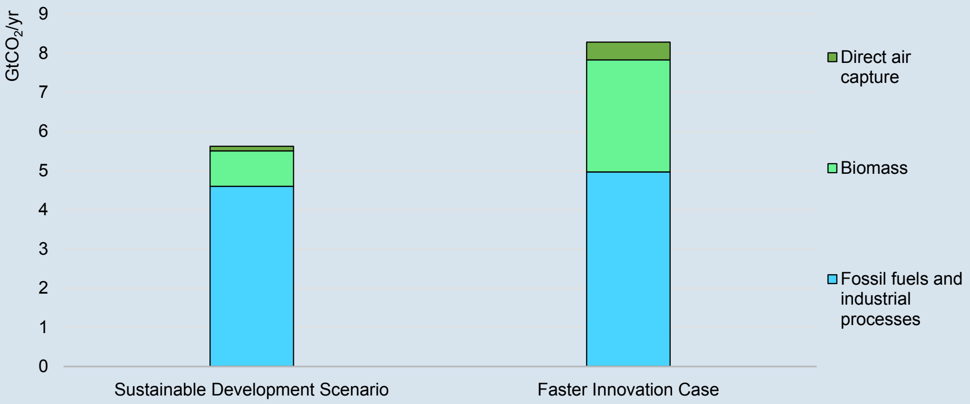
The Sustainable Development Scenario reaches net-zero emissions from the energy sector within five decades on the back of ambitious technological change and optimised innovation systems comparable to the fastest and most successful clean energy technology innovation success stories in history. The Faster Innovation Case explores the opportunity to accelerate this transition to bring the global energy system to net-zero emissions 20 years earlier, by 2050. This variant of the Sustainable Development Scenario considers a more rapid deployment of new technologies, and innovative techniques to enable additional carbon removal, for example by expanding sustainable biomass supply (Box 2.3).

Box 2.3 A faster transition requires mores CCUS

Attaining global climate goals critically depends on the time at which net-zero emissions are achieved: the sooner net-zero emissions are achieved the higher are the chances to meet the most ambitious climate goals. The Faster Innovation Case, a special case of the Sustainable Development Scenario, is designed to explore how much additional clean energy technology innovation would be needed over the level of the Sustainable Development Scenario to bring forward the time at which net-zero emissions are reached to 2050.*

In the Faster Innovation Case, significantly shorter periods to market introduction and higher adoption rates enable nearly 10 $GtCO_2$ of additional net emissions savings compared to the Sustainable Development Scenario in 2050. CCUS contributes around one quarter of the additional emissions reductions in the Faster Innovation Case. The overall level of captured CO_2 emissions is almost 50% higher in the Faster Innovation Case in 2050 at over 8 $GtCO_2$ per year, with the amount of CO_2 stored almost 200 times greater than today.

Global CO_2 capture in the Sustainable Development Scenario and Faster Innovation Case, 2050



Negative emissions technologies, namely DACS and BECCS, account for the bulk of increased capture volume and are critical in offsetting residual emissions from long-distance transport and heavy industry. Emissions captured from bioenergy and the air in 2050 would triple relative to the Sustainable Development Scenario. Around 7 DACS facilities of 1 Mt capture capacity would need to be commissioned every year on average from today to 2050 in the Faster Innovation Case, compared with around 3 such facilities every two years in the Sustainable Development Scenario over the same period. The largest DAC plant currently being designed is of 1 Mt capture capacity; only pilot-scale units of 0.4% that size have been operated so far. For BECCS, around 90 plants of 1 Mt capture capacity would be needed each year, over three times as much as the capacity projected in the Sustainable Development Scenario from today to 2050.

* For details on the assumptions taken for the Faster Innovation Case see IEA (2020b).

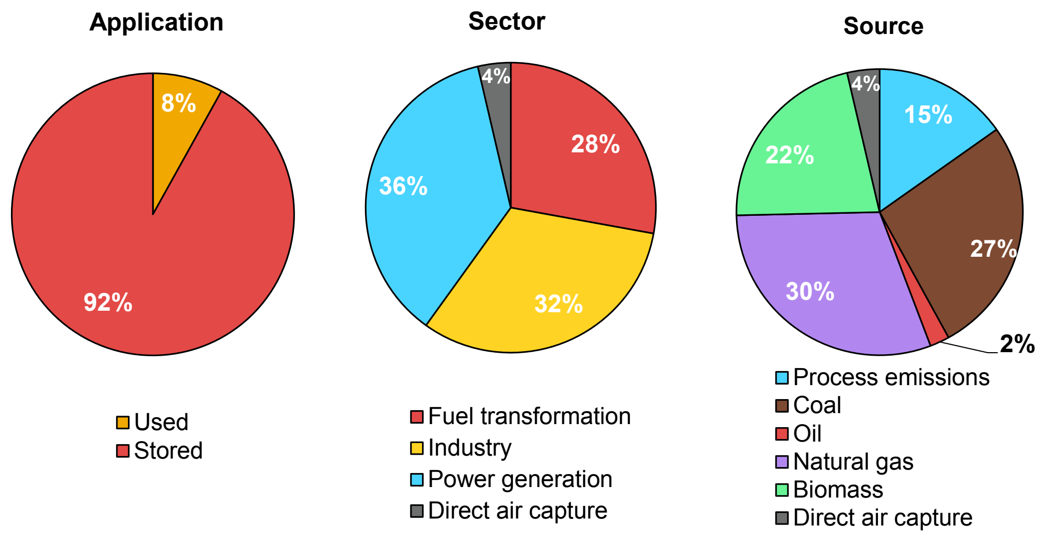
The role of CO_2 use

Captured CO_2 can be either permanently stored deep underground in geological formations or used in a variety of ways, including for EOR or as a raw material in the production of fuels, chemicals or building materials.[2] More than 90% of all the CO_2 captured over 2020-70 in the Sustainable Development Scenario is stored, with 80% of the stored CO_2 coming from fossil sources and industrial processes and 20% from bioenergy and DAC (Figure 2.5). Of the CO_2 that is used, around 95% is used as feedstock for synthetic fuel production, while the remainder is used in the chemicals sector.[3] This represents a major change in how CO_2 is used. Today, the majority of CO_2 captured and used is for EOR – where nearly all of the CO_2 is permanently stored – or in the chemicals sector where the CO_2 is captured and used within the same process to produce fertiliser and ultimately released into the atmosphere.[4] In the period to 2030, CO_2 use for synthetic fuel production is scaled up, building on projects already underway such as the planned Norsk-e Fuel project in Norway (see the section Long-distance transport below). This shift increases CO_2 use by around three-quarters relative to today, albeit from a small base, and paves the way for greater deployment of synthetic fuels in aviation in the longer term.

[2] Building materials and CO_2-EOR can also provide long-term storage of CO_2 (see Chapter 3).
[3] Other CO_2 use applications, such building materials, are beyond the scope of the ETP energy modelling framework. While some of these applications offer opportunities to achieve emission reductions, their contribution to the overall decarbonisation effort is expected to be relatively modest (see the section on CO_2 utilisation and carbon recycling in Chapter 3).
[4] Today, around 125 $MtCO_2$ per year is captured from ammonia production for on-site use in the manufacture of urea, which is widely used in fertilisers. This so-called internally-sourced CO_2 is accounted for in the ETP model. It declines in the Sustainable Development Scenario reflecting changes in fertiliser production (Chapter 3). Internally sourced CO_2 is not taken into account in discussions about CO_2 capture from operational large-scale CCUS projects in this chapter.

The contribution of CO_2 use to reaching net-zero emissions depends in large part on the source of the CO_2. By 2070, all synthetic fuel production uses CO_2 sourced from bioenergy or DAC so that burning these fuels is carbon-neutral (using CO_2 captured from fossil fuel sources would still result in emissions). In the preceding period, some of the CO_2 used come from fossil fuels or from industrial plants, which contributes to CO_2 reductions by reducing reliance on the direct use of fossil fuels in the transport and industry sectors (see Chapter 3 for a discussion of the climate benefits of CO_2 use).

Figure 2.5 Global cumulative captured CO_2 by application, sector and source in the Sustainable Development Scenario, 2020-70



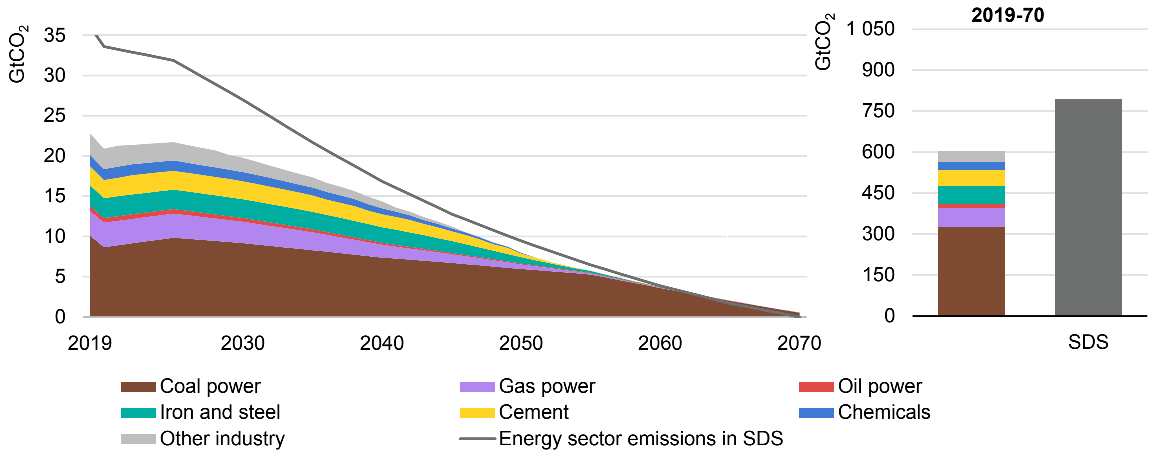
CO_2 is captured across a wide range of sectors and sources, with more than 90% destined for geological storage, in the Sustainable Development Scenario.

Tackling emissions from existing assets

One of the defining challenges for global energy transitions is how to reduce CO_2 emissions from the existing stock of energy-consuming assets – vehicles, factories, public and residential buildings, and infrastructure. Some of these assets, notably power stations and industrial plants, are built to last for decades, effectively locking in their emissions unless they are modified in some way to emit less or are retired early. Retrofitting CO_2 capture facilities to existing plants and storing the CO_2 underground is one way of addressing this challenge.

Existing industrial and power plants, if they continue to operate as they do now through to the end of their normal operating lifetimes, would generate over 600 Gt of CO_2 emissions worldwide between now and 2070 – around 17 years' worth of current global emissions (Figure 2.6). Continued operation of the existing transport fleet and building stock would increase cumulative locked-in emissions by a further 150 Gt. Emissions of that magnitude would exhaust the majority of the remaining CO_2 budget in the Sustainable Development Scenario through to 2070. In other words, it would permit hardly any new energy-consuming assets of any description to be brought into use ever again.

Figure 2.6 Global CO_2 emissions from existing fossil fuelled power and industrial plants against the CO_2 emissions trajectory of the Sustainable Development Scenario, 2019-70



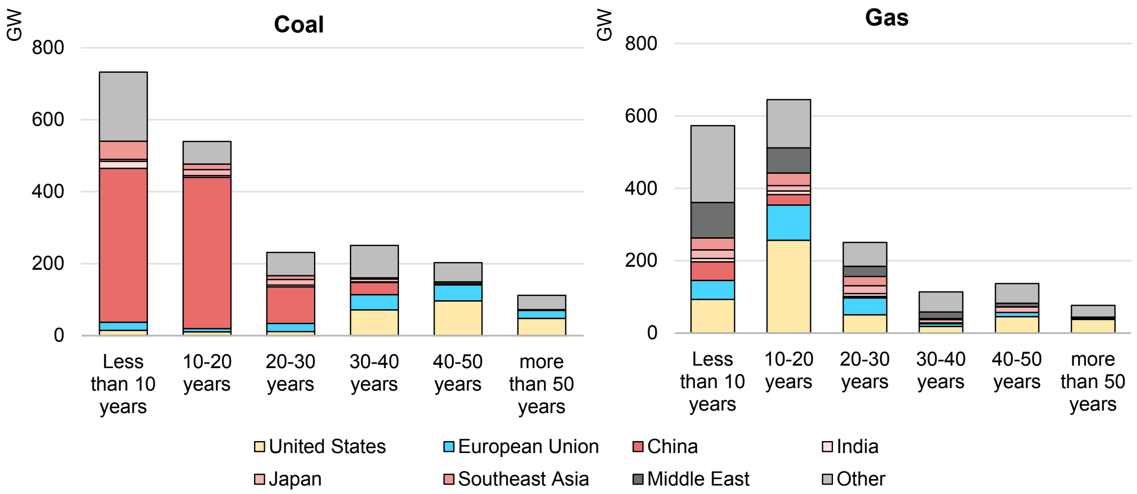
Notes: The sectors include assets under construction in 2019, the base year of this analysis. The analysis includes industrial process emissions and emissions are accounted on a direct basis. Annual operating hours over the remaining lifetime are assumed to be constant at 2019 levels. SDS: Sustainable Development Scenario.

Cumulative emissions from existing industrial plants and power stations alone would reach more than 600 Gt by 2070 unless those assets are modified or repurposed in some way to emit less, or are retired early.

Age and distribution of existing stock

The power sector is the main source of emissions from existing assets, accounting for 410 Gt worldwide to 2070 – 80% of which is from coal plants. China alone contributes almost half of global cumulative emissions from existing power plants, and other emerging economies most of the rest, mainly due to their younger fleets (Figure 2.7). Most of the investment in those assets occurred over the past two decades, when their economies were growing most rapidly. The average age of coal plants is less than 20 years in most Asian countries and just 13 years in China; in Europe, it is 35 years and in the United States around 40 years. Of the 2 100 GW of coal-fired capacity in operation worldwide today and 167 GW under construction, around 1 440 GW could still be operating in 2050 – 900 GW of it in China alone.

Figure 2.7 Age structure of existing coal and gas power capacity by region



Notes: Based on fossil power plants in operation in 2018.
Source: Informed by S&P Global Platts (2020).

Around a third of existing coal and gas-fired power capacity worldwide was added over the last decade.

Gas-fired power plants are generally younger, averaging less than 20 years in all major countries with the exception of Japan, the Russian Federation (hereafter "Russia") and the United States, since gas was introduced as a fuel for power generation in many countries only after the 1990s. Because of their shorter technical lifetime, 350 GW of the around 1 800 GW of gas power plants in operation today and 110 GW under construction could still be operational in 2050.

Industry, particularly heavy industry sectors, is the other major contributor to emissions from existing assets. Of the nearly 200 Gt of cumulative CO_2 emissions from existing industrial assets, the steel and cement sectors each account for around 30% and the chemicals sector for around 15%. As with the power sector, China is the main contributor, due to its dominance as an industrial producer and the relatively young age of its industrial plants. The country accounts for nearly 60% of the capacity used to make iron from iron ore, the most energy-intensive step of primary steel production, for just over half of the world's kiln capacity for making cement, and for around 30% of total production capacity for ammonia, methanol and high-value chemicals (HVCs) combined.

The majority of China's industrial capacity is at the lower end of the age range for each type of assets, averaging between 10 and 15 years, compared with a typical lifetime of 30 years for chemical plants and 40 years for steel and cement plants. The phenomenal growth over the last two decades in China's output of steel – more than sevenfold – and cement – nearly fourfold – bears testimony to the relatively short time frame over which most of the country's steel works and cement plants were added. In contrast, the chemical sector is characterised by a more even distribution of capacity both regionally and across different age ranges.

CCUS retrofits in the Sustainable Development Scenario

There are three options for cutting locked-in emissions in the power generation and industrial sectors:

- investing in modifications to existing industrial and power equipment to either use less carbon-intensive fuels or improve energy efficiency
- retiring plants before the end of their normal operating lifetimes, or making less use of them (e.g. by repurposing fossil fuel power plants to operate at peak-load rather than base-load)
- retrofitting CO_2 capture facilities and storing or using the CO_2.

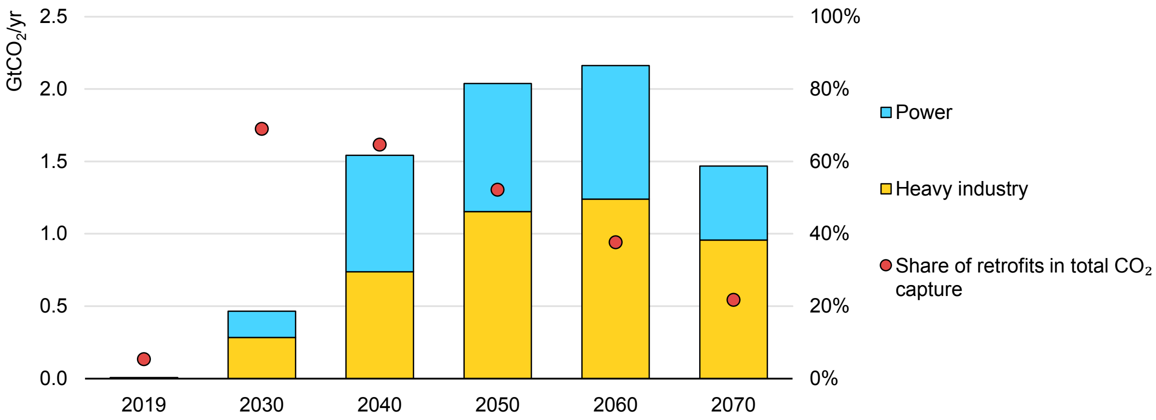
For the world to reach net-zero emissions by 2070 or earlier, a combination of the three will be required. Their relative contribution will vary by country depending on their economic viability, social acceptability and implications for energy security. At the level of an individual plant, the least-cost option, in terms of the cost per tonne of CO_2 emissions avoided, depends on the age and technological characteristics of the assets as well as on the market conditions and regulatory framework. In practice, plant modifications and repurposing may be limited by the specific plant characteristics and, in the case of industry, by non-combustion processes. For example, CCUS is effectively the only option for achieving significant reductions in emissions from cement production short of closing the plant, due to the large amount of process emissions and the need for high-temperature heat, which cannot be provided easily and cheaply by non-fossil energy.

In many cases, early retirement of assets before full repayment of capital costs is an expensive option for plant owners and governments, particularly in emerging economies with younger assets. Retrofitting these assets with CCUS to allow continued operation can provide plant owners with an asset protection strategy and may prove cheaper than early retirement, depending on the size of any carbon penalty and other policy incentives.

From a broader economic perspective, retrofitting CCUS generally makes most sense for power plants and industrial facilities that are young, efficient and located near places with opportunities to use or store CO_2, including for EOR, and where alternative generation or technological options are limited (see Chapter 4). Other technical features that have to be considered when assessing whether a retrofit is likely to make commercial or economic sense are capacity, availability of on-site space for carbon capture equipment, load factor, plant type, proximity to CO_2 transport infrastructure and confidence in the long-term availability of CO_2 storage capacity. In advanced economies, where industrial capacity is generally older, there is greater potential for early retirement, as the economic losses involved are typically lower. In emerging economies with younger assets, the emphasis is likely to be more on retrofitting plants with more energy-efficient and CCUS technologies.

Retrofitting with CCUS plays a major role in reducing emissions from coal and gas-fired power assets in the Sustainable Development Scenario. Around 190 GW of coal-fired capacity, mainly in China, and 160 GW of gas-fired capacity is retrofitted with CCUS. Globally, retrofits on existing plants account for around a third of all the CO_2 captured from power plants over the period 2020-70, and account for 16% of emissions reductions from existing plants relative to the Stated Policies Scenario (Figure 2.8). Some existing coal power plants are also repurposed to provide reserve capacity to the power system, thus generating smaller amounts of electricity and CO_2 emissions, and some plants co-fire coal with biomass, also reducing CO_2 emissions. Despite these measures, early retirements of some power plants are unavoidable: around 600 GW of the existing global coal capacity of 2 100 GW today are retired globally earlier than in the Stated Policies Scenario.

Figure 2.8 Global CO_2 emissions reductions from CCUS retrofits in power generation and heavy industry in the Sustainable Development Scenario



Notes: The quantities exclude CO_2 capture in the fuel transformation and pulp and paper sectors. A 40-year typical lifetime for cement and steel plants and a 30-year typical lifetime for chemical plants are assumed in the calculation of the retrofit share. All CO_2 capture applied to the production of ammonia for urea CO_2 feedstock sourcing in the chemicals sector is considered to be new-build capacity.

The share of retrofits in total CO_2 capture in the heavy industry and power sectors drops from more than two-thirds in 2030 to around one-fifth by 2070 in the Sustainable Development Scenario.

CCUS retrofits also play an important role in addressing emissions from existing assets in heavy industry. They account for nearly 90% of CO_2 captured in heavy industry sectors by 2030 and 55% of the cumulative capture volume to 2070 in the Sustainable Development Scenario. Post-combustion capture technologies are generally more suited to retrofitting than oxy-fuelling and pre-combustion technologies as there is less need for fundamental overhauls in combustion equipment (see Chapter 3). As with power stations, the regional deployment of retrofits in heavy industry is primarily determined by the age of existing assets, as well as future growth in production: if existing capacity levels are largely sufficient to meet local demand, such as in Europe and North America, retrofits may be an attractive option. Conversely, in countries such as India where production capacities are set to grow strongly, the share of retrofits is lower, given the relatively high investment in new assets. Worldwide, CO_2 capture from retrofits in heavy industry declines rapidly after 2060 in the Sustainable Development Scenario, as the bulk of existing capacity today will have come to the end of its lifetime.

A solution for hard-to-abate emissions

No part of the energy system can avoid the need to reduce emissions, including those sectors where it is particularly difficult or expensive, if the world is to reach net-zero emissions. The main sectors in which emissions are hard to abate are heavy industry, notably iron and steel, cement and chemicals, and the three modes of long-distance transport – trucking, shipping and aviation.

CCUS – alongside electrification, bioenergy and hydrogen – is a major component of the portfolio of technology options to deliver deep emissions reductions in the hard-to-abate sectors in the Sustainable Development Scenario (Figure 2.2). Improvements in the performance of existing technologies, material efficiency in heavy industry and measures to conserve energy in transport, by avoiding journeys and shifting between modes, can deliver substantial emissions reductions in the near-term. But for the energy sector as a whole to reach net-zero emissions in the longer-term, technologies that significantly reduce the emissions intensity of producing a tonne of material or of moving passengers and freight around the world are required.

Table 2.2 Principal CCUS and alternative technologies to reduce CO_2 emissions in selected sectors

Sector	Barriers	Technology options (year available in the SDS [TRL])
Cement	• High reliance on coal for high temperature heat • Large share and quantity of process emissions • Low-margins • The need to locate capacity relatively near to the point of use	**CCUS** • Chemical absorption with full capture rates (available from 2024 [TRL 7-11]) • Calcium looping (2025 [TRL 7]) • Direct separation (2030 [TRL 6]) • Oxy-fuel (2030 [TRL 6]) • Novel physical adsorption (using silica or organic-based adsorption) (2035 [TRL 6]) **Alternatives** • Raw material substitution: calcined clay to reduce emissions associated with clinker production (today [TRL 9]) • Alternative binding agents that avoid substantial shares of process emissions (some available today [TRL 3-9])
Steel	• High reliance on coal for high temperature heat and iron reduction • Limits to the availability of scrap for steel recycling • Globally traded commodity with relatively low margins	**CCUS** • DRI: natural gas-based with CO_2 capture (today [TRL 9]) • Smelting reduction with CCUS (2028 [TRL 7]) • Blast furnace: process gas hydrogen enrichment and/or CO_2 removal for use or storage (2030 [TRL 5]) **Alternatives** • Blast furnace: electrolytic hydrogen (H_2) blending (2025 [TRL 7]) • Ancillary processes: H_2 for high temperature heat (2025 [TRL 5]) • DRI: Natural gas-based with high levels of electrolytic H_2 blending, or solely based on electrolytic H_2 (2030 [TRL 5])

Chemicals	• Large share of process emissions
	• Fossil fuels used as feedstock that are difficult to fully substitute with bioenergy or electrolytic hydrogen
	• Globally traded commodities with highly complex supply-chains
		CCUS
		• Chemical absorption (available today for ammonia [TRL 11] and methanol [TRL 9]; in 2025 for HVCs [TRL7])
		• Physical absorption (today for ammonia [TRL 9]; 2023 for methanol [TRL 7]; 2025 for HVCs [TRL 7)
		• Physical adsorption (today for HVCs [TRL 7])
		Alternatives
		• Hydrogen: Electrolytic H_2 supplied by variable renewables (2025 for ammonia [TRL 8] and methanol [TRL 7])
		• Direct electrification: methanol production from methane pyrolysis (2025 [TRL 6])
		• Bioenergy:
		    ○ Bioethanol dehydration for ethylene (today [TRL 5-9])
		    ○ Lignin-based benzene/toluene/mixed xylenes production (2030 [TRL 6])

Sector	Barriers	Technology options (year available in the SDS [TRL])
Long-distance transport	• Dense energy carriers are required • Direct electrification is difficult, particularly for aviation and shipping • Biofuels are limited by sustainability constraints	**CCUS** • Synthetic hydrocarbon fuels (2025 [TRL 5-7]) **Alternatives** • Biofuels in shipping, aviation and trucks (some today [TRL 3-10]) • Electrification of trucks (today [TRL 8-9]) • Ammonia in shipping (2024 [TRL 4-5]) • Hydrogen in shipping and trucks (2021 [TRL 4-8])

Notes: TRL = technology readiness level; DRI = direct reduced iron; H_2 = hydrogen; HVC = high-value chemicals. Year available corresponds to market introduction – although the time period to materiality (1% market share) varies in global deployment projections in the Sustainable Development Scenario. A number of other technologies, including energy and material efficiency, play important roles in decarbonising these sectors in the Sustainable Development Scenario. See IEA, 2020a for additional details and Chapter 3 of this report for further details on the technology readiness of different CCUS options for heavy industry.

Heavy industry and long-distance transport together emit around 10 Gt of CO_2 today, or around 30% of total emissions from the energy system, including industrial process emissions. In the Sustainable Development Scenario, emissions from these sectors decline by almost 90% to around 1.5 Gt in 2070. Achieving these reductions requires widespread adoption of near-zero emissions production routes in heavy industry and the substantial replacement of fossil fuels with low-carbon alternatives in long-distance transport. CCUS plays a critical role in both sectors. By 2070, around 2.7 $GtCO_2$ is captured in the steel, cement and chemicals sectors, and around 5 mb/d of synthetic fuels are consumed in the aviation sector using around 0.8 Gt of captured CO_2.

Heavy industry

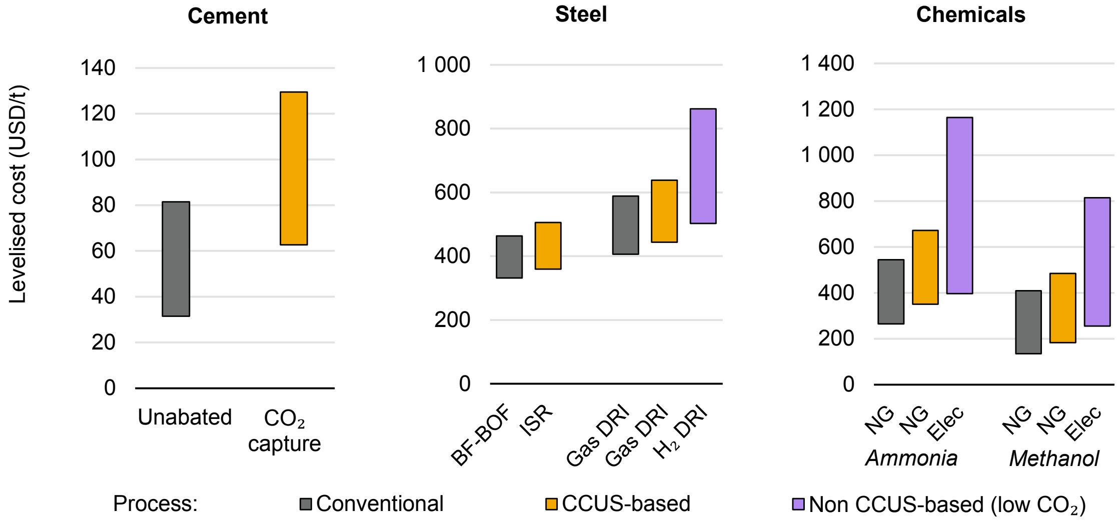
Technology options and costs

In heavy industry, CCUS can be applied directly to production facilities to manage industrial process and energy-related CO_2 emissions, through both retrofits as well as the construction of new plants with integrated CO_2 capture facilities. Industry produces large quantities of bulk materials for sale in highly competitive global market places; margins tend to be slim and energy costs account for a large share of overall production costs. In this context, technology costs, along with local regulatory contexts and infrastructure constraints, will be critical in determining the eventual deployment of CCUS alongside other emissions abatement options.

It is generally difficult to reduce industrial process emissions, which are inherent to the chemical reactions involved in producing certain bulk materials, without CO_2 capture. The production of clinker – the key active ingredient in Portland cement – is the prime example here. Process emissions account for around two-thirds of the emissions in a cement kiln. Even if the kiln in which it is produced were to be electrified or fuelled with bioenergy, these emissions would persist. Industrial process emissions amounted to 2.5 $GtCO_2$ in 2019, of which the cement sector accounted for 63% (the chemicals and steel sectors account for more than half of the rest). There are no alternatives to CCUS at comparable levels of technology maturity that can support deep emissions cuts in this sector. Alternative binding agents could one day constitute an alternative to the use of Portland cement, which produces around 520 kg CO_2 of process emissions per tonne of clinker. Alternative binding materials that could lead to substantial reductions in process emissions (e.g. magnesium oxide derived from magnesium silicates) are still in the research and development (R&D) phase today.

There are also limited alternatives to CCUS for now for reducing emissions in steel and chemicals production. CCUS concepts in the steel and chemicals sectors also tend to be at higher levels of technology maturity than their hydrogen-based alternatives. The hydrogen-based direct reduced iron (DRI) route for making steel, which reduces emissions substantially, could emerge as an economically viable alternative to CCUS-equipped facilities, but probably only in regions with access to very low-cost renewable electricity for hydrogen production via water electrolysis. Based on current estimates of the levelised costs of production for commercial-scale plants, producing one tonne of steel via CCUS-equipped DRI and innovative smelting reduction processes is typically 8-9% more expensive than today's main commercial production routes, but the hydrogen-based DRI route typically raises costs by around 35-70% (Figure 2.9). The story is similar in the chemicals sector. Electrolytic hydrogen as a feedstock for ammonia and methanol production could become an important alternative to CCUS, but in most regions today, it is more expensive than applying CCUS to existing or new plants. The cost of CCUS-equipped ammonia and methanol production is typically around 20-40% higher than is that of their unabated counterparts, while the cost of electrolytic hydrogen routes is 50-115% higher.

Figure 2.9 Simplified levelised cost of producing low-carbon cement, iron and steel, and chemicals for selected production routes



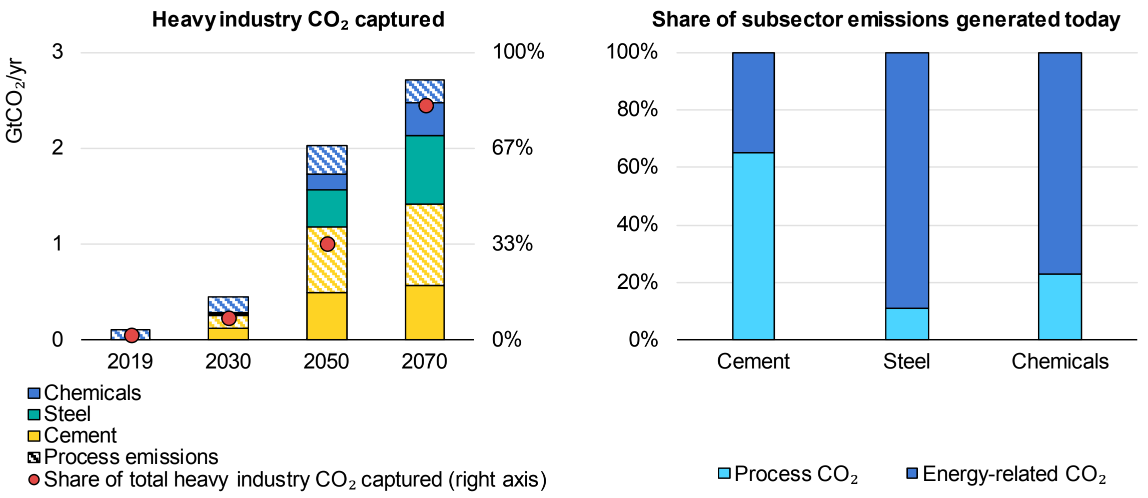
Notes: BF-BOF = blast furnace basic oxygen furnace; ISR = innovative smelting reduction; Gas DRI = natural gas-based direct reduced iron/electric arc furnace (EAF) route; H_2 DRI = 100% electrolytic hydrogen-based; NG = natural gas; Elec = electrolytic; Indicative cost ranges are based on the technical and economic methodology and data in Chapter 4 of IEA (2020a), which reflects varying energy prices and technological uncertainty. The ranges shown reflect electricity prices from USD 30-90/MWh. Processes shown cover conventional unabated fossil fuel based processes that are the principal current production methods, as well as low carbon options based on CCUS or on other alternatives that do not use CO_2 capture. For cement production, while CCUS is the only known technology that could achieve widespread and deep emissions reductions in cement production, demand reductions, as well as biomass and other low-carbon heat sources (including in combination with CO_2 capture) are also significant measures for reducing the sector's emissions. For iron and steel production, costs for recycling using scrap-based EAF processes, and innovative blast furnace routes with process gas hydrogen enrichment and CO_2 removal are not shown, but also contribute to low-CO_2 steelmaking in the Sustainable Development Scenario, as do direct electrification and bioenergy-based processes from chemicals production.

CCUS is a cost-competitive low-carbon option in industry, with a less variable cost range than electrolysis-based pathways that depend highly on regional electricity prices.

CCUS in industry in the Sustainable Development Scenario

CCUS accounts for nearly 40% of the total cumulative reduction in global CO_2 emissions in the steel, cement and chemicals sectors combined in the Sustainable Development Scenario relative to the Stated Policies Scenario. CO_2 emissions captured in industry – including those utilised in the commercial production of urea – increase by a factor of four in the period to 2030 (to 0.5 Gt) and by almost a factor of 25 to 2070 (to 2.7 Gt) in the Sustainable Development Scenario (Figure 2.10). Industrial CCUS applications account for around 54% of total CO_2 capture in the energy system by 2030 and 26% by 2070. The amount of CO_2 captured cumulatively is largest in the cement industry (43 Gt), followed by the chemicals (18 Gt) and steel industries (16 Gt). By 2070, almost 90% of the CO_2 generated in cement production is captured, about 75% in the steel sector and just under 80% in the chemicals sector.

Figure 2.10 Industrial process emissions by sector in the Sustainable Development Scenario

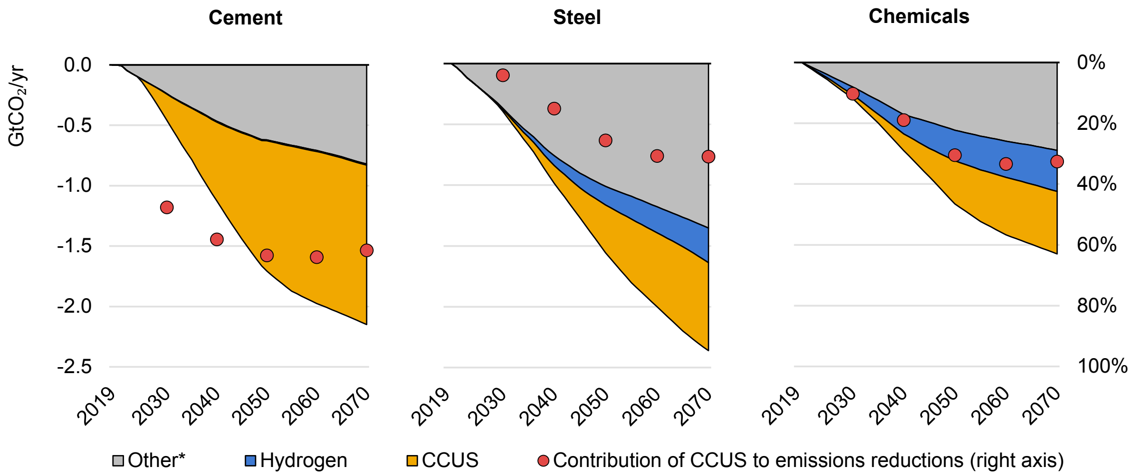


Notes: Share of heavy industry CO_2 captured represents total capture in cement, steel and chemicals production as a share of the total emissions generated in those sectors. In iron and steel production the accounting of energy-related emissions differs from that of "CO_2 emissions from fuel combustion" in the IEA's *World CO_2 Emissions* dataset, where emissions arising from the transformation of fuels in coke ovens and blast furnaces are not included, following the IPCC designation of energy transformation processes as process CO_2 emissions. Process emissions in the iron and steel sector include those arising from the use of lime fluxes and from ferroalloy production. See the forthcoming IEA *Iron and Steel Technology Roadmap* for details.

In heavy industry, process emissions persist in 2070, requiring CO_2 management through CCUS to achieve global net-zero emissions in the Sustainable Development Scenario.

The role of CCUS in reducing emissions in each sub-sector grows rapidly over time to 2050, after which its contribution begins to plateau (Figure 2.11). By 2070, CCUS accounts for 61% of annual emissions reductions in the cement sector, 31% in the steel sector and 33% in the chemicals sector. Cement production accounts for the largest share of the process CO_2 emissions captured. CCUS is also deployed in the pulp and paper sector, but on a much smaller scale. Around 18 Mt is captured annually in this sector by 2070 in the Sustainable Development Scenario, or 1% of all the CO_2 captured in industry. CCUS in that sector is mainly applied to steam boilers, some of which are fed by biomass (e.g. bark and other pulp and papermaking residues), resulting in some CO_2 removal (-3.5 Mt in 2070).

Figure 2.11 Global CO_2 emissions reductions by abatement measure in heavy industry in the Sustainable Development Scenario relative to the Stated Policies Scenario



* *Other* includes material efficiency, technology performance, electrification, bioenergy and other fuel shifts.

CCUS accounts for between one quarter and two-thirds of the cumulative emissions reductions in industry subsectors in the Sustainable Development Scenario.

The pace of CCUS deployment in industry is daunting, emphasising the need to get the ball rolling as quickly as possible. By 2030, around 450 $MtCO_2$ is captured per year in industry worldwide, mainly in the cement sector, in the Sustainable Development Scenario. Assuming an average capture rate of 0.5 $MtCO_2$ per year for each facility, this implies a need for close to one CCUS-equipped cement facility coming online per week between now and then. The rate accelerates to almost 6 per month on average in the period 2030-70. Much of this capacity is retrofitted to existing plants or those currently under construction. This deployment hinges on a matching expansion of CO_2 transport and storage infrastructure.

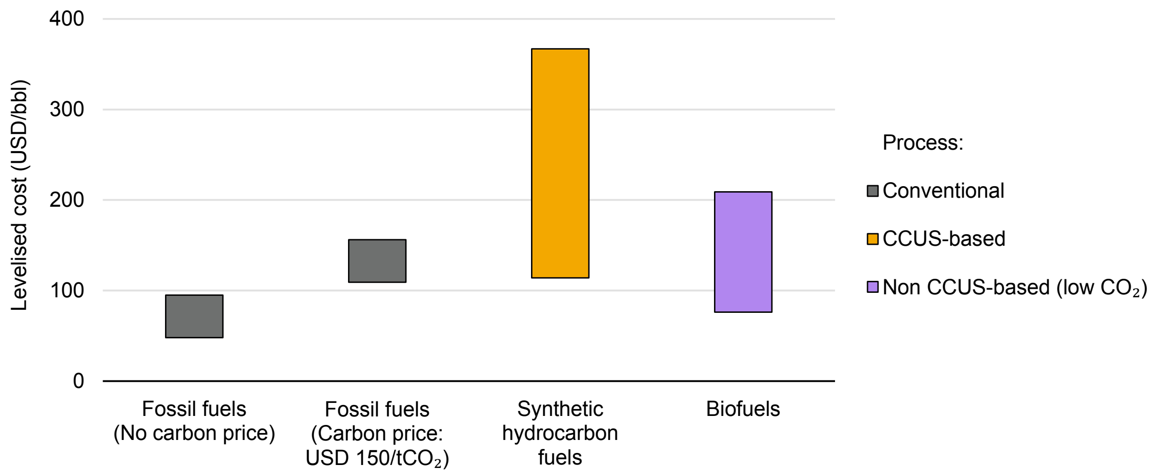
Long-distance transport

Technology options

CCUS is an option for effecting deep emissions reductions in long-distance transport, including heavy-duty trucking, shipping and aviation. Together, these three sub-sectors make up nearly half of global annual energy use (1 192 Mtoe) for transport and related CO_2 emissions (3.6 Gt). They are among the most difficult to decarbonise. Electrification of trucks and the direct use of hydrogen and ammonia in ships are among the main alternatives to the use of biofuels (the supply of which is constrained by the availability of land to grow crops for energy purposes) and synthetic fuels. By contrast, electrification of long-distance air travel is a nascent technology, constrained by limits on the gravimetric energy density of batteries (Box 2.4). An all-electric passenger commercial aircraft capable of operating over ranges of 750-1 100 kilometres, for instance, would require battery cells with densities of 800 Wh/kg – more than three-times the current performance of lithium-ion (Li-ion) batteries (Schäfer et al., 2019**).**

CCUS can contribute to the decarbonisation potential of long-distance transport as a source of CO_2 for synthetic hydrocarbon fuels. Captured CO_2 can be used to convert low-carbon hydrogen into synthetic hydrocarbon fuels (diesel, gasoline and kerosene) that are easier to store, transport and use, but with potentially lower lifecycle CO_2 emissions than conventional fossil fuels (see Chapter 3). However, the production of synthetic hydrocarbons is energy-intensive and requires large amounts of hydrogen, making them relatively expensive. As CO_2 emissions constraints increase over time, the feedstock CO_2 must increasingly be sourced from biomass or the air (DAC).

Figure 2.12 Simplified levelised cost of low-carbon fuels for long distance transport



Notes: Indicative cost ranges are based on the technical and economic methodology and data in IEA (2020a), which reflect varying energy prices and technological uncertainty. Processes shown cover conventional unabated fossil fuels as well as a low carbon option based on CCUS and one that does not involve CO_2 capture. For long-distance transport modes, fossil fuel costs reflect a USD 50/bbl to USD 100/bbl crude oil cost range, and the carbon price variant represents a USD 150/tCO_2 shadow carbon price, which in practice could take the form of other regulatory policy measures such as fuel standards. Synthetic hydrocarbon fuel cost ranges consider CO_2 from bioenergy or DAC, and hydrogen from electrolysis powered by a dedicated renewable energy system. Electricity prices for hydrogen production range from USD 20/MWh to USD 60/MWh across regions; given that these fuels are expected to materialise in the market somewhat later than CCUS in industry, the cost range is lower than in Figure 2.9 to better reflect anticipated electricity prices. DAC CO_2 capture costs range from USD 135/tCO_2 to USD 345USD/tCO_2, while biogenic CO_2 feedstock costs range from USD 15/tCO_2 to USD 30/tCO_2. Biofuels covers hydrotreated vegetable oils (HVO) and biomass-to-liquids (BTL) fuels reflecting biomass feedstock costs from USD 5/GJ to USD 15/GJ.

CO_2-derived synthetic hydrocarbon fuels are among the limited options to decarbonise long-distance transport, but require strong policy support.

Given the high cost of producing synthetic fuels, their long-term use at scale is likely to be mostly limited to long-distance aviation, where practically no other alternatives to conventional oil-based fuels and biofuels exist, and where the higher cost are likely to be more easily absorbed. The estimated levelised cost of synthetic fuels is around two to seven times that of kerosene produced from crude oil (at a price of USD 50/bbl) and bio kerosene is around 1.5-4 times that of kerosene produced from crude oil (at a price of USD 50/bbl) (Figure 2.12). The cost of capturing the CO_2 needed to make synthetic fuels is a major component of the total cost of making those fuels. CO_2, generated in the production of bioethanol is expected to be the cheapest source of biogenic CO_2, at around 15-30/tCO_2. CO_2 captured from the atmosphere in a DAC facility is projected to cost in the region of USD 135-345/t, though future costs are highly uncertain since this family of technologies is at a comparatively early stage of development. Electricity accounts for around 30-80% of the cost of synthetic fuel production, based on a future renewable energy electricity price of USD 20-60/MWh.

Box 2.4 The role of CCUS in synthetic fuel production

Liquid fuels derived from crude oil have a high gravimetric energy density. This explains their widespread use in the transportation sector, which accounts for around 60% of global oil demand today. A litre of gasoline weighing around 0.75 kg contains around 35 MJ of energy. A Li-ion battery today can store the same quantity of energy when fully charged, but would weigh about 50 kg, and the battery does not get lighter as it discharges. This weight constraint can be offset to a large degree by the increased efficiency of electric motors (2.5-5 times more efficient than internal combustion engines), meaning the effective battery weight requirements of electric vehicles can be reduced accordingly for a given driving range. Nevertheless, the disparity in weight helps to explain the difficulty of directly electrifying long-distance transport modes, where the weight of the fuel is a critical parameter. This is particularly the case in aviation, where the gap between the efficiency of electric motors and jet turbines is smaller, and where regenerative breaking cannot compensate for the added weight of batteries. Synthetic fuels offer an indirect pathway from low-carbon electricity to energy-dense fuel applications.

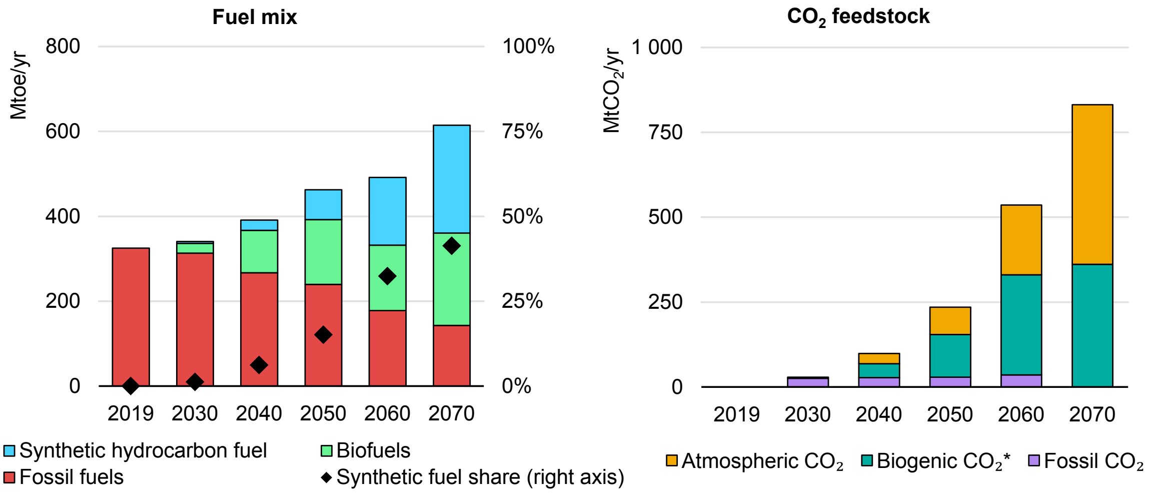
Synthetic fuels are produced by converting hydrogen and a source of carbon into long-chain hydrocarbons, which are then upgraded to usable fuels. The Fischer-Tropsch process, which uses carbon monoxide (CO) as the carbon source, is a key component of most pathways to produce synthetic fuels that are direct substitutes for the fossil fuels used in long-distance transport modes (kerosene, diesel and heavy fuel oil). To be carbon-neutral, this CO_2 has to be generated from biogenic CO_2 (captured from a biofuel production or biomass-fired power plant) or atmospheric CO_2 (captured using DAC).The production of these fuels also requires significant amounts of electricity. Overall, the production of one litre of synthetic kerosene from electrolytic hydrogen together with CO_2 captured through DAC requires around 25 kWh of energy. Over 80% of this is electricity used to produce hydrogen and around 15% is heat and electricity for capturing CO_2 through DAC. The remainder is used in the Fischer-Tropsch synthesis step. With current technology, only around 40% of the energy input ends up in the final liquid product, although process optimisation could potentially increase the overall conversion efficiency beyond 45%. Some projects aiming to produce synthetic hydrocarbons have been announced recently. For example, the Norsk e-Fuel project is planning the first commercial plant in Europe using this technology. It is expected to come on line in 2023 with a production capacity of 10 million litres/year (Norsk-e Fuel, 2020).

CO_2 for synthetic fuels in the Sustainable Development Scenario

CCUS contributes indirectly to emissions reductions in all three long-distance transport sub-sectors in the Sustainable Development Scenario. While conventional biofuels expand most rapidly in the near term, synthetic hydrocarbon fuels and BTL with CCUS start to make inroads in the late 2020s. By 2070, biofuels make up 17% (418 Mtoe) of the total fuel mix and synthetic hydrocarbon fuels make up 10% (254 Mtoe).

Synthetic hydrocarbon fuels make the largest contribution in aviation, accounting for almost all synthetic fuel use and 40% of the total demand for kerosene in 2070 (biofuels account for 35%) (Figure 2.13). In the Sustainable Development Scenario, synthetic hydrocarbon fuels play a modest role in the trucking sector over the period 2030 to 2060, with the sector transitioning to other low-carbon fuels thereafter. By 2070, the production of synthetic hydrocarbon fuels across all sub sectors requires around 120 Mt (350 Mtoe) of electrolytic hydrogen, 830 Mt of CO_2, and 5 500 TWh of electricity – around 8% of all the electricity produced worldwide in 2070. As the CO_2 is sourced from the atmosphere (55% of all CO_2 used in 2070) or captured at biomass power or biofuel production plants (45%), the aviation fuel produced is carbon-neutral.

Figure 2.13 Global energy demand in aviation and CO_2 use as feedstock for synthetic kerosene in the Sustainable Development Scenario



* Biogenic CO_2 is the CO_2 captured in the production of biofuels such as bioethanol or during the production of electricity at biomass-fired power plants.

By 2070, nearly half of global energy demand for aviation is met by synthetic fuels, requiring the capture of around 830 Mt of CO_2 for use as feedstock in the Sustainable Development Scenario.

CCUS in low-carbon hydrogen production

CCUS can play an important role in facilitating the production of low-carbon hydrogen for use across the energy system. Hydrogen is a low-carbon fuel or feedstock that can be used without direct emissions of air pollutants or GHGs. It offers a way to decarbonise a range of energy sectors, in particular where direct electrification is difficult, including long-haul transport, chemicals, iron and steel production, and power and heat generation (see the previous section). CCUS can help decarbonise hydrogen production in two key ways:

- **By reducing emissions from existing hydrogen plants:** Around 75 Mt H_2 of hydrogen is currently produced each year for industrial use,[5] almost entirely from natural gas (76%) and coal (23%), with the remainder from oil and electricity. This is associated with more than 800 $MtCO_2$, corresponding to the combined total energy sector CO_2 emissions of Indonesia and the United Kingdom (IEA, 2019b). Unabated production of hydrogen from fossil fuels results in emissions of

[5] The leading uses of pure hydrogen today are in oil refining (33%) and for the production of ammonia (27%).

9 $tCO_2/t\ H_2$ in the case of natural gas and 20 $tCO_2/t\ H_2$ in the case of coal. Seven projects based on the generation of hydrogen from fossil fuels with CCUS are in operation today [6] with a combined annual production just over 0.4 MtH_2, capturing close to 6 $MtCO_2$. Of the seven projects, four are at oil refineries and three at fertiliser plants. There is significant potential to expand CCUS retrofitting to reduce emissions from existing facilities and enable these facilities to continue operations sustainably. Capturing CO_2 from hydrogen production is a relatively low-cost CCUS application, and existing facilities are often concentrated in coastal industrial zones, with potential to share CO_2 transport and storage infrastructure with other industrial facilities.

- **By providing a least-cost pathway to scale up new hydrogen production**: Gas- and coal-based hydrogen production with CCUS is currently less expensive than using renewable energy for water electrolysis in most regions and will remain so where both CO_2 storage and low-cost fossil fuels are available (see below).

Technology options

Hydrogen production from natural gas using reforming processes and from coal using gasification are well-established technologies. In the case of natural gas, steam methane reforming (SMR) is the leading production route today, with part of the natural gas (30-40%) used as fuel to produce steam, giving rise to a "diluted" CO_2 stream, while the rest of it is split with the help of the steam into hydrogen and more concentrated "process" CO_2. The concentration of the CO_2 in the output streams affects capture costs. Capturing CO_2 from the concentrated "process" stream costs around USD 50/t, leading to overall emission reductions of 60%. CO_2 can also be captured from the more diluted gas stream. This can boost the level of overall emissions reduction to 90% or more, but it also increases costs to around USD 80/tCO_2 in merchant hydrogen plants. Several SMR CCUS projects are currently at the feasibility study stage with ambitions to be operational by 2030, in particular in densely industrialised zones. These include the H-Vision project, which aims to retrofit CO_2 capture to up to 0.6 MtH_2/yr for industrial use in Rotterdam, the Netherlands (PoR, 2019), and the Magnum Project in the Netherlands, which could create demand for 0.2 MtH_2/yr for each of the three gas power plant units converted to hydrogen (NIB, 2018).

Auto-thermal reforming (ATR) is an alternative technology in which the required heat is produced in the process itself. This means that all the CO_2 is produced inside the

[6] These include facilities that produce pure hydrogen and capture CO_2 for geological storage or sale. CO_2 captured from ammonia plants for use in urea manufacturing is excluded.

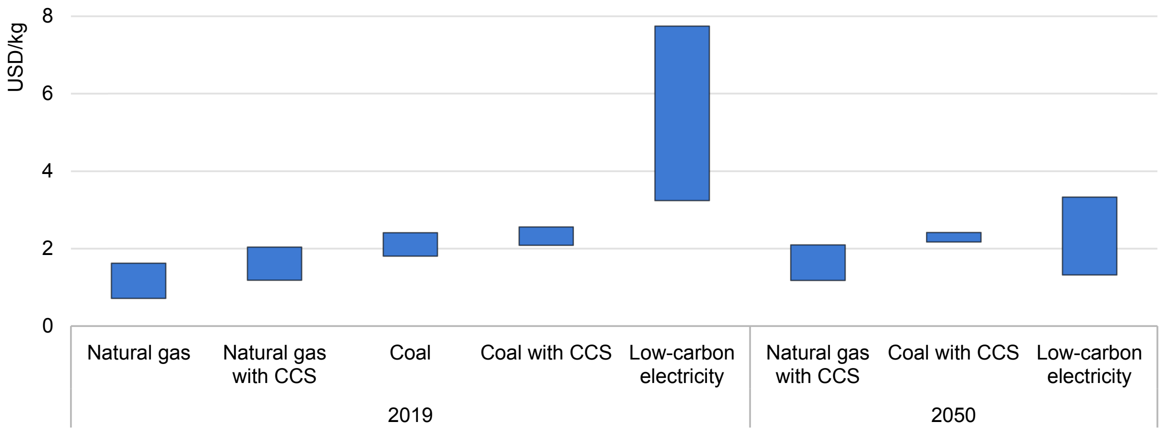
reactor, which allows for higher CO_2 recovery rates than can be achieved with SMR. ATR can also be cheaper than SMR because the emissions are more concentrated. A large share of global ammonia and methanol production already uses ATR technology, and two new projects in the United Kingdom – HyNet and H21 – plan to use that technology, too (Northern Gas Networks, 2018; HyNet, 2020).

Other options for using natural gas to produce hydrogen exist, but are still at a laboratory or demonstration stage. In an alternative SMR design, natural gas would still be required as feedstock, but the necessary steam could be produced by alternative sources, such as electricity or concentrated solar energy, thus eliminating the diluted CO_2 stream from heat generation in conventional SMR designs. Methane pyrolysis (or splitting) is another emerging technology. It involves splitting methane at high temperatures, for example in a plasma generated by electricity, to produce hydrogen and solid carbon, but no CO_2. The resulting carbon can be potentially used as feedstock in the chemical, steel or aluminium industry, providing another revenue stream besides the hydrogen (Daloz et al., 2019). In the United States, Monolith Materials operates a pilot methane pyrolysis plant in California and a commercial demonstration plant in Nebraska. In Australia, the 100 t H_2/yr Hazer Commercial Demonstration Plant, which will use biogas to produce hydrogen and graphite, is under construction (FuelCellsWorks, 2020).

Coal gasification is a mature technology used today mainly in the chemical industry for the production of ammonia, in particular in China. Coal gasification can be combined with CCUS, though there are technical challenges. In particular, few technologies exist that produce both high-purity hydrogen and CO_2 that is pure enough for other uses or storage, since gas separation technologies focus on either hydrogen removal or CO_2 removal. The choice and design of the capture technology therefore depends on what the hydrogen is going to be used for, as well as on production costs. In Australia, the planned Hydrogen Energy Supply Chain Latrobe Valley project is seeking to produce hydrogen from lignite using gasification, with the CO_2 being transported and stored via the CarbonNet project.

Producing hydrogen from fossil fuels with CCUS will likely remain the cheapest low-carbon route in regions with low-cost domestic coal and natural gas and available CO_2 storage, such as the Middle East, North Africa, Russia and the United States. The cost of producing hydrogen that way is currently in the range of USD 1.2/kg H_2 to USD 2.6/kg H_2, depending on local gas and coal prices (Figure 2.14). This cost is not projected to change significantly in the coming decades. The future economics of the technology and competing options depend on factors that will continue to vary regionally, including prices for fossil fuels, electricity and carbon. The cost of electrolytic hydrogen is expected to come down substantially in the long term, driven by cost reductions from scaling up the deployment of electrolysers and their manufacturing capacities as well as due to declining costs for electricity from renewables. Water electrolysis could become a competitive option for low-carbon hydrogen production in regions with abundant renewable energy resources, including Northern Africa and most of Australia, with costs projected to range from USD 1.3/kg to USD 3.3/kg of hydrogen by mid-century.

Figure 2.14 Global average levelised cost of hydrogen production by energy source and technology



Notes: natural gas = steam methane reforming (SMR); coal = coal gasification. Coal and coal with CCS apply to China only. Electrolysis using low-carbon electricity assumes dedicated renewables-based generation.

Capital expenditure (CAPEX) assumptions: SMR without CCUS – USD 910/kW H_2 (2019 and 2050); SMR with CCS – USD 1 583/kW H_2 (2019) and 1 282/kW H_2 (2050); coal without CCUS – USD 2 672/k W H_2 (2019 and 2050); coal with CCS – USD 2 783/kW H_2 (2019 and 2050); electrolysis – USD 872/kW_e (2019) and USD 269/kW_e (2050).

Operating expenditure (OPEX) assumptions (as % of CAPEX): SMR without CCS – 4.7% (2019 and 2050), SMR with CCS – 3.0 % (2019 and 2050); coal with and without CCS – 5.0% (2019 and 2050); electrolysis – 2.2% (2019) and 1.5% (2050).

Efficiency assumptions (lower heating value): SMR without CCS – 76% (2019 and 2050), SMR with CCS – 69% (2019 and 2050): coal without CCS – 60% (2019 and 2050), coal with CCS – 58% (2019 and 2050); electrolysis – 64% (2019) and 74% (2050).

Full-load hour assumptions: SMR and coal gasification 8 322 hours (2019 and 2050); electrolysis 3 000-4 000 hours (2019) and 2 000-3 000 hours (2050). *Stack lifetime*: 100 000 hours.

System lifetime assumptions: 30 years.

Fuel price assumptions: natural gas – USD 1.4-6.3 per gigajoule (GJ) (2019) and USD 1.7-7.0/GJ (2050); coal – USD 1.6-3.8/GJ (2019) and USD 1.0-2.2/GJ (2050); electricity – USD 36-116 per megawatt-hour (MWh) (2019) and USD 20-60/MWh (2050).

CO_2 capture rate assumptions: SMR with CCS – 95%, coal with CCS – 90%.

CO_2 price assumptions: USD 0-15/tCO_2 (2019) and USD 180/tCO_2 (2050).

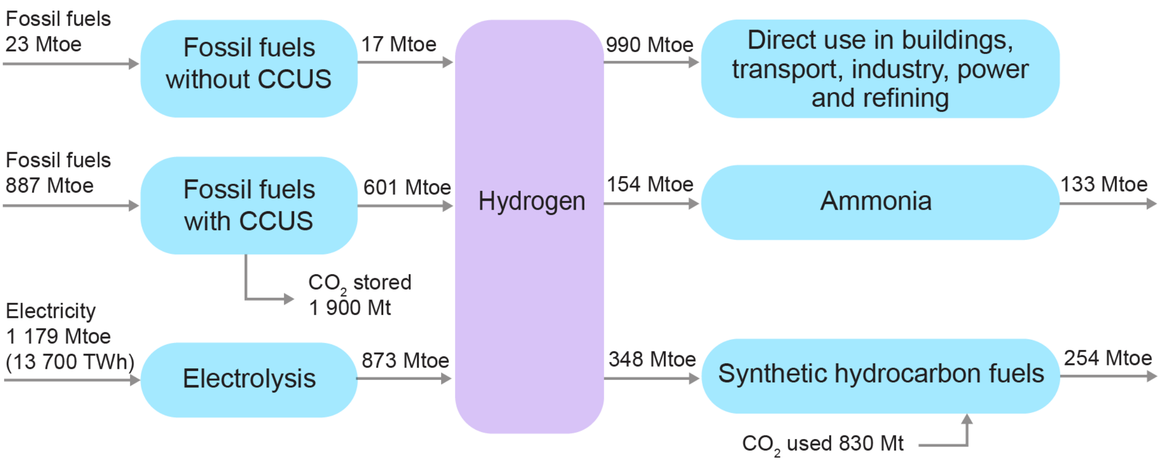
CO_2 transport and storage cost assumptions: USD 20/tCO_2. Representative *discount rate* for this analysis is 8%.

Producing low-carbon hydrogen from fossil fuels with CCUS will likely remain the cheapest option in regions with cheap domestic coal and natural gas and available CO_2 storage.

Hydrogen with CCUS in the Sustainable Development Scenario

Low-carbon hydrogen plays a key role in decarbonising transport, industry, buildings and power generation in the Sustainable Development Scenario, with global hydrogen demand increasing seven-fold to 520 Mt by 2070. Hydrogen is used in a wide range of new applications as an alternative to current fuels and raw materials, including as a transport fuel for cars, trucks and ships, as an input for chemicals and steel making, to produce heat in buildings and industry, and for energy storage to balance the variability of renewables in the power sector. The direct use of hydrogen in transport, buildings, industry, and power generation accounts for two-thirds of hydrogen demand in 2070, while nearly a quarter is used to produce synthetic hydrocarbon fuels and 10% is converted into ammonia as a fuel for the shipping sector (Figure 2.15). Ammonia produced from natural gas with CCS covers more than a third of fuel needs in the shipping sector in 2070.

Figure 2.15 CCUS in hydrogen and synthetic fuel production for energy purposes in the Sustainable Development Scenario, 2070



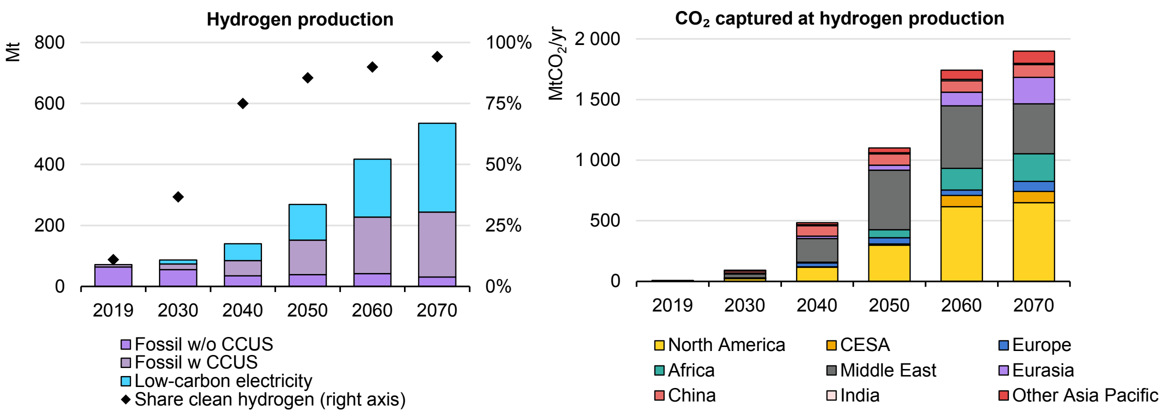
Around 40% of low-carbon hydrogen supply is linked to CCUS in 2070 in the Sustainable Development Scenario

Overall, the production of hydrogen with CCUS and its use leads to cumulative CO_2 reductions of around 40 Gt by 2070, or 3.5% of the cumulative emissions reductions in the Sustainable Development Scenario relative to the Stated Policies Scenario. Production reaches 18 Mt (52 Mtoe) worldwide in 2030 in the Sustainable Development Scenario, meeting 20% of global hydrogen needs, compared with

7.8 Mt[7] (22 Mtoe) in 2020. Both existing and new hydrogen plants are equipped with CO_2 capture, including in some of the main industrial clusters in ports of the North Sea, the US Gulf Coast and southeast China.

The shares of water electrolysis and fossil fuels with CCS in total low-carbon hydrogen supply is roughly equal up to 2030, but moves slightly in favour of water electrolysis over time, reflecting expected cost reductions for electrolysers and renewable energy generation (Figure 2.16). By 2070, low-carbon hydrogen production from fossil fuels with CCUS accounts for 40% of global hydrogen production or around 210 Mt (600 Mtoe) – nearly 500 times more than the total hydrogen capacity with CCUS in operation today. Around 1.9 $GtCO_2$ is captured and stored from hydrogen production in that year, representing around 18% of all CO_2 being captured globally in 2070.

Figure 2.16 Hydrogen production (left) and CO_2 capture by region (right) in the Sustainable Development Scenario



Notes: CESA = Central & South America. Numbers show hydrogen produced in pure form coming from merchant hydrogen plants, industrial ammonia facilities and as a by-product of catalytic naphtha reforming in refineries. CCUS includes both geological storage and CO_2 use in urea production.

Fossil fuels with CCUS play a critical role in the production of low-carbon hydrogen in the Sustainable Development Scenario, in particular in North America, Asia and the Middle East.

[7] These include facilities producing pure hydrogen and capture CO_2 for geological storage or use, either for urea production or other purposes.

Removing carbon from the atmosphere

Approaches and technologies

Carbon removal technologies involve extracting CO_2 from the atmosphere, directly or indirectly (via the absorption of CO_2 in biomass), and permanently storing it. The main attraction of carbon removal technologies is their potential to offset residual emissions from sectors where emissions are hard to abate, to achieve net-zero emissions across the energy sector. While some CO_2 could be stored in products (e.g. concrete), geological storage will undoubtedly be needed to achieve large-scale carbon removal with these technologies.

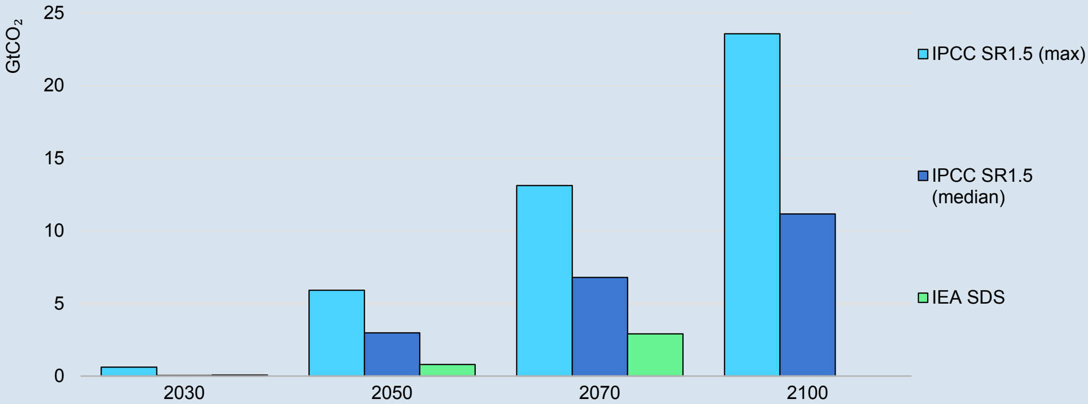
Carbon removal is also often seen as a way of producing net-negative emissions in the second half of the century to counterbalance excessive emissions earlier on (Box 2.5). This feature of many climate scenarios however should not be interpreted as an alternative to cutting emissions today or a reason to delay action. In the Sustainable Development Scenario, carbon removal technologies are part of the portfolio of technologies and approaches to cut emissions in the near term and in the future, helping a faster transition to net-zero emissions. From a policy perspective, support for carbon removal technologies can additionally serve as a means to hedge against the risk of delay or even failure in the development and deployment of other CO_2 abatement technologies across the energy sector: technology development and deployment tends to be a non-linear process in which delays can occur for many different reasons (IEA, 2020c).

Box 2.5 Reliance on carbon removal in different climate mitigation pathways

Both the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC, 2014) and more recently the IPCC Special Report on *Global Warming of 1.5°C*, or *SR1.5* (IPCC, 2018) highlight the central role that carbon removal technologies will need to play in meeting ambitious climate targets. Most scenarios referenced in *SR1.5* rely on carbon removal technologies to meet climate targets, in particular BECCS.* Scenarios in which carbon removal technologies do not contribute to emissions reductions involve energy demand falling at a rate that the IPCC describes as unprecedented.

In the *SR1.5* scenarios that are comparable to the Sustainable Development Scenario in having a 66% probability of limiting the global mean temperature increase by 2100 to 1.7-1.8°C, the highest levels of carbon removal projected are almost 6 Gt of CO_2 in 2050 and 13 Gt in 2070. This is well above that in the Sustainable Development Scenario, in which BECCS and DACS combined remove almost 3 Gt from the atmosphere in 2070. The median value of the contribution of carbon removal in these *SR1.5* scenarios by 2070 is more than twice as high as that projected in the Sustainable Development Scenario. While BECCS is the main contributor to carbon removal in the Sustainable Development Scenario, as in these SR1.5 scenarios, DACS plays a much larger role, reaching around 270 Mt in 2070. Only one comparable *SR1.5* scenario deploys DAC, at a level around 9 Mt (after 2060).

Carbon removal through BECCS and DACS in the Sustainable Development Scenario and IPCC SR1.5 scenarios



Notes: Values for the IPCC SR1.5 refer to either the maximum or median deployment of BECCS and DAC in all scenarios with a 66% likelihood of limit average future temperature increases to 1.7-1.8°C. SDS = Sustainable Development Scenario.

Source: Huppmann et al. (2018).

* Only six integrated assessment models referenced in the IPCC report model the deployment of DAC: WITCH, TIAM-Grantham (Realmonte et al., 2019), C-ROADS-5.005, MERGE-ETL 6.0, MERGE-ETL 6.0, and REMIND 1.7 (Huppmann et al., 2018).

Carbon removal approaches can include either nature-based solutions, enhanced natural processes, or technological solutions (Table 2.3).[8] Nature-based solutions include afforestation (the repurposing of land use by growing forests where there were none before) and reforestation (re-establishing a forest where there was one in the past).[9] Enhanced natural processes include land management approaches that increase the carbon content in soil through modern farming methods (for instance,

[8] Nature-based solutions and enhanced natural processes, which are not part of the energy system, are outside the scope of this analysis and have not been included in the IEA modelling framework.
[9] Afforestation/reforestation can also provide biomass for bioenergy.

by adding biochar[10] or fine mineral silicate rocks) and ocean fertilisation, in which nutrients are added to the ocean to increase its capacity to absorb CO_2. BECCS and DACS are the main technological solutions available today – they are the primary route for the energy sector to contribute to carbon removal in the transition to net-zero emissions, and therefore the focus of this analysis (see Chapter 1).

While all these approaches can be complementary, technology solutions can offer advantages over nature-based solutions, including the verifiability and permanency of underground storage; the fact that they are not vulnerable to weather events; including fires that can release CO_2 stored in biomass into the atmosphere; and their much lower land area requirements. BECCS and DACS are also at a more advanced stage of deployment than some carbon removal approaches. Land management approaches and afforestation/reforestation are at the early adoption stage and their potential is limited by land needs for growing food. Other non-technological approaches – such as enhanced weathering, which involves the dissolution of natural or artificially created minerals to remove CO_2 from the atmosphere, and ocean fertilisation/alkalinisation, which involves adding alkaline substances to seawater to enhance the ocean's ability to absorb carbon – are only at the fundamental research stage. Thus, their carbon removal potentials, costs and environmental impact are extremely uncertain.

BECCS, DAC, land management approaches and ocean fertilisation/ alkalinisation have the highest cumulative potential; however, they all come with potential negative side effects such as land use changes, food security and biodiversity losses (BECCS, land management approaches), high CO_2 capture costs (DAC), and ocean eutrophication (ocean fertilisation/alkalinisation). DAC has the smallest land footprint among the most mature carbon removal options, while BECCS and afforestation/reforestation have similar ranges for the land footprint, which depends mainly on the source of biomass.

[10] Charcoal used as a soil amendment for the purposes of both carbon sequestration and soil health.

Table 2.3 Main carbon removal approaches and technologies

Approach	Approach type	Current maturity category	Carbon removal potential (cumul. to 2100, $GtCO_2$)*	CO_2 capture cost (USD/tCO_2)
Bioenergy with CCS	Technology	Demonstration	100-1170	15-85
Direct Air Capture and Storage	Technology	Demonstration	108-1000	135-345
Enhanced weathering of minerals	Enhanced natural processes	Fundamental research	100-367	50-200
Land management and biochar production	Enhanced natural processes	Early adoption	78-1468	30-120
Ocean fertilisation/alkalinisation	Enhanced natural processes	Fundamental research	55-1027	-
Afforestation/reforestation	Nature-based	Early adoption**	80-260	5-50

* Estimates for carbon removal potential are not additive, as CDR approaches partially compete for resources

** While afforestation/reforestation is an established practice, it is at early adoption in the context of carbon removal.

Sources: EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Keith et al. (2018), Minx et al. (2018), Nemet et al. (2018), Realmonte et al. (2019), Smith et al. (2015).

BECCS

BECCS involves the capture and permanent storage of CO_2 from processes where biomass is converted to energy or used to produce materials. Examples include biomass-based power plants, pulp mills for paper production, kilns for cement production and plants producing biofuels. Waste-to-energy plants may also generate negative emissions when fed with biogenic fuel. In principle, if biomass is grown sustainably and then processed into a fuel that is then burned, the technology pathway can be considered carbon-neutral; if some or all of the CO_2 released during combustion is captured and stored permanently, it is carbon negative, i.e. less CO_2 is released into the atmosphere than is removed by the crops during their growth. In practice, a life cycle assessment is needed to identify whether a specific technology and application is genuinely producing negative emissions or not, depending on the sustainability of the biomass feedstock, the scope of the application, changes in land management and use, and the timing of emissions and removals (IEA Bioenergy, 2013).

BECCS is the most mature of all the carbon removal technologies, as both bioenergy production and CCS have been separately proven at commercial scale. BECCS is already operating in the fuel transformation and power generation sectors, with different levels of maturity depending on the specific application. The most advanced BECCS projects capture CO_2 from ethanol production or biomass-based power generation, while industrial applications of BECCS are only at the prototype stage (IEA, 2020d). There are currently more than ten facilities capturing CO_2 from bioenergy production around the world (Table 2.4). The Illinois Industrial CCS Project, with a capture capacity of 1 $MtCO_2$/yr, is the largest and the only project with dedicated CO_2 storage, while other projects, most of which are pilots, use the captured CO_2 for EOR or other uses.

Table 2.4 Leading bioenergy with CCS/CCU projects currently operating worldwide

Plant	Country	Sector	CO_2 storage or use	Start-up year	CO_2 capture capacity (kt/year)
Stockholm Exergi AB	Sweden	Combined heat and power	-	2019	Pilot
Arkalon CO_2 Compression Facility	United States	Ethanol production	Storage (EOR)	2009	290
OCAP	Netherland	Ethanol production	Use	2011	<400*
Bonanza BioEnergy CCUS EOR	United States	Ethanol production	Storage (EOR)	2012	100
Husky Energy CO_2 Injection	Canada	Ethanol production	Storage (EOR)	2012	90
Calgren Renewable Fuels CO_2 recovery plant	United States	Ethanol production	Use	2015	150
Lantmännen Agroetanol	Sweden	Ethanol production	Use	2015	200
AlcoBioFuel bio-refinery CO_2 recovery plant	Belgium	Ethanol production	Use	2016	100
Cargill wheat processing CO_2 purification plant	United Kingdom	Ethanol production	Use	2016	100
Illinois Industrial Carbon Capture and Storage	United States	Ethanol production	Dedicated storage	2017	1000
Drax BECCS plant**	United Kingdom	Power generation	-	2019	Pilot
Mikawa post combustion capture plant	Japan	Power generation	-	2020	180
Saga City waste incineration plant	Japan	Waste-to-energy	Use	2016	3

* The OCAP plant receives its CO_2 from a fuel refining facility (hydrogen production) and from an ethanol production plant. Therefore only part of the total CO_2 (400 kt/year) qualifies as bioenergy with CCU.

** The project is currently releasing CO_2 after its capture, but the long-term plan is to focus on offshore storage as part of the Zero Carbon Humber project.

DAC

DAC technologies extract CO_2 directly from the atmosphere for permanent storage (carbon removal), or for use, for example, in food processing or to produce synthetic hydrocarbon fuels (where the CO_2 is ultimately re-released). Currently, technologies to capture CO_2 from the air rely either on liquid sorbents (liquid DAC [L-DAC]), using a hydroxide solution (Carbon Engineering, 2020)) or solid sorbents (solid DAC [S-DAC]), making use of a CO_2 "filter" (Climeworks, 2020) or dry, amine-based chemical sorbents (Global Thermostat, 2020).

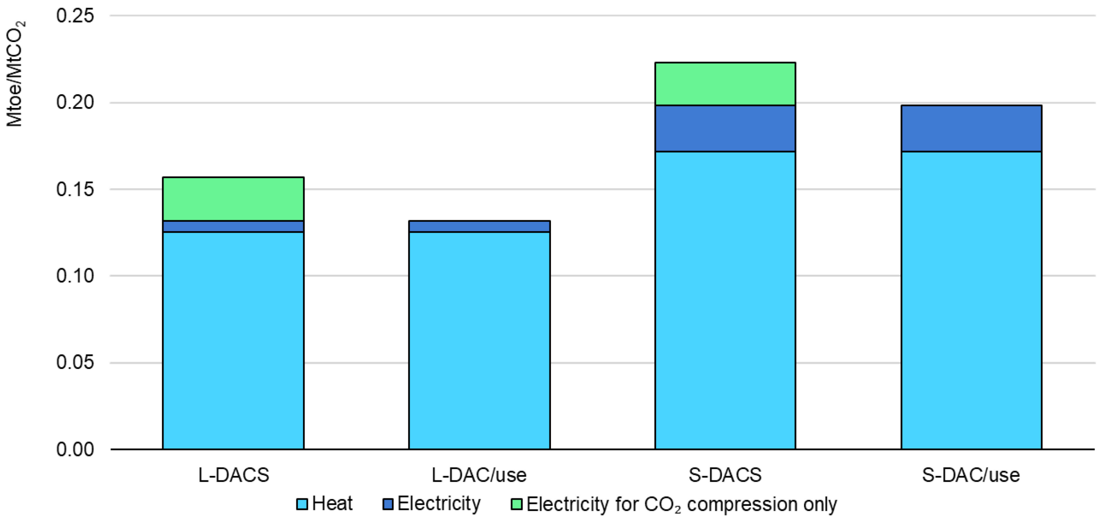
While existing DAC technologies rely on both fuel for heat and electricity to power rotating equipment for their operation, S-DAC could operate solely on electricity, which could come from renewable power sources. On the other hand, L-DAC will most likely always need a source of heat such as natural gas in order to achieve the high operating temperature needed in the calciner (around 900°C), unless a new way of providing a low-carbon source of heat (which does not currently exist [IEA, 2019a[11]] becomes commercially available. If gas were used to provide the heat (as it is the case nowadays), the associated CO_2 emissions would also need to be captured and stored along with the CO_2 captured directly from the air to maximise carbon removal.

An advantage of DAC is the potential for flexibility in siting. For example, a DAC plant could be located next to a plant that needs CO_2 as a feedstock or on top of a geological storage site to reduce the need for CO_2 transport. DAC facilities can also be co-located with other CO_2 capture facilities, such as CCUS-equipped power or industrial plants, to facilitate access to existing CO_2 transport infrastructure and enabling these facilities to reach net zero or even negative emissions.

The main drawback of DAC is the low CO_2 concentration in ambient air compared with other sources of CO_2, such as industrial or power plants, which makes this technology highly energy-intensive and expensive compared with other options for carbon removal. The amount of energy needed and the share between fuel and electricity differs depending on the type of technology and whether the CO_2 needs to be compressed for transportation and storage (Figure 2.17). L-DAC for CO_2 use applications requires relatively small amounts of electricity (less than 5% of total energy needs); S-DAC for storage typically requires more (23%). Natural gas – usually the cheaper source of energy for heat-raising – is mainly used to regenerate the solvent, either at around 100°C (S-DAC) or around 900°C (L-DAC).

[11] Heat technologies can currently reach up to around 500°C if they employ biomass and/or biogas and up to around 1 000°C if they employ electricity (in very specific applications such as steel and aluminium making).

Figure 2.17 Specific energy consumption for CO_2 capture using current DAC technologies



The amount of energy needed for DAC depends on the technology and whether the CO_2 is compressed for storage or used at low pressure.

A total of 15 DAC plants are currently operating in Canada, Europe, and the United States (Table 2.5). Most of them are small-scale pilot and demonstration plants, with the CO_2 diverted to various uses, including for the production of chemicals and fuels, beverage carbonation and in greenhouses, rather than geologically stored. Two commercial plants are currently operating in Switzerland, selling CO_2 to greenhouses and for beverage carbonation. There is only one pilot plant, in Iceland, currently storing the CO_2: the plant captures CO_2 from air and blends it with CO_2 captured from geothermal fluid before injecting it into underground basalt formations, where it is mineralised, i.e. converted into a mineral (CarbFix, 2020). In North America, both Carbon Engineering and Global Thermostat have been operating a number of pilot plants, with Carbon Engineering (in collaboration with Occidental Petroleum) currently designing what would be the world's largest DAC facility, with a capture capacity of 1 $MtCO_2$ per year, for use in EOR (Carbon Engineering, 2019).

Table 2.5 DAC plants in operation worldwide, 2020

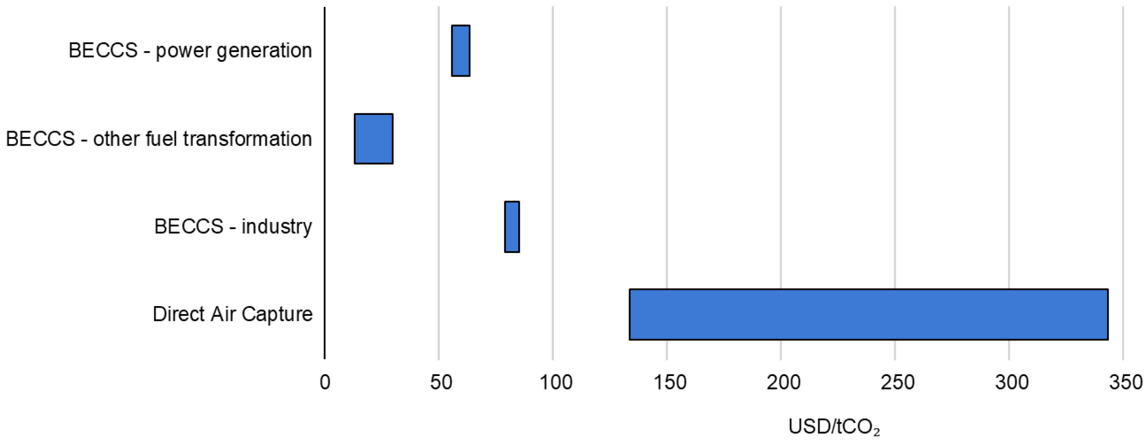
Company	Country	Sector	CO_2 storage or use	Start-up year	CO_2 capture capacity (tCO_2/year)
Climeworks	Switzerland	Greenhouse fertilisation	Use	2017	900
Climeworks	Switzerland	Beverage carbonation	Use	2018	600
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Netherlands	Power-to-X	Use	2019	3
Climeworks	Germany	Power-to-X	Use	2019	3
Climeworks	Switzerland	Power-to-X	Use	2018	3
Climeworks	Germany	Customer R&D	Use	2015	1
Climeworks	Switzerland	Power-to-X	Use	2016	50
Climeworks	Italy	Power-to-X	Use	2018	150
Climeworks	Germany	Power-to-X	Use	2020	50
Climeworks	Iceland	Mineralisation of CO_2	Storage	2017	50
Carbon Engineering	Canada	Power-to-X	-	2015	365 (max)
Global Thermostat	United States	-	-	2013	2500
Global Thermostat	United States	-	-	2010	500
Global Thermostat	United States	-	-	2019	4000

Note: Power-to-X refers to a suite of technologies that convert electricity into other forms of energy such as ammonia or hydrogen.

Costs of BECCS and DAC

At present, BECCS is the cheaper of the technology-based approaches for carbon removal (Figure 2.18). Generally speaking, the higher the initial concentration of CO_2 before capture, the lower the capture cost, which is why BECCS is cheaper than DAC. In the case of BECCS, capture from fuel transformation processes (such as bioethanol production from sugar or starch cane) or biomass gasification (where only pre-treatment and compression are needed to capture CO_2) are the cheapest at present, with costs ranging from about USD 15/tCO_2 to USD 30/tCO_2. Capture in biomass based power generation costs around USD 60/tonne, while BECCS applied to industrial processes has a capture cost of around USD 80/t.

Figure 2.18 Current cost of CO_2 capture for carbon removal technologies by sector



Notes: CO_2 capture costs are based on the following assumptions: technical lifetime = 25 years; representative discount rate = 8%; the price of fuel = USD 7.50/GJ; the price of electricity = USD 6.7/GJ. BECCS applied to industrial processes is based on chemical absorption.

Sources: EASAC (2018), Fuss et al. (2018), Haszeldine et al. (2018), Keith et al. (2018), Realmonte et al. (2019).

BECCS in fuel transformation is currently the cheapest carbon removal technology per tonne of CO_2 captured

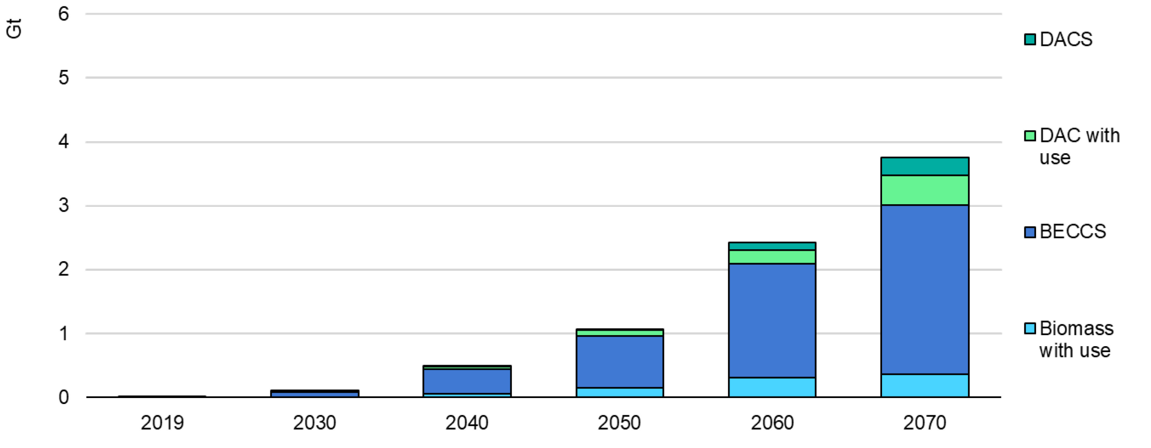
Capture costs for DAC are much higher than for BECCS capture – by a factor of between 2 and 25 – due mainly to the lower initial concentration of CO_2 compared with industrial streams. DAC costs vary according to the type of technology (solid- or liquid- based technologies) and whether the captured CO_2 needs to be compressed to high pressure for transport and storage rather than used immediately at low pressure. As the technology has yet to be demonstrated on a large scale, future costs are extremely uncertain. Cost estimates reported in the literature are wide, typically ranging from USD 100/tCO_2 to 1 000/tCO_2 (Realmonte et al., 2019). Carbon Engineering claimed that costs as low as USD 94/t to USD 232/t were achievable depending on financial assumptions, energy costs and the specific plant configuration (Keith et al., 2018).

The energy needs for a DAC plant will be a major factor in determining plant location and production costs. The choice of location needs to take into account the source of the energy needed to run the DAC plant, which will also determine if the system is carbon negative, as well as the cost of the energy. For instance, low-carbon energy sources such as solar thermal, photovoltaic (PV) and wind power generation could power DAC plants in isolated areas, though the utilisation rate of the plant (and, therefore, its economic viability) would vary according to the availability of sunshine and wind.[12]

Carbon removal in the Sustainable Development Scenario

Carbon removal accounts for a large and increasing share of the CO_2 captured over the projection horizon in the Sustainable Development Scenario. Bioenergy with CCS/CCU and DAC together account for 25% of all the CO_2 cumulatively captured to 2070. Of all the CO_2 captured by the two technologies, around 48 Gt, or 78%, is stored permanently and so counts as carbon removal. Captured and stored volumes reach around 2.7 Gt for BECCS and almost 0.3 Gt for DACS in 2070 (Figure 2.19). In both the Stated Policies and Sustainable Development Scenarios, the availability of sustainable biomass is assumed to be limited to around 3 000 Mtoe/year (125 EJ/year), which constrains the deployment of BECCS (see below). Stronger policy incentives, including higher carbon prices, are nonetheless assumed to drive much faster growth in BECCS in the Sustainable Development Scenario.

Figure 2.19 Global CO_2 capture from biomass and DAC for use or storage in the Sustainable Development Scenario

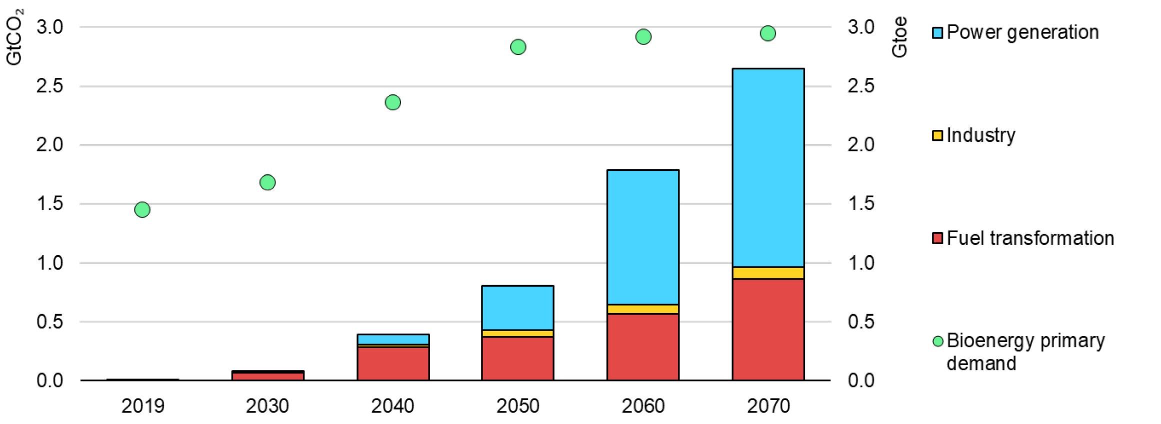


More than 60 Gt of CO_2 is captured from biomass and the air in the period to 2070, with around 77% of this permanently stored

[12] The potentially lower cost of the variable renewable energy would need to be weighed against the lower utilisation rate and, therefore, higher levelised capital cost of the plant per tonne of CO_2 captured (Fasihi, Efimova and Breyer, 2019).

BECCS starts to be deployed at scale from 2030, and by 2070, it has captured a cumulative total of around 45 $GtCO_2$ in the Sustainable Development Scenario. It is mainly installed in power generation (55%) (Box 2.2) and fuel transformation (40%), with the remainder in the cement and pulp and paper industries (Figure 2.20). By 2070 half of biomass-fired generation is associated with CCUS. When BECCS is deployed in the fuel transformation sector (where CO_2 capture is cheaper than in other sectors) around half of the carbon remains in the biofuel product, providing a carbon-neutral fuel for hard-to-abate transport modes.

Figure 2.20 Global CO_2 capture from BECCS by sector (left) and bioenergy primary demand (right) in the Sustainable Development Scenario



BECCS cumulatively captures more than 53 Gt of CO_2 in the Sustainable Development Scenario, mainly in power generation and fuel transformation.

Land and water requirements

BECCS and DACS can play a decisive role in getting the global energy system to net-zero emissions. However, there remains considerable uncertainty regarding the potential contribution of these technologies in practice, notably with respect to future costs and performance, how fast they can be commercialised, public understanding and acceptance, the limits to the availability of sustainable biomass, and how quickly CO_2 transport and storage infrastructure can be developed. This underscores the need for intensive RD&D to ensure that these technologies are ready to be deployed on a large scale within the next decade given the lead times involved.

Particular concerns have been expressed regarding the land requirements associated with both BECCS and DACS. The land footprint for BECCS is estimated at between 1 000 and 17 000 km^2 per Mt of CO_2 removed, depending on a number of factors including location and the source for the biomass (e.g. forest and agricultural residues, and purpose-grown energy crops). The land needs for DAC are smaller, at a maximum of around 15 km^2 per Mt of CO_2 removed, including the space needed for solar PV panels if they are the sole source of the electricity used to run the plants.[13] The 740 $MtCO_2$ captured by DAC in 2070 in the Sustainable Development Scenario would require approximately 10 500 km^2 of land if using solar PV – roughly one-third the size of Belgium. The same level of removal through afforestation would require between 0.5 and 11.5 million km^2, the latter being a land area bigger than the United States. An emerging DAC technology, based on electro swing adsorption (ESA-DAC)[14] has potential for a smaller land footprint (Voskian and Hatton, 2019).

Water requirements for DAC are highly dependent on the chosen technology. L-DAC requires significant amounts of water while, by contrast, some S-DAC options produce water, which could be beneficial within integrated systems with water demand such as hydrogen production (Breyer, et al., 2019).

[13] The land footprint of solar PV is about 1 km^2 for a power generation of 25 MW.
[14] ESA can capture CO_2 from gas containing up to 15 vol% CO_2 and therefore has the potential to be suitable for more applications than just DAC.

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Chapter 3: CCUS technology innovation

HIGHLIGHTS

- The extent to which CCUS will be able to contribute to achieving net-zero emissions hinges in large part on technological progress. The maturity of CCUS varies considerably by technology type and application: several technologies are already mature and could be scaled up rapidly in applications such as coal-fired power generation and hydrogen production, while others require further development.
- Two-thirds of the cumulative emissions reductions from CCUS through to 2070 in the Sustainable Development Scenario relative to the Stated Policies Scenario come from technologies that are currently at the prototype or demonstration stage. Given the time lags involved, innovation needs to be stepped-up now to ensure key applications are commercially available in the coming decade.
- There is a disconnect between the level of maturity of individual CO_2 capture technologies and the areas in which they are most needed. For example, the most advanced technology for CO_2 capture in the cement industry is only at the demonstration stage, but a lack of alternative technology options means CCUS is needed to deliver 60% of the sector's emissions reductions in the Sustainable Development Scenario. Other CCUS applications that will require a major innovation push include chemicals and steel production, gas-fired power generation, BECCS and DAC.
- Transport and storage of CO_2 has been demonstrated for several decades but innovation can improve existing technologies and unlock new opportunities, including large-scale shipping of CO_2 and more advanced technologies for long-term monitoring of stored CO_2. Innovation in CO_2 use applications, including for synthetic fuels and chemicals, will be important to secure cost reductions.
- The theoretical capacity for storing CO_2 in deep geological formations globally is vast and far exceeds that required to reach net-zero emissions; in the Sustainable Development Scenario, only 3% of potential global storage capacity is used. Further exploration and assessment will be critical to provide confidence in the availability of CO_2 storage in key regions.

Technology readiness along the CCUS value chain

The capture, transport and utilisation or storage of CO_2 as a successful mitigation strategy hinges on the availability of technologies at each stage of the process as well as on the development and expansion of CO_2 transport and storage networks. All of the steps along the value chain need to be technologically ready and developed in tandem for CCUS to scale up.

CCUS technologies are at varying levels of maturity today. Several technologies in CO_2 capture, transport, utilisation and storage are already deployed at large scale, but other technologies, including those that hold out the promise of better performance and lower unit costs, require further development. One way to assess where a technology is in its journey from the laboratory to the marketplace is to use the TRL scale, which provides a common framework that can be applied to any technology to assess and compare the maturity of technologies across and within different sectors (Box 3.1).

Box 3.1 Technology readiness level scale

Originally developed by the United States National Aeronautics and Space Administration (NASA) in the 1970s, the TRL provides a snapshot in time of the level of maturity of a given technology within a defined scale. It is now widely used by research institutions and technology developers around the world to set research priorities and design innovation support programmes. The scale, which ranges from 1 to 9, can be applied to any technology. However, arriving at a stage where a technology can be considered commercially available (TRL 9) is not sufficient to describe its readiness to meet energy policy objectives, for which scale is often crucial. For this reason, the IEA has extended the TRL scale used in this report to incorporate two additional levels of readiness: one where the technology is commercial and competitive but needs further innovation efforts for the technology to be integrated into energy systems and value chains when deployed at scale (TRL 10), and a final one where the technology has achieved predictable growth (TRL 11). The TRLs are grouped in this report into four broader readiness categories: prototype, demonstration, early adoption and mature. All of the CCUS technologies and CCUS value chains that are projected to play a role in the Sustainable Development Scenario before 2070 are already at least at the prototype stage. For more details, see IEA (2020a) and IEA (2020b).

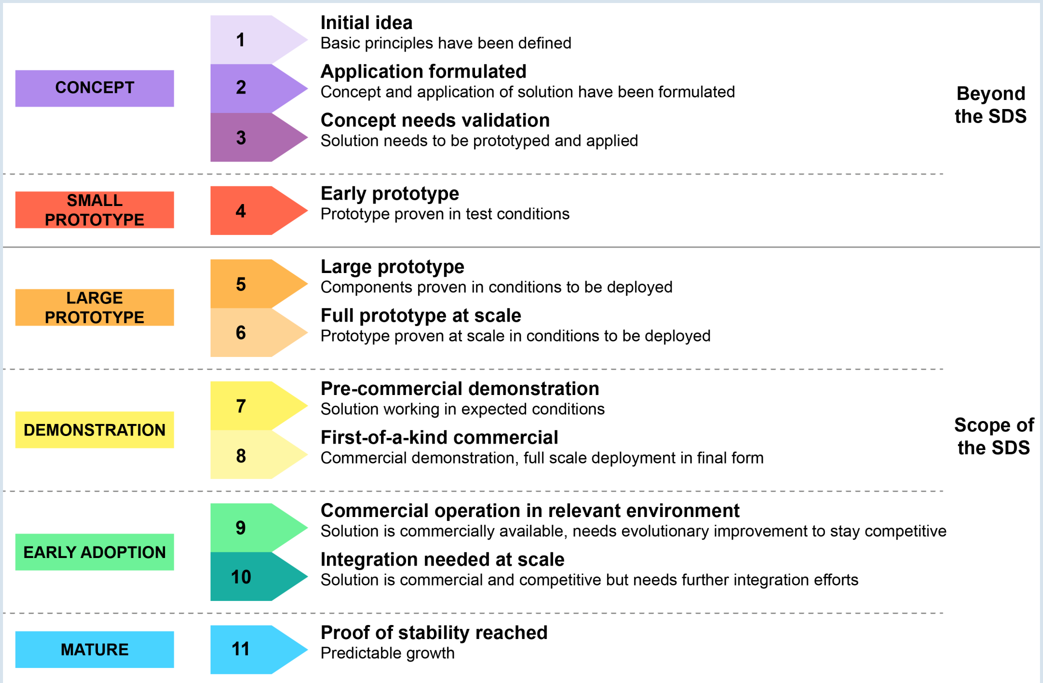
Mature for commercial technology types that have reached sizeable deployment and for which only incremental innovations are expected. Technology types in this category have all designs and underlying components at TRL 11. Hydropower and electric trains are examples.

Early adoption for technology types for which some designs have reached market and require policy support for scale-up, but where there are competing designs being validated at the demonstration and prototype stages. Technology types in this category have an underlying design of TRL ≥ 9. Offshore wind, electric batteries and heat pumps are examples.

Demonstration for technology types for which designs are at demonstration stage or below, meaning no underlying design at TRL ≥ 9, but with at least one design at TRL 7 or 8. Carbon capture in cement kilns, electrolytic hydrogen-based ammonia and methanol, and large long-distance battery-electric ships are examples.

Prototype for technology types for which designs are at prototype stage of a certain scale, meaning no underlying design at TRL 7 or 8, but with at least one design at TRL 5. Ammonia-powered vessels, electrolytic hydrogen-based steel production and DAC are examples.

Technology readiness level scale applied by the IEA



The TRLs and categories used in this report (prototype, demonstration, early adoption and mature) refer not only to the stages of technological development, but also to their adoption in the market. Most technologies that are at the early adoption stage today have already gone through the full technological development cycle, but have not been labelled as "mature" because they have not been widely deployed yet – as is the case for most CCUS applications. A broad range of technologies therefore fall into the "early adoption" category, including many advanced CCUS technologies but also renewable technologies such as electric vehicles, onshore wind and solar PV, which are commercial and competitive but require further integration efforts. Technologies in the early adoption category can be scaled up rapidly once the necessary policy and legal framework conditions are in place.

Figure 3.1 TRL of select technologies along the CCUS value chain

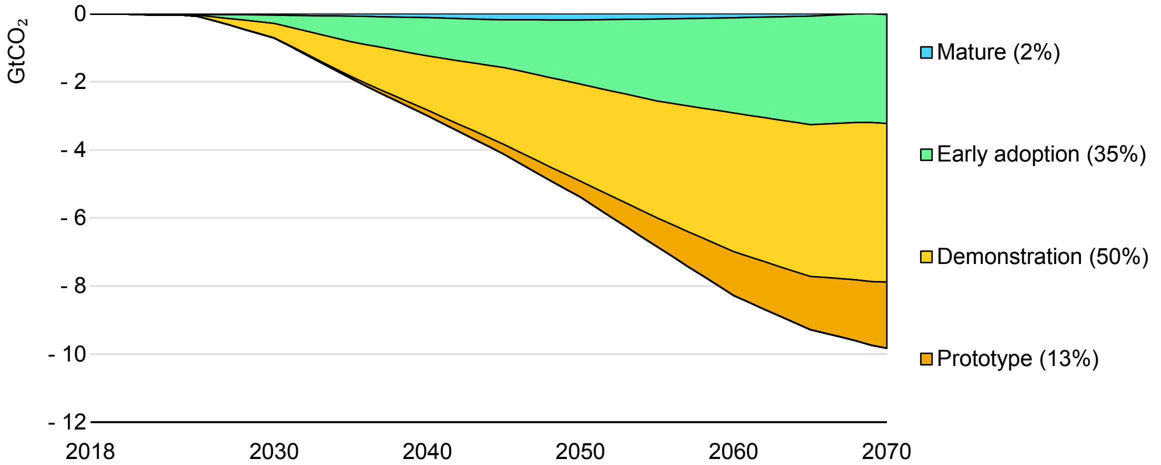
Notes: Technologies included are at large prototype or a more advanced stage. Each technology is assigned the highest technology readiness level of the underlying technology designs. For more detailed information on individual technology designs for each of these technologies and designs at small prototype stage or below, such as mineral CO_2 storage, see: www.iea.org/articles/etp-clean-energy-technology-guide.

Not all parts of the CO_2 value chain are operating at commercial scale today: many key technologies are still at the demonstration and the large prototype stage.

Several applications of CCUS are already widely deployed today, including chemical absorption of CO_2 from ammonia production and natural gas processing, CO_2 use in the production of fertiliser (urea), and long-distance pipeline transport and injection of CO_2 for EOR (Figure 3.1). A number of other applications have been demonstrated at scale over the last decades, but are still at the early adoption stage, such as chemical absorption from coal-fired power generation and hydrogen production from natural gas, compression of CO_2 from bioethanol production and coal-to-chemicals plants, and CO_2 storage in saline aquifers. Several other applications, including DAC and CO_2 capture from cement and iron and steel making, are still at the demonstration or prototype stage. In each of these potential new applications, a range of CO_2 capture technologies need to be tailored to the particular conditions of each individual process.

In the Sustainable Development Scenario, nearly two-thirds of the cumulative emissions reductions from CCUS through to 2070 relative to the Stated Policies Scenario come from technologies that are currently at the prototype or demonstration stage (Figure 3.2). The other one-third comes from technologies that are already mature or at the early adoption stage, which can be scaled up rapidly, bringing forth incremental technological improvements and cost savings. In the decade to 2030, such technologies in power and fuel transformation, including hydrogen production, contribute around half of the cumulative emissions savings in the Sustainable Development Scenario. Most of these applications are based on chemical absorption as the CO_2 capture technology, with this already widely used in commercial capture facilities and embedded in demonstration plants today.

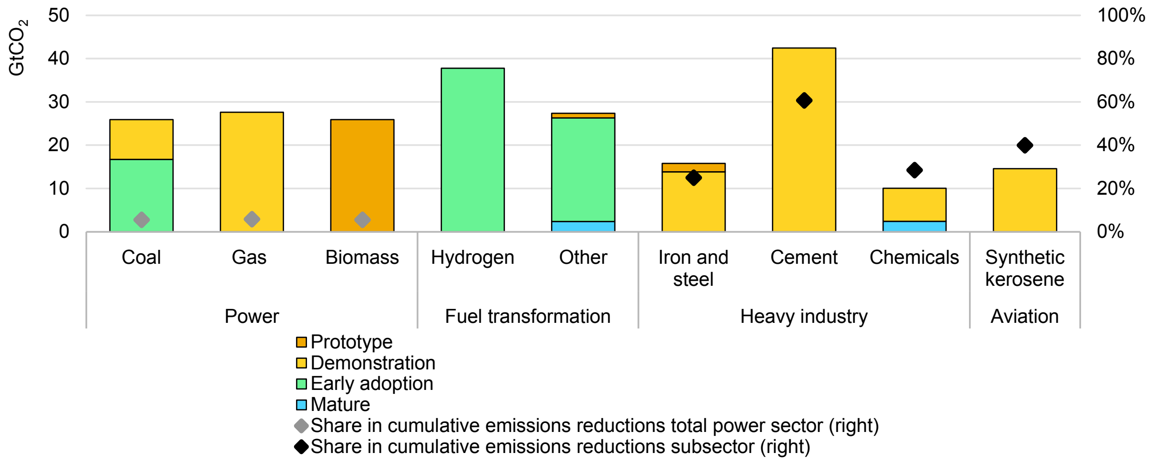
Figure 3.2 World CO_2 emissions reductions from CCUS by technology readiness category in the Sustainable Development Scenario relative to the Stated Policies Scenario



CCUS technologies that are only at the prototype or demonstration stage today contribute nearly two-thirds of the cumulative emissions reductions achieved by CCUS through to 2070 in the Sustainable Development Scenario.

Major improvements to a wide range of technologies that are at the prototype or demonstration stage today are needed. Important applications that start to play a pivotal role in the next decade or so, but that still require a near-term push from RD&D, include chemical absorption from gas-fired power generation and cement and chemicals production, BECCS and CO_2 capture from iron and steel manufacturing (Figure 3.3). Some applications have multiple technology maturities as they represent several sub-applications with different capture technologies (e.g. coal power generation), or different energy conversion or production processes from which the CO_2 is captured (e.g. other fuel transformation, chemicals, and iron and steel).

Figure 3.3 World cumulative CO_2 emissions reductions from CCUS by application and technology readiness in the Sustainable Development Scenario relative to the Stated Policies Scenario, 2020-70



Note: The grey diamonds show the share of CCUS in coal, gas and biomass in the total power sector's cumulative emissions reductions, while the black diamonds show the share of CCUS of the heavy industry and aviation subsectors in its own subsector, for example the share of CCUS in cement in total cumulative emissions reductions of the cement sector. Synthetic hydrocarbon fuels are shown only for aviation as the vast majority of the fuels is used in this sector. The contribution of CCUS to overall emission reductions is not shown for hydrogen production or other fuel transformation as the emission reductions from CCUS are shared with other sectors, such as industry, transport, buildings and power.

CCUS is only at the prototype stage in some sectors, including cement, where it is needed to deliver a large share of the emissions reductions.

DAC and CO_2 conversion to synthetic hydrocarbon fuels, which play important roles later in the projection period, also require considerable further RD&D to ensure that they can start to be deployed at scale from the 2030s. Efforts to develop DAC early can provide an important technology hedge against the risk of slower-than-expected innovation or commercialisation of other technologies.

CO_2 capture

CO_2 capture is an integral part of several industrial processes and, accordingly, technologies to separate or capture CO_2 from flue gas streams have been commercially available for many decades. The most advanced and widely adopted capture technologies are chemical absorption and physical separation; other technologies include membranes and looping cycles such as chemical looping or calcium looping (Box 3.2). In practice, the most appropriate capture technology for a given application depends on a number of factors, including the initial and final desired CO_2 concentration, operating pressure and temperature, composition and flow rate of the gas stream, integration with the original facility, and cost considerations.

Box 3.2 Principal CO_2 capture technologies

Chemical absorption of CO_2 is a common process operation based on the reaction between CO_2 and a chemical solvent (such as compounds of ethanolamine). This operation is usually performed using two columns, one for the absorption and the other operating at a higher temperature, releasing pure CO_2 and regenerating the chemical solvent for further operation. Chemical absorption using amine-based solvents is the most advanced CO_2 separation technique (TRL 9-11). It has been widely used for decades and is currently applied in a number of small and large-scale projects worldwide in power generation (e.g. Boundary Dam in Canada and Petra Nova in the United States), fuel transformation (e.g. Quest in Canada) and industrial production (e.g. Al Reyadah CCUS project and Japan's COURSE50 Project in steel production, the Enid Fertilizer Plant in the United States and the Uthmaniyah CO_2-EOR demonstration project in Saudi Arabia). There are also other large-scale CCUS projects currently planned (e.g. cement production in Norway, waste-to-energy in Norway and The Netherlands) which will all be using chemical absorption for CO_2 separation.

Physical separation of CO_2 is based on either adsorption, absorption, cryogenic separation, or dehydration and compression. Physical adsorption makes use of a solid surface (e.g. activated carbon, alumina, metallic oxides or zeolites), while physical absorption makes use of a liquid solvent (e.g. Selexol or Rectisol). After capture by means of an adsorbent, CO_2 is released by increasing temperature (temperature swing adsorption [TSA]) or pressure (pressure swing adsorption [PSA] or vacuum swing adsorption [VSA]).

Physical separation is currently used mainly in natural gas processing and ethanol, methanol and hydrogen production, with nine large plants in operation (TRL 9-11), all of them in the United States. They typically employ proprietary solvents (at the

Century Plant in Texas, the Great Plains Synfuels Plant in North Dakota, the Lost Cabin Gas Plant in Wyoming, and the Terrell Natural Gas Processing Plant in Texas), VSA (Air Products' carbon capture from hydrogen production facility in Texas) or cryogenic separation techniques (the Shute Creek Gas processing plant in Wyoming). The Illinois Industrial Carbon Capture and Storage Project is the largest CCUS facility applied to biofuels production and relies on dehydration and compression (due to the composition of the gas stream, exclusively CO_2 and water), while the Coffeyville Gasification Plant uses CO_2 physical separation through separation and compression of highly concentrated CO_2 streams.

Oxy-fuel separation involves the combustion of a fuel using nearly pure oxygen and the subsequent capture of the CO_2 emitted. Because the flue gas is composed almost exclusively of CO_2 and water vapour, the latter can be removed easily by means of dehydration to obtain a high-purity CO_2 stream. Typically, oxygen is produced commercially via low-temperature air separation, which is energy-intensive. Lowering the energy consumption of this step and of the overall oxy-fuel process are, therefore, key factors in reducing capture costs. Advanced concepts with potential for cost reduction include oxy-fuel gas turbines (used within supercritical CO_2 power cycles) and pressurised oxy-fuel CO_2 capture, both of which make more efficient use of materials and are thus potentially cheaper to build and operate. The technology is currently at the large prototype or pre-demonstration stage (TRL 5 to 7). A number of projects have been completed in coal-based power generation (the Callide project in Australia and the Compostilla project in Spain) and in cement production (HeidelbergCement's Colleferro plant in Italy, LafargeHolcim's Retznei plant in Austria and the Cement Innovation for Climate facility in Germany).

Membrane separation is based on polymeric or inorganic devices (membranes) with high CO_2 selectivity, which let CO_2 pass through but act as barriers to retain the other gases in the gas stream.* Their TRLs vary according to the fuel and application. In natural gas processing, they are mainly at the demonstration stage (TRL 6-7). The only existing large-scale capture plant based on membrane separation is operated by Petrobras in Brazil. Membranes for CO_2 removal from syngas and biogas are already commercially available, while membranes for flue gas treatment are currently under development (He, X. et al., 2017). Several membrane technologies for CO_2 separation have been tested in the United States through collaborations between the National Carbon Capture Center and various partners including the Gas Technology Institute, the Department of Energy's National Energy Technology Laboratory, Membrane Technology and Research, and France's Air Liquide.

Calcium looping is a technology that involves CO_2 capture at a high temperature using two main reactors. In the first reactor, lime (CaO) is used as a sorbent to capture CO_2 from a gas stream to form calcium carbonate ($CaCO_3$). The $CaCO_3$ is subsequently transported to the second reactor where it is regenerated, resulting in lime and a pure stream of CO_2. The lime is then looped back to the first reactor.

Calcium looping technologies, currently at TRL 5-6, have been tested, mostly at the pilot plant scale, for coal-fired fluidised bed combustors and cement manufacture. Two European projects are developing calcium looping capture technologies in steel (C4U) and cement production (CLEANKER) at pilot and pre-commercial scales.

Chemical looping is a similar two-reactor technology. In the first reactor, small particles of metal (e.g. iron or manganese) are used to bind oxygen from the air to form a metal oxide, which is then transported to the second reactor where it reacts with fuel, producing energy and a concentrated stream of CO_2, regenerating the reduced form of the metal. The metal is then looped back to the first reactor. Chemical looping technologies have been developed by academia, research organisations and several companies, including manufacturers operating in the power sector. This has led to the development and operation of around 35 pilot projects (TRL 4-6) with capacity up to 3 MW for coal, gas, oil and biomass combustion (IEAGHG, 2019a).

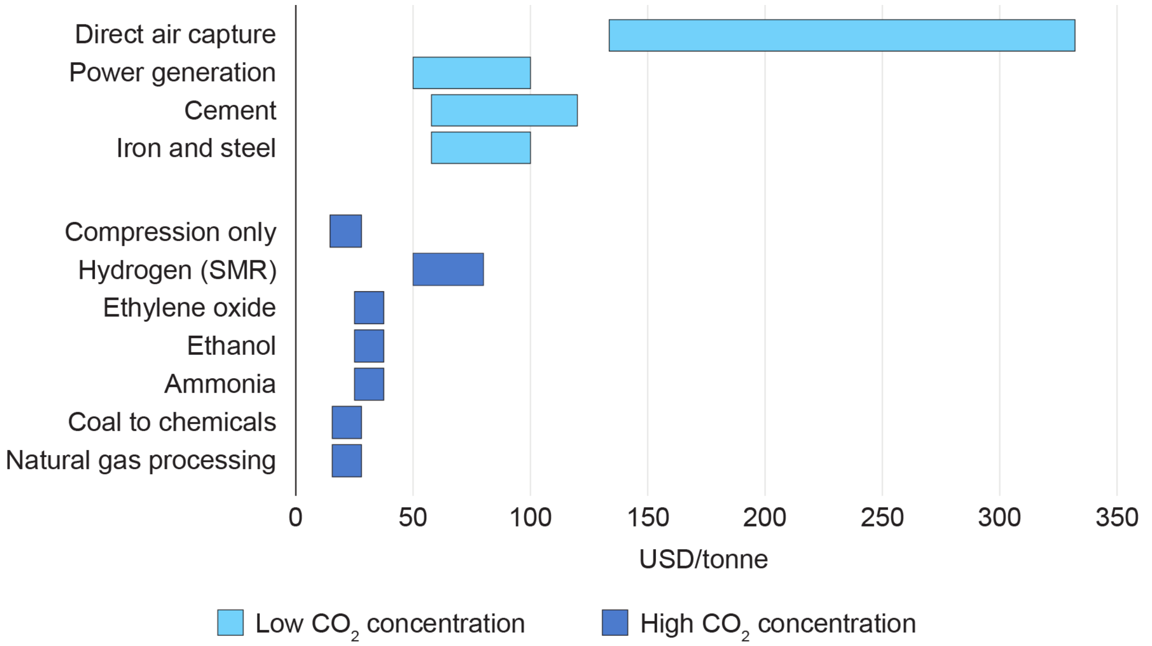
Direct separation involves the capture of CO_2 process emissions from cement production by indirectly heating the limestone using a special calciner (TRL 6). This technology strips CO_2 directly from the limestone, without mixing it with other combustion gases, thus considerably reducing energy costs related to gas separation. The Low Emissions Intensity Lime and Cement (LEILAC) pilot plant developed by Calix at the HeidelbergCement plant in Lixhe, Belgium, is one example where this technology is being applied in practice (LEILAC, 2019).

While in conventional thermal power plants, flue gas or steam is used to drive one or multiple turbines, in **supercritical CO_2 power cycles**, supercritical CO_2 (i.e. CO_2 above its critical temperature and pressure) is used instead. Supercritical CO_2 turbines typically use nearly pure oxygen to combust the fuel, in order to obtain a flue gas composed of CO_2 and water vapour only. Two supercritical CO_2 power cycles are currently in operation: NET Power's Allam cycle and the Trigen Clean Energy Systems (CES) cycle (TRL 5-7). The 50 MW NET Power plant in Texas started operations in 2018, while a 300 MW commercial plant is currently at the design phase. The 150 MW CES plant at the Kimberlina power station in California has been operating successfully since 2013.

* Membranes can also be highly selective to another permeate (such as hydrogen) and let that one through, retaining CO_2.

The cost of capturing CO_2 can vary significantly, mainly according to the concentration of CO_2 in the gas stream from which it is being captured, the plant's location, energy and steam supply, and integration with the original facility (Ferrari et al., 2019; IEAGHG, 2018c). For some processes, such as ethanol production or natural gas processing or after oxy-fuel combustion in applications such as power generation or cement, CO_2 can be already highly concentrated. This CO_2 can be simply pre-treated if necessary (e.g. dehydration) and then compressed for transport and storage or use at relatively low cost. For example, the cost of separating out the CO_2 contained in natural gas – which is often required for technical reasons before the gas can be sold or liquefied – can be as low as USD 15/t to USD 25/t (Figure 3.4).[1] For more diluted CO_2 streams, including the flue gas from power plants (where the CO_2 concentration is typically the 3-14%) or a blast furnace in a steel plant (20-27%), the cost of CO_2 capture is much higher (over USD 40/t of CO_2 and sometimes more than USD 100/t, accounting on average for around 75% of the total cost of CCUS (NPC, 2019).[2]

Figure 3.4 Levelised cost of CO_2 capture by sector and initial CO_2 concentration, 2019



Notes: CO_2 capture costs for hydrogen refers to production via SMR of natural gas; the broad cost range reflects varying levels of CO_2 concentration: the lower end of the cost range applies to CO_2 capture from the concentrated "process" stream, while the higher end applies to CO_2 capture from the more diluted stream coming out of the SMR furnace. Cost estimates are based on the United States. All capture costs include cost of compression.

Sources: IEA analysis based on own estimates and GCCSI (2017), Global costs of carbon capture and storage, 2017 update, IEAGHG (2014), CO_2 capture at coal based power and hydrogen plants, Keith et al. (2018), A Process for Capturing CO_2 from the Atmosphere, NETL (2014), Cost of capturing CO_2 from Industrial sources, Rubin, E. S., Davison, J. E. and Herzog, H. J (2015), The cost of CO_2 capture and storage.

The cost of CO_2 capture is much lower for concentrated sources such as hydrogen production, coal to chemicals and natural gas processing than for power generation, cement and steel production, and DAC.

[1] The CO_2 concentration of raw natural gas varies considerably by reservoir, ranging from CO_2-free natural gas in Siberian fields to exceptionally high shares of 90% CO_2 content in some fields in South-East Asia. Raw natural gas produced from the Norwegian Sleipner field has a CO_2 concentration of 9%, which is considered to be high compared to many other fields. The low capture cost is also due to the high pressure of the captured CO_2 stream, which reduces cost for CO_2 compression.

[2] The remaining 25% represents the cost of transport and storage.

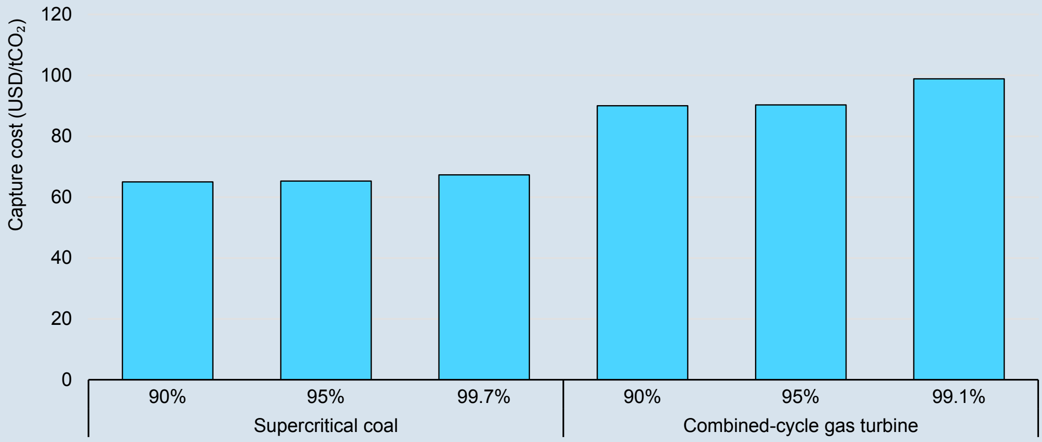
Most CO_2 capture systems have been designed to capture around 85-90% of the CO_2 from the point source, which results in the lowest cost per tonne of CO_2 captured. However, in a net-zero energy system, higher capture rates – approaching 100% – will be needed. This is technically and economically achievable according to recent studies (Box 3.3).

Box 3.3 The role of high CO_2 capture rates

To date, the developers of technology to capture CO_2 from low-concentration gas streams, such as flue gas from power stations or industrial furnaces (where the CO_2 makes up 3% to 14% by volume) have generally aimed for capture rates of 85% to 90%. These rates result in the lowest cost per tonne of CO_2 captured (Rao and Rubin, 2006). For example, the two large-scale CCUS projects in the power sector – the coal-based Boundary Dam and Petra Nova projects in North America – are designed to separate out around 90% of the CO_2 from the flue gas. Similar capture rates are applied in nearly all demonstration and pilot plants (IEAGHG, 2019b). In a net-zero emissions energy system, the residual emissions from fossil fuel-based power plants and industrial facilities would have to be mitigated as well, either by raising CO_2 capture rates, by co-firing biomass, or by integrating other carbon removal options.

There are no technical barriers to increase capture rates well beyond 90% for most mature capture technologies. In fact, natural gas processing today requires very high capture rates to meet product gas specifications for pipeline transport (typically less than 0.5% CO_2 by volume) and liquefaction (0.005% CO_2 by volume). While capturing 100% of the CO_2 is often prohibited by thermodynamic laws, capture rates of 98% or higher are technically feasible, but require modifications of the CO_2 separation process. These modifications typically include larger equipment, multiple process steps and higher energy consumption per tonne of CO_2 captured, which increases unit costs. The technical implications and costs of higher capture rates are best understood for chemical absorption systems. CO_2 capture rates as high as 99% can be achieved at comparably low additional marginal cost. For instance, increasing CO_2 capture rates for chemical absorption from 90% to over 99% increases capture costs by only 4% for coal-based and around 10% for gas-based power generation (IEAGHG, 2019b).

Indicative CO_2 capture costs for coal- and gas-fired power plants by capture rate



Source: IEA analysis based on own estimates and IEAGHG (2019b), Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass.

High capture rates become the dominant CCUS technology in the power sector and heavy industry in the Sustainable Development Scenario in the period after 2040. Gas-fired power plants, though having a lower carbon intensity than coal, are also equipped with high capture rate technology, as their residual emissions would otherwise be required to be compensated by carbon removal technologies.

CO_2 transport

The availability of infrastructure to transport CO_2 safely and reliably is an essential factor in enabling the deployment of CCUS. The two main options for the large-scale transport of CO_2 are via pipeline and ship, although for short distances and small volumes CO_2 can also be transported by truck or rail, albeit at higher cost per tonne of CO_2. Transport by pipeline has been practised for many years and is already deployed at large scale. Large-scale transportation of CO_2 by ship has not yet been demonstrated (TRL 4-7) but would have similarities to the shipping of liquefied petroleum gas (LPG) and LNG. Nonetheless, considerable possibilities for innovation remain, in particular for offshore unloading of CO_2, and spillovers from the general shipping industry, including automation and new propulsion technologies.

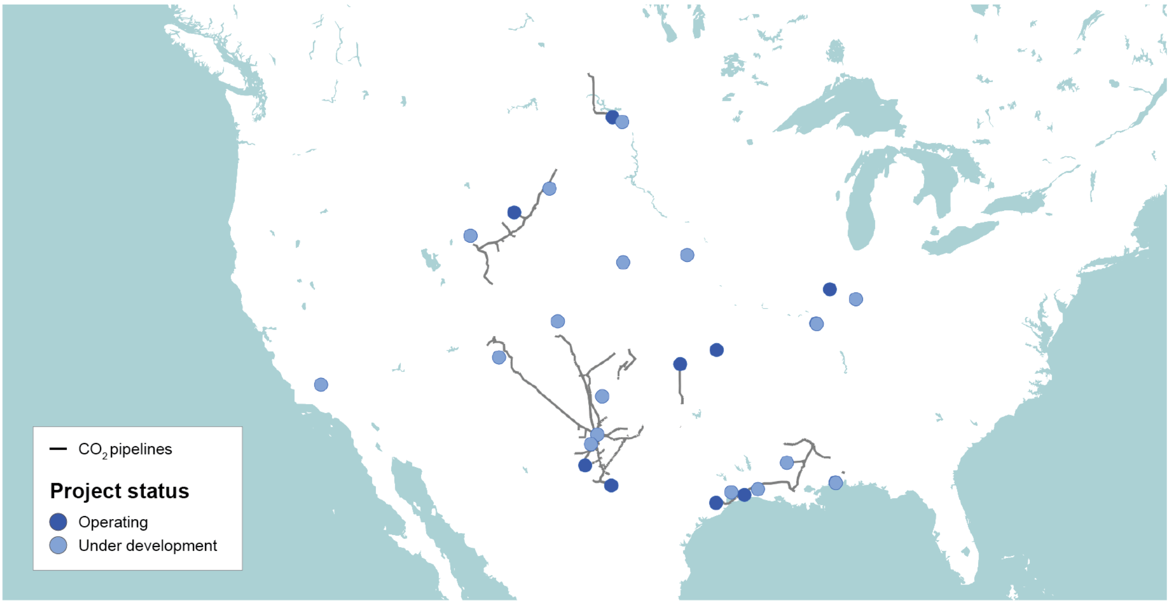
Economic factors and regulatory frameworks are the main considerations in the choice of CO_2 transport mode. Pipelines are the cheapest way of transporting CO_2 in large quantities onshore and, depending on the distance and volumes, offshore. There is already an extensive onshore CO_2 pipeline network in North America, with a combined length of more than 8 000 km – mostly in the United States. These onshore pipelines currently transport more than 70 Mt/year of CO_2, mainly for EOR. Combined with new policy incentives, including the 45Q tax credit, the vast existing pipeline network in the United States has been a key driver for recent project announcements (Figure 3.5). In June 2020, the Alberta Carbon Trunk Line (ACTL) in Canada came online with a pipeline capacity of 14.6 Mt CO_2, with significant excess capacity (some 90%) to accommodate CO_2 from future CCUS facilities. The ACTL received CAD 560 million (USD 430 million) in capital funding from the Canadian and Albertan governments, slightly below half of the CAD 1.2 billion (USD 920 million) estimated project cost (Government of Alberta, 2020; NRCAN, 2020a). There are also two CO_2 pipeline systems in Europe and two in the Middle East (Table 3.1).

Table 3.1 Table 3.1 CO_2 pipeline systems worldwide

Country	System	Length (km)	Capacity (Mt/year)
United States	Permian Basin (West Texas, New Mexico, Colorado)	4 180	
	Gulf Coast (Mississippi, Louisiana, East Texas)	1 190	
	Rocky Mountains (Colorado, Wyoming, Montana)	1 175	
	Midcontinent (Oklahoma, Kansas)	770	
	Other (North Dakota, Michigan)	345	
Canada	Alberta Carbon Trunk Line	240	14.6
	Quest	84	1.2
	Saskatchewan	66	1.2
	Weyburn	330	2
Norway	Hammerfest	153	0.7
Netherlands	Rotterdam	85	0.4
United Arab Emirates	Abu Dhabi	45	
Saudi Arabia	Uthmaniyah	85	

Source: IEA analysis based on IEAGHG (2013), CO_2 pipeline infrastructure report 2013/18 and Peletiri, Rahmanian and Mujtaba (2018), CO_2 Pipeline Design: A Review.

Figure 3.5 Existing CO_2 pipeline infrastructure and CCUS projects in the United States



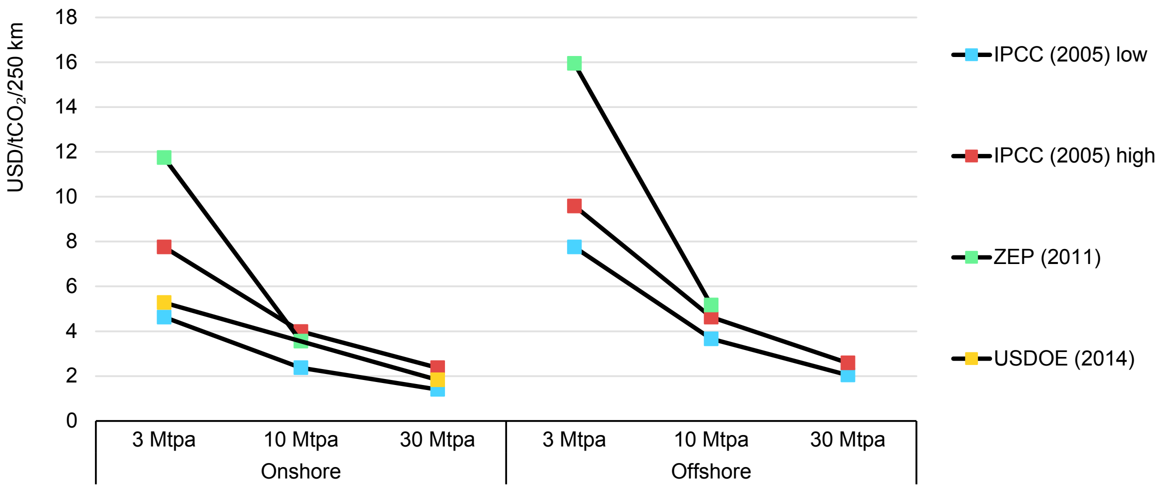
Source: Transport infrastructure based on Edwards, R. and Celia, M. (2018), Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States.

Proximity to pipeline infrastructure has been a key driver for recent CCUS project announcements in the United States.

The share of pipeline transportation in the total cost of a CCUS project varies according to the quantity transported as well as the diameter, length and materials used in building the pipeline. Other factors include labour cost and the planned lifetime of the system. Location and geography are significant factors that affect the total cost as well. In most cases, transport represents well under one-quarter of the total cost of CCUS projects. Pipelines located in remote and sparsely populated regions cost about 50-80% less than in highly populated areas (Onyebuchi et al., 2018). Offshore pipelines can be 40-70% more expensive than the onshore pipelines. There are strong economies of scale based on pipeline capacity, with unit costs decreasing significantly with rising CO_2 capacity (Figure 3.6). Pipeline costs are also likely to differ substantially among regions as new projects are developed. The cost of new pipelines is estimated to be generally 30% lower in Asia than in Europe (World Bank, 2015).

While the properties of CO_2 lead to different design specifications compared with natural gas, CO_2 transport by pipeline bears many similarities to high-pressure transport of natural gas. Repurposing existing natural gas or oil pipelines, where feasible, would normally be much cheaper than building a new line (Box 3.4). Design pressure and remaining service life are the two main considerations to be taken into account to evaluate the repurposing of existing oil and gas pipelines. Oil and gas pipelines typically operate at lower pressure, which leads to a reduction in CO_2 transport capacity compared with higher-pressure purpose-built CO_2 pipelines. Furthermore, many existing oil and gas pipelines have been in operation for more than 20 years. A case-by-case analysis is necessary to evaluate their remaining life, taking into account in particular internal corrosion and the remaining fatigue life (JRC, 2011).

Figure 3.6 Indicative unit CO_2 pipeline transport costs



Note: ZEP = Zero Emissions Platform; USDOE = United States Department of Energy.
Source: Based on Rubin, E. S., Davison, J. E. and Herzog, H. J (2015), The cost of CO_2 capture and storage.

Pipeline costs are highly sensitive to scale and location.

Box 3.4 Repurposing existing oil and gas pipelines for the transport of CO_2

There is considerable potential to reuse or repurpose existing oil and gas pipelines for the transport of captured CO_2 in many parts of the world. This could significantly reduce the costs of developing CO_2 infrastructure, as the investment needed to convert an existing pipeline is estimated at 1-10% of the cost of building a new one (Acorn, 2020). In addition, repurposing could help to avoid the substantial costs of decommissioning pipelines (Government of the United Kingdom, 2019). The UK Parliamentary Advisory Group on Carbon Capture and Storage and CCUS Cost Challenge Taskforce have emphasised the advantages associated with reusing oil and gas infrastructure for CO_2 transport.

Extensive pipeline networks exist in fossil fuel-producing regions. For example, there are nearly 3 million km of oil and gas pipelines in the United States (Bureau of

Transportation Statistics, 2019), close to 1 million km in Canada (NRCAN, 2020b) and 45 000 km in the North Sea (IOGP, 2019). A number of technical considerations regarding the nature of the oil and gas pipeline dictate the possibilities for reuse. In particular, the pressure and moisture content of the CO_2 must be suited to the pipeline (IEAGHG, 2018a). The pipeline also needs to be reasonably close to a depleted oil and gas reservoir or suitable saline storage reservoir.

Opportunities for converting pipelines also hinge on the pace of the energy transition in each region and its impact on oil and gas demand, as well as the rate of decline in production from existing basins due to the natural depletion of reserves. For example, the UK and Norwegian sectors of the North Sea have 850 pipelines with a combined length of 7 500 km that are planned to be decommissioned over the next decade at an estimated cost of GBP 1 billion (USD 1.3 billion) (ZEP, 2020).

The Acorn CCS project in the United Kingdom (IEAGHG, 2018a) plans to repurpose an onshore pipeline (with CO_2 storage in the North Sea), and the Queensland Carbon Hub/Carbon Transport and Storage Company (CTSCo) Project in Queensland's Surat Basin is also proposing to reuse existing pipelines.

CO_2 transportation by ship to an offshore storage facility offers greater flexibility, particularly where there is more than one offshore storage facility available to accept CO_2. The flexibility of shipping can also facilitate the initial development of a CO_2 capture hubs, which could later be connected or converted into a more permanent pipeline network as CO_2 volumes grow. Today, only around 1 000 tonnes of food-quality CO_2 is shipped in Europe every year from large point sources to coastal distribution terminals. In recent years, interest in CO_2 shipping has increased in several regions and countries where offshore storage has been proposed, including in Europe, Japan and Korea.

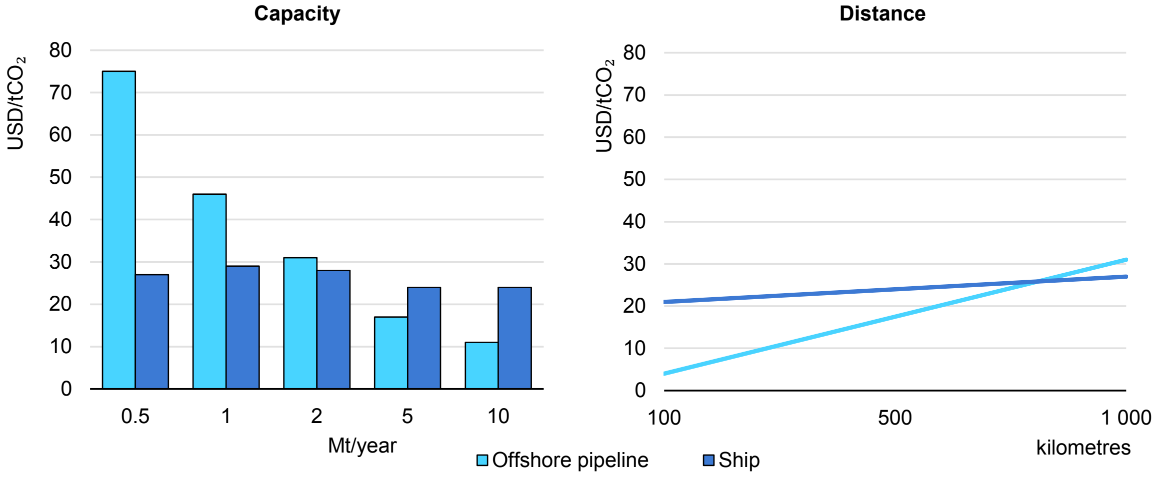
Large-scale transportation of CO_2 by ship has not yet been demonstrated but would have similarities to shipping of LPG and LNG.[3] The supply chain would consist of several steps: CO_2 would first have to be liquefied and stored in tanks before being loaded onto ships for transport. Destinations may be other ports or offshore storage sites. Unloading onshore would be relatively straightforward, based on experience with current CO_2 shipping operations and from large-scale shipping of other gases, such as LPG and LNG. Offshore unloading, either to an offshore platform before

[3] Several studies have investigated the potential to repurpose existing LPG and ethylene carriers for CO_2 transport, but this would face significant challenges for ships that were not originally designed for CO_2 transport.

conditioning and injection, or direct injection to the storage site after conditioning on ship, is not yet proven and the processes are less well-understood (IEAGHG, 2020b).

Shipping CO_2 by sea may be viable for regional CCUS clusters. In some instances, shipping can compete with pipelines on cost, especially for long-distance transport, which might be needed for countries with limited domestic storage resources. The share of capital in total costs is higher for pipelines than for ships, so shipping can be the cheapest option for long-distance transport of small volumes of CO_2 (up to around 2 Mt/year) (Figure 3.7). This would be the case with several early industrial CCUS clusters across Europe (see Chapter 4) (IEAGHG, 2020b).

Figure 3.7 Shipping and offshore pipeline transportation costs



Notes: Left-hand chart assumes a distance of 1 000 km. The right-hand chart assumes a capacity of 2 Mt/year.
Source: IEAGHG (2020b), The Status and challenges of CO_2 Shipping Infrastructure.

Shipping is competitive with offshore pipeline transport for long-distance transport of small volumes of CO_2.

CO_2 utilisation or "carbon recycling"

CO_2 can be used as an input to a range of products and services. The potential applications for CO_2 use include direct use, where the CO_2 is not chemically altered (non-conversion), and the transformation of CO_2 to a useful product (conversion).

Today, around 230 Mt of CO_2 are used globally each year.[4] The largest consumer is the fertiliser industry, which uses 125 Mt/year of CO_2 as a raw material in urea manufacturing, followed by the oil and gas industry, which consumes around 70 to 80 Mt per year for EOR. Other commercial uses of CO_2 include food and beverage production, cooling, water treatment, and greenhouses, where it is used to stimulate plant growth.

New CO_2 use pathways, involving chemical and biological technologies, offer opportunities for future CO_2 use. Many of these pathways are still in an early stage of development, but early opportunities are already being realised. There are three main categories of CO_2-based products:

- **Fuels:** The carbon in CO_2 can be used to convert hydrogen into a synthetic hydrocarbon fuel that is as easy to handle and use as a gaseous or liquid fossil fuel (see Chapter 2). The production of such fuels is highly energy-intensive and is most economically viable where both low-cost renewable energy and CO_2 are available. The largest plant currently in operation is the George Olah facility in Iceland, which converts around 5 600 tCO_2 per year into methanol using hydrogen produced from renewable electricity (CRI, 2019).
- **Chemicals:** The carbon in CO_2 can be used as an alternative to fossil fuels in the production of chemicals that require carbon to provide their structure and properties. These include polymers and primary chemicals such as ethylene and methanol, which are building blocks to produce an array of end-use chemicals. The need for hydrogen and energy varies significantly according to the chemical and production pathway. An example of a company active in the field is Covestro, which is operating a facility to produce around 5 000 t of polymers per year in Dormagen, Germany. CO_2 substitutes up to 20% of the fossil feedstock normally used in the process.
- **Building materials:** CO_2 can be used in the production of building materials to replace water in concrete, called CO_2 curing, or as a raw material in its constituents (cement and construction aggregates). The CO_2 is reacted with minerals or waste streams, such as iron slag, to form carbonates, the form of carbon that makes up concrete. This conversion pathway is typically less energy-intensive than for fuels and chemicals and involves permanent storage of CO_2 in the materials. Some CO_2-based building materials can have superior

[4] This number includes both internally and externally sourced CO_2. Internally sourced CO_2 refers to processes where CO_2 is produced and captured in a chemical manufacturing process, and ultimately consumed in a later process step; the most important example is integrated ammonia-urea plants. Externally sourced CO_2 refers to CO_2 that is external to the process and needs to be captured.

performance compared with their conventional counterparts. A few applications, such as the use of CO_2 in concrete mixing, are already commercially available in some markets today (IEA, 2019). Two North American companies, CarbonCure and Solidia, are leading the commercialisation of CO_2-curing technology, with CarbonCure now operating some 175 facilities in the United States and Canada (CarbonCure, 2020; Solidia, 2020). The British company Carbon8 is among the companies using CO_2 to convert waste materials into aggregates as a component of building materials. It is currently operating two commercial plants and aims to have five to six plants in operation by 2021 (Carbon8, 2019).

The prospects for CO_2-based products are very difficult to assess, as the technologies are generally at an early stage of development for many applications. Policy support will be crucial since they are likely to cost a lot more than conventional and alternative low-carbon products, mainly because of their high-energy intensity. The market for CO_2-based products is expected to remain small in the short term, but could grow rapidly in the longer term. A high-level screening of the theoretical potential for CO_2 use shows that it could reach as much as 5 $GtCO_2$/year for chemicals and building materials, and even more for synthetic hydrocarbon fuels (IEA, 2019). But in practice, these levels are unlikely to be attainable, mostly for economic reasons. Synthetic hydrocarbon fuels are unlikely to be able to compete with direct use of low-carbon hydrogen or electricity in most applications, but could become important in sectors that continue to need hydrocarbon fuels as the energy sector approaches net-zero emissions and where other fuel alternatives are limited, such as aviation. In the Sustainable Development Scenario, synthetic kerosene meets around 40% (250 Mtoe) of aviation energy demand in 2070, requiring around 830 Mt of CO_2.

Large-scale deployment of CO_2-based chemicals and fuels would involve large amounts of renewable electricity for their production, in particular for the generation of low-carbon hydrogen. In the Sustainable Development Scenario, the production of synthetic aviation fuels alone in 2070 requires around 5 500 TWh, which is around 8% of all the electricity produced worldwide in 2070 (see the section CCUS in low-carbon hydrogen production in Chapter 2).

The extent to which the capture and utilisation of CO_2 contributes to reducing emissions varies considerably depending on the origin of the CO_2 and the way the CO_2 is used. Quantifying the potential benefits in each case is less straightforward than for CO_2 storage as it depends on several factors (Box 3.5).

Box 3.5 How can CO_2 use deliver climate benefits?

Using CO_2 in products does not necessarily reduce emissions. Quantifying the potential climate benefits is complex and challenging, requiring a life-cycle approach. The climate benefits associated with CO_2 use primarily arise from displacing a product with one that has higher life-cycle CO_2 emissions, such as fossil-based fuels, chemicals or conventional building materials.

There are five main considerations in assessing the climate benefits of CO_2 use:

- the product or service the CO_2-based product or service is displacing
- how long the carbon is retained in the product
- the source of CO_2 (from fossil fuels, industrial processes, biomass or the air)
- how much and what form of energy is used to convert the CO_2
- the scale of the opportunity for CO_2 use.

Understanding the potential emissions reductions associated with the displaced product or service can be difficult as they differ depending on location and may change over time (for example, as the transport fuel mix becomes less dominated by fossil fuels). The retention time of carbon in a CO_2-based product also has a large impact on the climate benefits. Permanent carbon retention provides larger climate benefits than temporary carbon retention relative to the amount of CO_2 used. With the exception of building materials and EOR, most CO_2 use opportunities involve only temporary retention of the carbon, with it ultimately released to the atmosphere in the form of CO_2.

Not all sources of CO_2 are equally attractive from a climate perspective. CO_2 captured from fossil energy and industrial sources and used in fuel and cement production can deliver climate benefits as long as a higher-carbon alternative is displaced. However, this would still involve emissions from the fossil or industrial sources. From an energy system perspective, products or services derived from fossil or industrial CO_2 can achieve a maximum emissions reduction of 50%. This is because CO_2 can be avoided only once: either it can reduce the emissions from the fossil or industrial source when it was captured or it can reduce the emissions of the final product or service. It cannot do both. Over time as fossil fuel use declines, the CO_2 used must increasingly be sourced from biomass or through DAC if the energy system is to become carbon-neutral.

CO_2 storage

Storing CO_2 involves the injection of captured CO_2 into a deep underground geological reservoir of porous rock overlaid by an impermeable layer of rocks, which seals the reservoir and prevents the upward migration of CO_2 and escape into the atmosphere. There are several types of reservoir suitable for CO_2 storage, with deep saline formations and depleted oil and gas reservoirs having the largest capacity. Deep saline formations are layers of porous and permeable rocks saturated with salty water (brine), which are widespread in both onshore and offshore sedimentary basins. Depleted oil and gas reservoirs are porous rock formations that have trapped crude oil or gas for millions of years before being extracted and which can similarly trap injected CO_2.

When CO_2 is injected into a reservoir, it flows through it, filling the pore space. The gas is usually compressed first to increase its density, turning it into a liquid. The reservoir must be at depths greater than 800 metres to retain the CO_2 in a dense liquid state. The CO_2 is permanently trapped in the reservoir through several mechanisms: structural trapping by the seal, solubility trapping in pore space water, residual trapping in individual or groups of pores, and mineral trapping by reacting with the reservoir rocks to form carbonate minerals. The nature and the type of the trapping mechanisms for reliable and effective CO_2 storage, which vary within and across the life of a site depending on geological conditions, are well-understood thanks to decades of experience in injecting CO_2 for EOR and dedicated storage.

CO_2 storage in rock formations (basalts) that have high concentrations of reactive chemicals is also possible, but is in an early stage of development (TRL 3). The injected CO_2 reacts with the chemical components to form stable minerals, trapping the CO_2. However, further testing and research is required to develop the technology, notably to determine water requirements, which can be considerable (IEAGHG, 2017).[5] There are large basaltic formations in several regions around the world, and both onshore and offshore sites have been considered for storage. Such formations also exist in places, such as India, where there may be limited conventional storage capacity, potentially opening up new opportunities for CCUS.

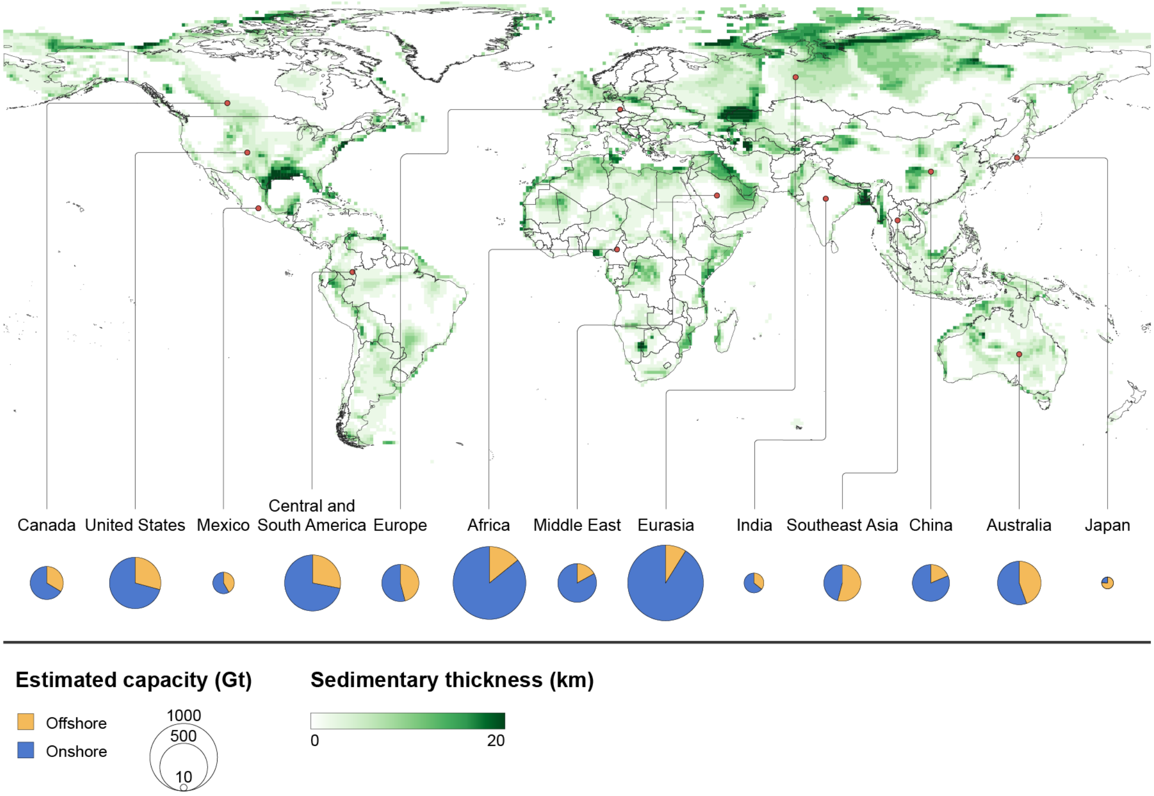
The overall technical storage capacity for storing CO_2 underground worldwide is uncertain, particularly for saline aquifers where more site characterisation and exploration is still needed, but potentially very large. As such, it is unlikely to be a

[5] The CO_2 is dissolved in water to speed up in situ carbonisation. This process, demonstrated at CarbFix, requires large volumes of water.

constraint on the development of CCUS. Total global storage capacity has been estimated at between 8 000 Gt and 55 000 Gt.[6]

The availability of storage differs considerably across regions, with Russia, North America and Africa holding the largest capacities (Figure 3.8). Substantial capacity is also thought to exist in Australia.

Figure 3.8 Theoretical CO_2 storage capacity by region



Notes: 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. Sedimentary thickness serves as an indicator of the theoretical potential of CO_2 storage sites. The offshore capacity estimates exclude sites in water depths of more than 300 metres and more than 300 kilometres offshore. The Arctic and Antarctic regions are also excluded.

Source: Kearns, J.et al., (2017), Developing a Consistent Database for Regional Geologic CO_2 Storage Capacity Worldwide.

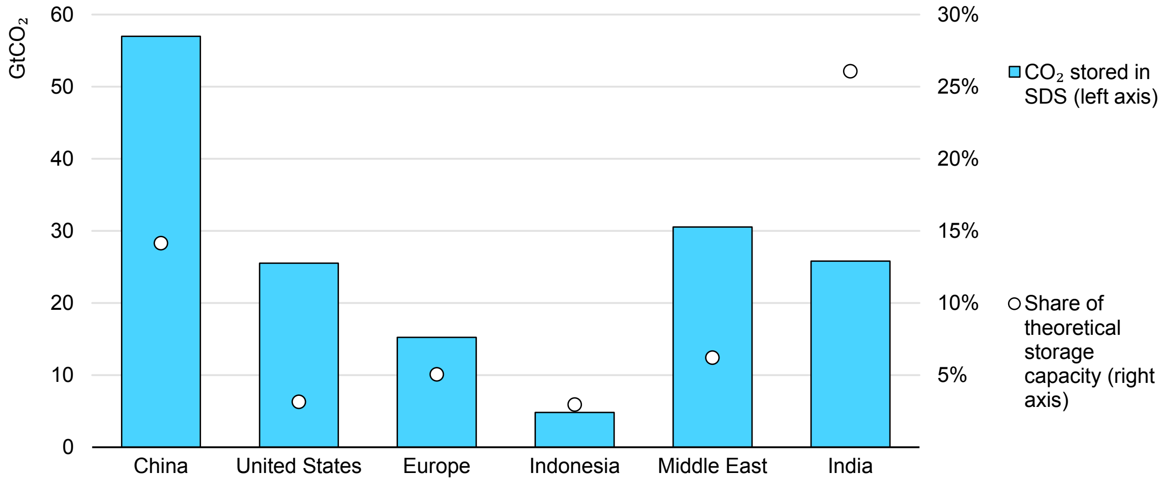
The overall technical storage capacity for storing CO_2 underground worldwide is uncertain, but potentially very large.

[6] These global estimates are based on an estimated average CO_2 storage capacity per cubic kilometre of sedimentary rock (Kearns et al., 2017). While this methodology has limitations, it offers a consistent approach to obtaining global CO_2 storage capacity estimates.

The vast majority of the estimated CO_2 storage capacity is onshore in deep saline aquifers and depleted oil and gas fields. Storage capacity is estimated to range from 6 000 Gt to 42 000 Gt for onshore sites. There is also significant offshore capacity ranging from 2 000 Gt to 13 000 Gt (taking into account only sites within 300 kilometres of the shore, at water depths of less than 300 metres, and outside the Arctic and Antarctic).

Even the lowest estimates of global storage capacity of around 8 000 Gt far exceeds the 220 Gt of CO_2 that is stored over the period 2020-70 in the Sustainable Development Scenario (Figure 3.9). Despite the stark regional variation in storage capacity, only a few countries might face a shortfall in domestic storage capacity over that time frame.[7]

Figure 3.9 Theoretical CO_2 storage capacity and cumulative CO_2 storage in the Sustainable Development Scenario by region



Theoretical storage capacity far exceeds that needed in the Sustainable Development Scenario to 2070.

While notional storage volumes are considerable, a smaller fraction will most likely prove to be technically or commercially feasible. CO_2 storage capacity is analogous to oil or gas insofar as it is a natural resource requiring exploration and appraisal, involving extensive data gathering. While success rates might prove to be higher than in the oil and gas exploration sector, failure rates, costs and delays in the exploration

[7] A recent study on storage potential in Japan can be found at www.rite.or.jp/Japanese/project/tityu/fuzon.html#up.

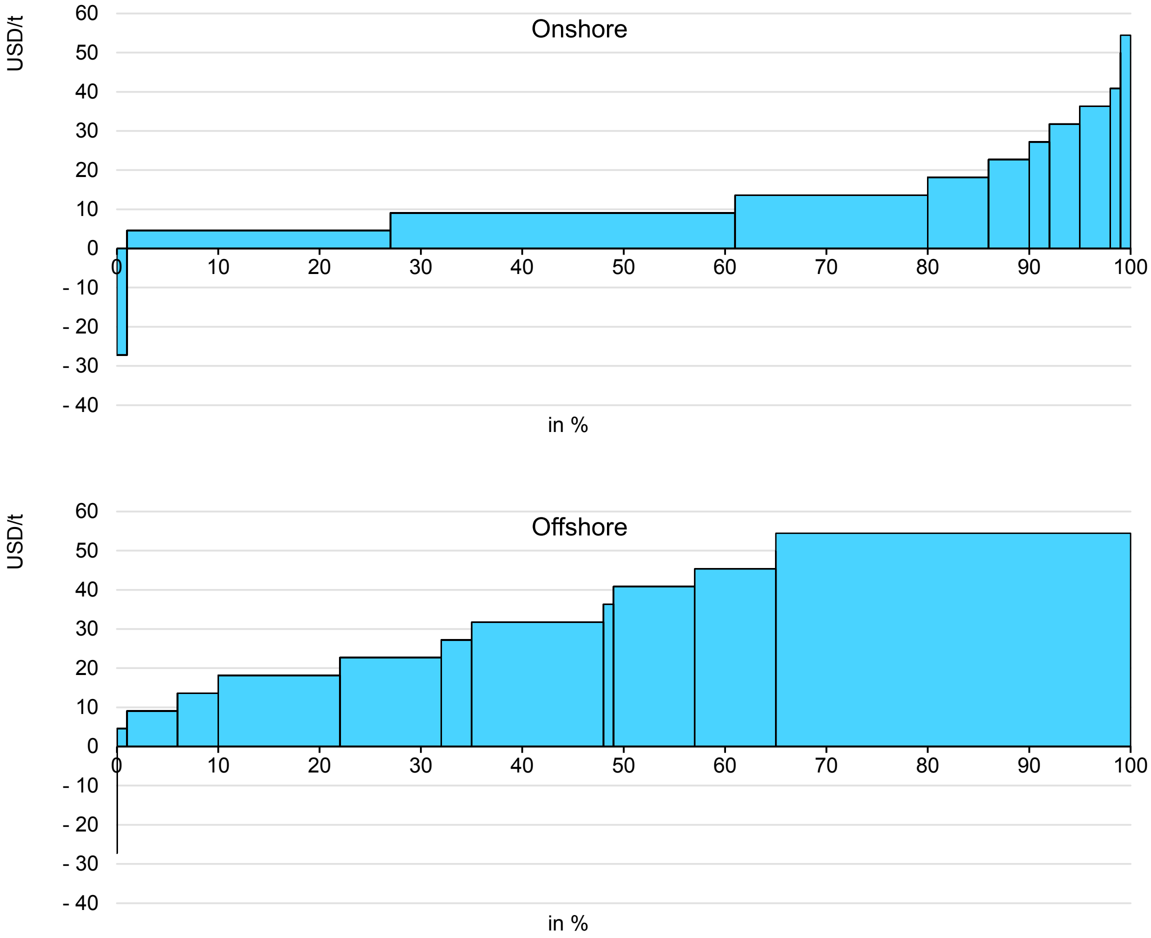
and appraisal phase are likely to be significant. The process of moving along the Society of Petroleum Engineers CO_2 Storage Resource Management System (SRMS) scale from undiscovered resource status to sub-commercial and then commercial status can take between 5 and 12 years for petroleum assets and even longer for undiscovered saline formations (OGCI, 2017). A valuable first step in characterising the progress of storage sites has been made by the OGCI's CO_2 Storage Resource Catalogue, which classifies storage sites in 13 countries following closely the definitions of the SRMS (OGCI, 2020). The majority of resource assessments are not project-based and so are automatically categorised as non-commercial on the SRMS scale.

The possibility that CO_2 stored underground could leak out has raised questions about the effectiveness of CCUS as a climate mitigation measure and public concerns about safety risks. Decades of experience with large-scale CO_2 storage has demonstrated that the risk of seepage of CO_2 to the atmosphere or the contamination of groundwater can be managed effectively. The probability and potential impact of such events have been studied comprehensively and have been found to be generally low, with risks declining over time. Nonetheless, careful storage site selection and thorough assessment is critical to ensure the safe and permanent storage of CO_2 and to reduce risks to acceptable levels. Thorough assessment includes detailed modelling of the anticipated behaviour of the CO_2 over time, together with ongoing monitoring, measurement and verification. A robust legal and regulatory framework is important to ensure appropriate site selection and safe operation of geological CO_2 storage sites. This already exists in many countries. Project developers and the public authorities have to address public concerns through effective stakeholder engagement.

The cost of developing CO_2 storage sites will be an important factor in how quickly CCUS is deployed in the coming decades in some regions, though generally costs are expected to be low relative to CO_2 capture. Current and estimated CO_2 storage costs vary significantly depending on the rate of CO_2 injection and the characteristics of the storage reservoirs, as well as the location of CO_2 storage sites. The cost of developing new sites, especially where CO_2 storage has not been carried out before, is very uncertain, particularly with regard to the effect of reservoir properties and characteristics.

In some cases, storage costs can be quite low. Indeed, when the CO_2 is stored as a consequence of CO_2-EOR operations, the cost of storage can effectively be negative net of the incremental revenues from oil production (Box 3.6). More than half of onshore storage in the United States is estimated to be below USD 10/tCO_2, which would typically represent only a minor part of the overall cost of a CCUS project. Depleted oil and gas fields using existing wells are expected to be the cheapest storage option. A small number of storage reservoirs with less favourable storage conditions are caught in the asymptotic parts of the curve (Figure 3.10). About half of offshore storage is estimated to be available at costs below USD 35/tCO_2. Similar cost curves are expected to apply in other regions, but further research is needed to confirm this (Rubin, Davison and Herzog, 2015).

Figure 3.10 Indicative CO_2 storage cost curve for the United States (onshore and offshore)



Source: Based on US EPA (2018), Inventory of U.S Greenhouse Gas Emissions and Sinks 1990-2017.

CO_2 storage costs can vary considerably, with CO_2-EOR at negative costs and the majority of the onshore storage capacity being available at below USD 10/tCO_2.

Box 3.6 The potential for CO_2 storage through EOR

The oil industry is the largest consumer of externally sourced CO_2, with an estimated annual global consumption of around 70 Mt to 80 Mt (in 2017) for EOR (US EPA, 2018). CO_2-EOR is a well-established commercial technology that has been applied since the 1970s, primarily in the United States. The technology involves the injection of CO_2 into oilfields to enhance production. This increases the overall reservoir pressure and improves the mobility of the oil, resulting in a higher flow of oil towards the production wells. The United States continues to dominate the CO_2-EOR industry, which is facilitated by an extensive pipeline infrastructure of around 8 000 km. Other countries applying CO_2-EOR, but on a smaller scale, include Brazil, Canada, China and Turkey. The majority of purchased CO_2 is currently produced from underground CO_2 deposits; for example, in the United States, less than 30% of the CO_2 is derived from non-geological sources, mainly due to the absence of available anthropogenic CO_2 sources close to oilfields (IEA, 2018).

Today, between 0.3 t and 0.6 t of CO_2 is injected in EOR processes per barrel of oil produced in the United States, although this varies between fields and across the life of projects (IEA, 2018). During the process, a portion of the CO_2 remains below the ground, while the remainder returns to the surface as the oil is extracted.* Most CO_2-EOR projects recycle CO_2 returning to the surface as it is an expensive input to the production process, resulting in over 99% of the injected CO_2 being permanently stored over the life of the project. The cost of CO_2 is generally linked to the oil price and can range from around USD 15/t to USD 30/t of CO_2. Injecting 0.5 tCO_2 per barrel of oil produced would therefore cost USD 7.5/bbl to USD 15/bbl (IEA, 2018).

Globally, an estimated 190 billion bbl to 430 billion bbl of oil are technically recoverable with CO_2-EOR. This would require injecting between 60 billion t and 390 billion t of CO_2 (IEA, 2018), compared with total energy-related emissions of CO_2 of around 33 billion t in 2019. The United States has the greatest potential, but there are also good prospects in Central Asia, the Middle East and Russia. Today, the key obstacles to wider deployment of CO_2-EOR are high capital outlay for projects, suitable geology, a lack of CO_2 transport infrastructure, and limited availability of low-cost and reliable sources of CO_2 in close proximity to oilfields.

CO_2-EOR has the potential to deliver climate benefits but assessing the net impact on emissions requires a quantitative life-cycle assessment, involving modelling of oil market dynamics and taking account of project-specific characteristics. The results of IEA modelling suggest that the net emissions savings from EOR using CO_2 from anthropogenic sources can be significant, amounting to 0.5 t to 1.5 t of CO_2 per tonne injected, depending on the configuration of the project and the type of oil displaced (IEA, 2015). These results are broadly in line with those of studies of life-cycle emissions using data for the United States (Azzolina et al., 2016; Cooney et al., 2015). A study of the Boundary Dam project in Saskatchewan in Canada found a reduction in emissions of up to 63% across the full life cycle, which includes CO_2 capture from the coal-fired power plant and CO_2-EOR in the Weyburn oil field (Manuilova et al., 2014). If a non-fossil source of CO_2 is used and the amount of CO_2 stored exceeds the emissions from the production and combustion of the oil itself, the oil could be described as net "carbon-negative". In other words, to produce "carbon-negative oil" – that is for CO_2-EOR actually to reduce the stock of CO_2 in the atmosphere – the CO_2 either has to come from the combustion or conversion of biomass or has to be captured from the air.

* The ISO 27916 standards provide a method for accounting the share of CO_2 that is permanently stored and isolated from the atmosphere. More generally, life-cycle analysis is an important tool in determining how much CO_2 is permanently removed from the atmosphere for various utilisation and storage pathways.

Cost reduction potential

There is considerable potential for reducing costs along the CCUS supply chain. Some of the factors that will drive cost savings are specific to the different stages along the chain – capture, transport, use and storage – while others apply to all stages. Across the supply chain, cost reductions could be achieved in a number of ways:

- **Learning by doing:** There is evidence that the growing portfolio of large-scale CCUS projects has already contributed to cost reductions through learning-by-doing. For instance, the capture costs at Petra Nova are 35% lower than Boundary Dam, which was built just few years earlier, while a detailed feasibility study for retrofitting the Shand coal-fired power station in Canada with CCUS suggests that cost reductions of around 70% for capex and opex are possible, relative to the Boundary Dam project (GCCSI, 2019; IEAGHG, 2018b). Similarly, the Quest CCS project has identified that its capex would be 20% to 25% lower if the plant were to be built again today (IEAGHG, 2017).
- **Technology spillovers**: Cost reductions may come from spillover effects (see section below) and learning-by-researching. In the Sustainable Development Scenario, CO_2 capture costs reduction based on learning-by-doing, learning-by-researching and spillover effects for applications in both power and industrial sectors has been estimated to be around 35% between 2019 and 2070.
- **Reduced capital and operating costs:** Capital costs have typically accounted for more than half of the total cost of capture at first-generation retrofitted plants. These costs can be reduced by economies of scale, improved site layout and modularisation, optimisation of the CCUS operating conditions and supply chain, and technology development. CCUS facilities can also have significant operating costs due to the additional energy required to operate the facilities, as well as solvents, chemical reagents, catalysts, the disposal of waste products and

additional staff needed to run them. Operating costs can be reduced by means of optimised maintenance strategies, thermal energy and water use optimisation, increased compression efficiency, and digitalisation.

- **Digitalisation:** There are number of new technologies, including robotics, drones and autonomous systems, novel sensors, digital innovations, virtual and augmented reality, additive manufacturing, and advanced materials that could reduce costs along the CCUS chain. The greatest potential for reducing costs lies in the application of artificial intelligence and the internet of things in predictive maintenance and automation (IEAGHG, 2020a). The biggest scope for cutting costs using these technologies is thought to lie in storage (see below).
- **Improved business models:** Business models that involve the separation of the capture, transport and storage components of the CCUS value chain, including through shared transport and storage infrastructure around industrial hubs, have potential to reduce unit costs through economies of scale while reducing commercial and technical risks. These risks increase the cost of capital and financing, which can have a large overall impact on project cost. decreases in the cost of capital in recent years have been vital to the global scaling-up of renewables (IEA, 2020c).[8]

CO_2 capture

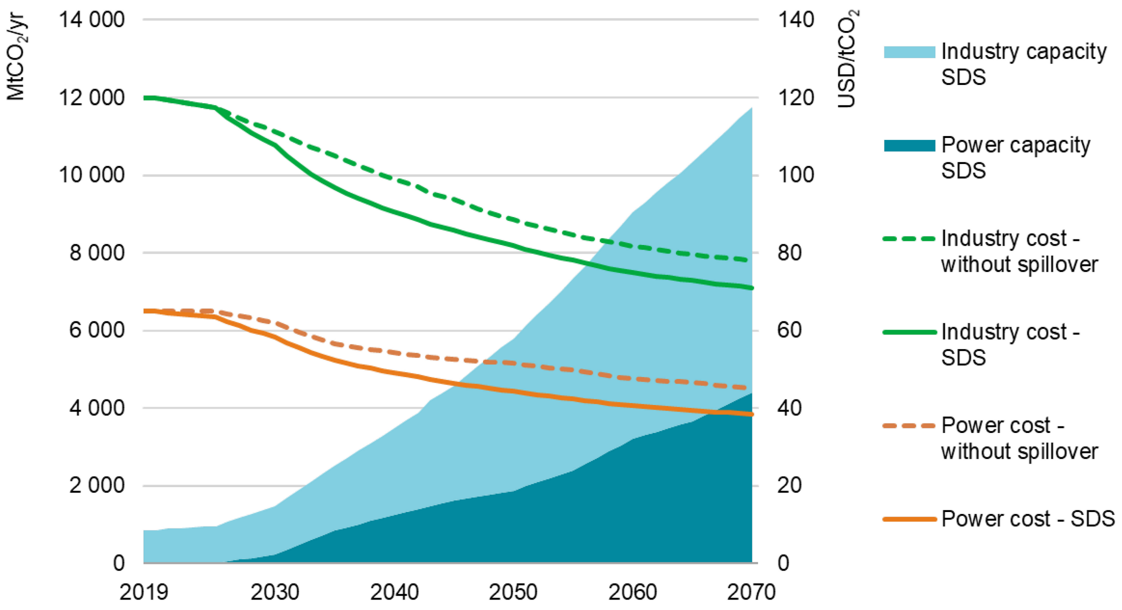
Reducing the cost of CO_2 capture, including by lowering energy needs, has been the focus of a large amount of RD&D by private and public research centres around the world in recent years. The main potential areas for cutting both capital and operating costs include the use of innovative solvents, standardisation of capture units, modularisation and off-site manufacture, reduced contingencies, and better integration with the process plant, as well as increasing the size of facilities in order to exploit economies of scale and learning-by-doing benefits. Cost estimates for technologies at low TRLs are highly uncertain but generally, these technologies have greater potential for cost reduction than mature technologies that are well established in markets. Earlier-stage capture technologies, which could be deployed 10 to 20 years from now, could be 30% to 50% cheaper than current designs (NPC, 2019). Capture costs could also be lowered by designing innovative production technologies, such as the HIsarna steel-making process in which iron ore is processed almost directly into liquid iron using less energy and emitting less CO_2 (Bellona, 2018).

Knowledge and application spillovers – the positive externalities of learning-by-doing or learning-by-researching that increase the rate of innovation in a technology area

[8] For example, applying a standard average real weighted average cost of capital (WACC) of 8% to a US solar PV project in 2019 yields a levelised cost of electricity (LCOE) of around USD 80/MWh. The LCOE for the same project with access to a WACC of just 4% is just over USD 50/MWh.

that was not the target of the original innovation effort – can also bring down the cost of CO_2 capture. For instance, in the Sustainable Development Scenario, the learning gained from various applications of chemical absorption in industry and power generation (e.g. when CO_2 needs to be separated during standard process operations without being stored or used) cuts the cost of deploying this technology for CCUS by around 12% (Figure 3.11).

Figure 3.11 Cumulative capacity (left) and capture cost learning curve (right) for CO_2 chemical absorption in coal-fired power generation and small industrial furnaces in the Sustainable Development Scenario



Note: SDS = Sustainable Development Scenario. Solid line for technology costs represents the cost trajectory in the Sustainable Development Scenario while the "without spillover" case is a counterfactual that shows the slower price decline that would be observed if the technology could not benefit from experience gathered in different applications.

Cost reductions in deploying chemical absorption accelerates in the Sustainable Development Scenario as a result of sharing learnings gained from different applications.

In power generation, capture costs are expected to be reduced by the adoption of various emerging technologies. For instance, electrochemical separation is projected to lower the LCOE with CO_2 capture by 30%; chemical absorption with advanced solvents and configurations, membrane separation, PSA and TSA, calcium looping, and cooling and liquefaction by between 10% and 30%; and pressurised oxy-fuel combustion, chemical looping combustion and sorption-enhanced water gas shift by up to 10% (IEAGHG, 2019a). These cost reductions are based on the current development trajectory of these technologies, which have recently moved from the prototype to the demonstration phase. For CCUS applied to industrial process emissions, capture cost reductions can be achieved not only through innovative technologies, but also through strategies such as capturing from units emitting larger volumes of CO_2 (e.g. recovery boilers rather than lime kilns for pulp and paper production) and recovering excess heat (e.g. in steel production) (IEAGHG, 2019c).

Transport and storage

CO_2 transport by pipeline is a mature technology, with practical experience spanning several decades, mostly in North America. The maturity and relative simplicity of the technology has resulted in few technological improvements that have affected costs since the 1980s. Experience with CO_2 storage over the last decade has also grown, including with five dedicated storage operations (i.e. not associated with EOR) but the site-specific nature of geological storage makes it difficult to discern clear downward cost trends.

The main scope for reducing costs is by exploiting economies of scale through pooling of transport and storage demand. This can be achieved by developing industrial clusters with shared infrastructure (see Chapter 1). In some cases, the repurposing of existing oil and gas pipeline infrastructure could contribute to lowering costs (see above).

CO_2 transport and storage are expected to benefit from technology innovation and digitalisation that are currently revolutionising the oil and gas industry. The largest cost reductions are likely to come from advanced sensing and real-time monitoring technologies that allow for reduced downtime and early detection of CO_2 migration or leakage, due to improved tracking and predictive maintenance[9] (IEA, 2017). Drones, robotics and automated systems will be particularly important as they can significantly reduce the need for labour, for example on offshore storage platforms. Smart drilling and developments in seismic analysis could also accelerate site appraisals and reduce costs. The potential for cost reductions through innovation is greater for CO_2 storage for which the costs of new projects are projected to fall by around 20-25% by 2040, (IEAGHG, 2020a).

[9] Predictive maintenance technologies help determine the condition of equipment in use in order to estimate when maintenance should be performed.

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Chapter 4: Regional opportunities

HIGHLIGHTS

- The contribution of CCUS to the energy transition will vary considerably across countries and regions. In the Sustainable Development Scenario, China sees the largest deployment of CCUS, accounting for around one-quarter of all the CO_2 captured cumulatively to 2070. Europe and North America –two other key regions for CCUS activity – also see a big increase in capture capacity. From 2030, CCUS is deployed on a significant scale in other parts of Asia, notably India, and the Middle East.

- The **United States** is the global leader in CCUS, accounting for more than 60% of global CO_2 capture capacity and half of all planned capacity, underpinned by new policy incentives and a supportive investment environment. The majority of stationary emission sources in the United States are located close to potential geological storage sites: 85% of emissions come from plants located within 100 km of a site and 80% within 50 km. Total potential storage is estimated at 800 Gt, or 160 years of current US energy sector emissions.

- The North Sea is at the centre of CCUS deployment in **Europe**. Two facilities there already store 1.7 $MtCO_2$/year and at least 11 other projects with a combined capacity of almost 30 Mt/year are in development in Europe. Almost 70% of emissions from power generation and industry are located within 100 km of a potential storage site and 50% within 50 km, though most of these sites are onshore where public opposition may hinder their development. Total storage capacity could be as much as 300 Gt, or almost 80 years of current emissions.

- **China** is home to the largest and some of the youngest assets for coal-fired power plants as well as cement, iron and steel, and chemical plants. CCUS retrofits will be important to prevent emissions from these plants being locked in for decades. There is vast potential for CO_2 storage in the western and northern provinces, as well as offshore. Some 45% of the CO_2 emissions from power and energy-intensive industries is within 50 km of potential CO_2 storage, and 65% of emissions within 100 km. Potential storage could total 425 Gt, or 40 years of current emissions.

Overview

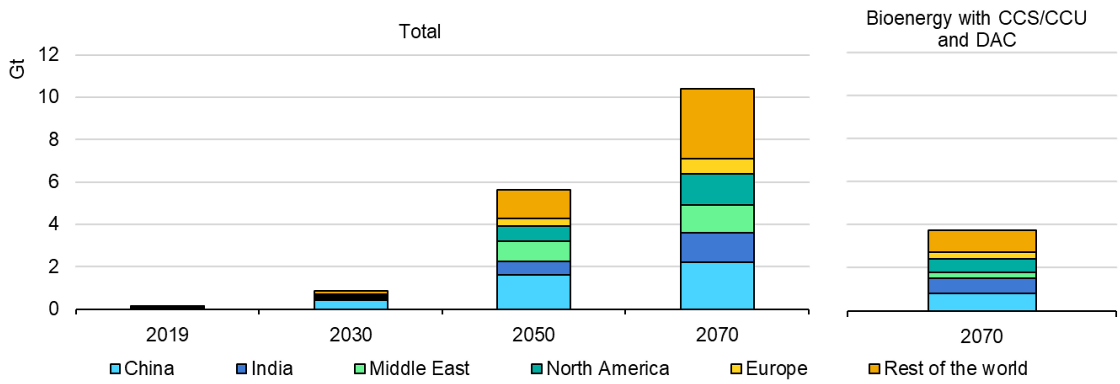
The contribution of CCUS to clean energy transitions will undoubtedly vary considerably across countries and regions. When, how and where CCUS is applied will depend on a number of considerations, including the size and age of existing power and industrial plants, domestic energy resources (both fossil and renewable), the cost and availability of alternative low-carbon technologies, the availability and proximity of CO_2 storage resources to emissions sources, and public acceptance of CCUS. The level of climate ambition and the strength of associated policy measures will also be critical factors in determining the role CCUS plays in each country (Table 4.1).

Table 4.1 National and regional factors favourable to CCUS deployment

Factor	Potential role for CCUS where:
Existing energy assets	• Large fleet and low average age of fossil-based power stations and industrial plants • High economic and/or social cost of retiring assets early
Current and future energy needs	• Heavy reliance on fossil fuels in current power generation and industrial energy mix • Strong projected growth in electricity demand, industrial output and aviation • Limited availability of alternative (non-fossil) energy sources • Large planned role for low-carbon hydrogen in energy system
Domestic energy resources	• Abundant low-cost coal and gas resources • Abundant and low-cost renewable energy (for BECCS and DAC)
Industrial profile	• Large cement, steel or chemicals industry, where availability of alternative decarbonisation options is currently limited • Good potential availability of low-cost CO_2 to produce low-carbon materials
Climate policies	• Ambitious climate targets, including for net-zero emissions, that require deep emissions cuts across all sectors and/or carbon removal technologies • Comprehensive climate plan and supportive measures for low-carbon technologies
CCUS readiness	• Availability of CO_2 storage resources within reasonable proximity to emissions sources • Easy access to CO_2 transport infrastructure and/or the possibility to repurpose existing assets • Legal and regulatory frameworks that enable and encourage CCUS deployment • Public acceptance of CCUS as an emissions abatement option

CCUS contributes to emissions reductions in all regions in the Sustainable Development Scenario. In absolute terms, its contribution is largest in China, accounting for around one-quarter of all the CO_2 captured cumulatively to 2070 worldwide. In the period to 2030, China makes up around half of the increase in CO_2 capture worldwide, primarily through retrofits to recently built coal-fired power plants and industrial plants (Figure 4.1). Europe and North America also see a significant increase in deployment of CCUS, accounting for 11% of the increase to 2030 and 21% to 2070.

Figure 4.1 Captured CO_2 emissions by country/region in the Sustainable Development Scenario



China accounts for around one-quarter of all the CO_2 captured worldwide cumulatively to 2070 in the Sustainable Development Scenario, driven mainly by retrofits to existing power stations and industrial plants.

Other regions account for a growing share of CO_2 capture over the projection period in the Sustainable Development Scenario. In the Middle East, demand for CO_2 for EOR is a key driver in the near term, alongside measures to decarbonise the refining and petrochemical sectors. Increased electricity demand also stimulates uptake of natural gas with CCUS in the power sector in some Middle Eastern countries. There are currently two large-scale CCUS facilities operating in the Middle East (in Saudi Arabia and the United Arab Emirates), linked to natural gas processing and steel production, with the CO_2 used for EOR. The Abu Dhabi National Oil Company (ADNOC) has also announced a target of capturing 5 $MtCO_2$/year from its natural gas processing plants by 2030 (ADNOC, 2020).

CCUS also emerges as an important emissions abatement option across other parts of Asia, including India and Southeast Asia, after 2030. Emerging economies in Asia have relatively new coal-fired power stations and factories, which are unlikely to be retired early in view of economic and social development priorities. India, where there are no large-scale CCUS projects at present, sees deployment of CCUS in power and industry in the long term on the assumption that sufficient storage capacity or CO_2 use opportunities can be developed (Figure 4.2).

The projected deployment of bioenergy and DAC (for both CO_2 use and dedicated storage) is driven in large part by the availability of bioenergy and land resources for the former, and cheap low-carbon electricity or heat for the latter. In the short term, they are deployed primarily in China, North America and the Middle East, with those regions together accounting for almost 70% of total capture worldwide in 2030. China sees the fastest growth in deployment in the longer term, capturing over 600 $MtCO_2$ from biomass in 2070 – one-fifth of the 3 Gt captured globally. The Middle East sees the biggest increase in DAC capacity, reaching over 60 Mt in 2050 and around 275 Mt in 2070 – about a quarter of the global total.

Figure 4.2 Deployment of CCUS by country/region and application in the Sustainable Development Scenario

	Relative deployment of CCUS by application					
	Power (coal)	Power (gas)	Industry(cement, steel and chemicals)	Low-carbon hydrogen production	Other fuel transformation	Carbon removal (BECCS and DAC)
China	Large	Limited	Large	Large	Moderate	Moderate
Europe	Limited	Limited	Large	Moderate	Moderate	Large
India	Large	Limited	Large	Moderate	Limited	Large
Middle East	Limited	Large	Limited	Large	Large	Large
North America	Moderate	Large	Moderate	Large	Large	Large
Rest of World	Limited	Limited	Large	Moderate	Moderate	Large

Legend:
Large Moderate Limited

The role of CCUS varies across countries and regions in the Sustainable Development Scenario.

The rest of this chapter focuses on opportunities for deploying CCUS in the United States – the leading country for CCUS today – Europe and China. These regions together account for around two-thirds of CCUS in operation today (by CO_2 capture capacity) and almost 90% of capacity under construction or planned. The analysis examines the potential for CCUS to tackle emissions from existing emissions-intensive plants as well as opportunities to promote the development of industrial CCUS hubs. Geographic information system (GIS) mapping – a framework for gathering, managing and analysing spatial location data – is used to identify the proximity of existing power and industrial facilities to potential geological storage sites, based on transport distances of 50 km and 100 km.[1]

United States

CCUS today and in the Sustainable Development Scenario

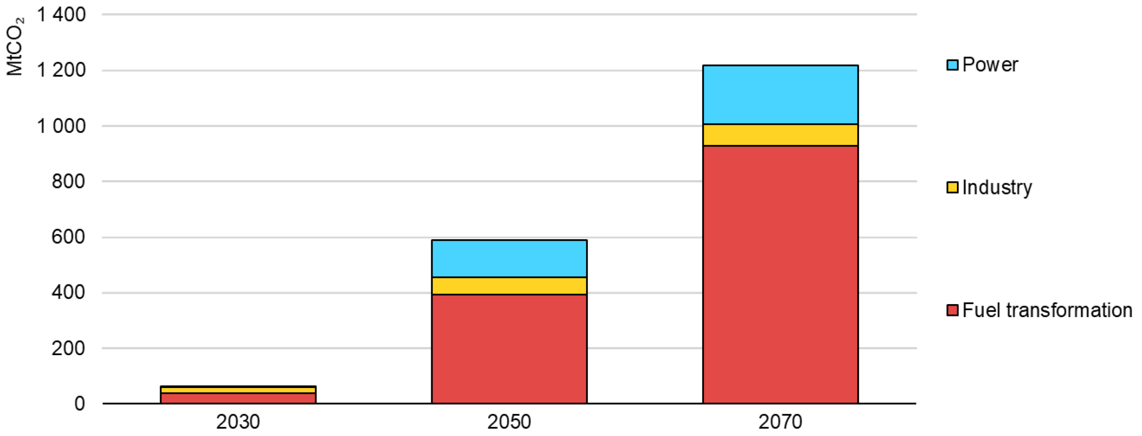
The United States is the global leader in CCUS development and deployment, with ten commercial CCUS facilities, some dating back to the 1970s and 1980s. These facilities have a total CO_2 capture capacity of around 25 Mt/year – close to two-thirds of global capacity. Another facility in construction has a capture capacity of 1.5 Mt/year of CO_2, and there are at least another 18-20 planned projects that would add around 46 Mt/year were they all to come to fruition. Most existing CCUS projects in the United States are associated with low-cost capture opportunities, including natural gas processing (where capture is required to meet gas quality specifications) and the production of synthetic natural gas, fertiliser, hydrogen and bioethanol. One project – Petra Nova – captures CO_2 from a retrofitted coal-fired power plant for use in EOR though operations were suspended recently due to low oil prices (see Chapter 1). All but one of the ten existing projects earn revenues from the sale of the captured CO_2 for EOR operations. There are also numerous pilot- and demonstration-scale projects in operation as well as significant CCUS R&D activity, including through the Department of Energy's National Laboratories.

CCUS deployment in the United States accelerates over the projection horizon in the Sustainable Development Scenario. Capture reaches around 1 200 $MtCO_2$ by 2070 in that scenario, of which more than 95% is permanently stored (Figure 4.3). Most capture facilities are in fuel transformation and the power sector, including gas-fired power generation. The share of CCUS in the technologies and measures that

[1] These distances are relatively short compared with currently operating CCUS facilities, which have pipeline transport ranging from less than 2 km to as long as 450 km. In the United States, the average CO_2 transport distance for existing CCUS facilities is around 180 km. The recently commissioned ACTL in Canada is 240 km long.

contribute to reducing CO_2 emissions relative to the Stated Policies Scenario increases over the period to 2070, as lower-cost mitigation options are exhausted and as DACS and BECCS are needed to produce negative emissions to compensate for residual emissions in hard-to-abate sectors.

Figure 4.3 CO_2 capture in the United States in the Sustainable Development Scenario



CCUS is increasingly called upon over the projection horizon to achieve the deep emissions cuts needed in the United States in the Sustainable Development Scenario.

Tackling emissions from existing plants

Industry and fuel transformation together with power and heat plants in the United States emitted around 2.6 $GtCO_2$ in 2019 – more than half of the country's total energy sector CO_2 emissions of 5 Gt and over 7% of global emissions. Over a third of US emissions come from power generation, two-thirds of which are from coal-fired power plants and the remainder largely from gas-fired plants. CO_2 emissions from the chemicals (180 Mt), cement (60 Mt), and iron and steel (75 Mt) sectors are responsible for around 55% of overall US industry emissions (Table 4.2). Emissions come from some 2 150 plants of various sizes, but just 200 of them accounted for more than half of total power and industrial emissions. Power stations and industrial sites are widely distributed, but are clustered in Appalachia, the Gulf Coast, parts of California and along the East Coast.

Table 4.2 Stationary sources of energy sector CO_2 emissions in the United States, 2019

Sources	CO_2 emissions (Mt/yr)	Number of plants
Power and heat generation	1 800	1 350
Chemicals	180	380
Iron and steel	75	120
Cement	60	100
Fuel refining	230	200
Total	**2 345**	**2 150**

Notes: The numbers of plants are based on estimations. The number of chemical plants in the table is a subset of the total fleet of chemical plants in the United States. It includes naphtha crackers and plants manufacturing HVCs.

Existing power and industrial plants in the United States would emit more than 40 $GtCO_2$ between now and 2070 if operated under normal conditions – unless they are retrofitted with CCUS or are retired early (see Chapter 2 for a discussion of existing infrastructure). Despite the advanced age of the fleet of coal-fired power plants, which averages around 40 years, their cumulative emissions would still be around 16 Gt if they ran to the end of their technical lives. Gas-fired power plants average 22 years in age and would emit 12 Gt. Cumulative locked-in emissions from existing industrial facilities amount to 14 Gt, of which nearly 4 Gt is in the chemicals sector with a young fleet of plants averaging only about 10 years (methanol plants have an average of just 5 years). While CCUS retrofits may be an attractive low-cost solution for some of the younger assets in the United States, they may not be for some older plants.

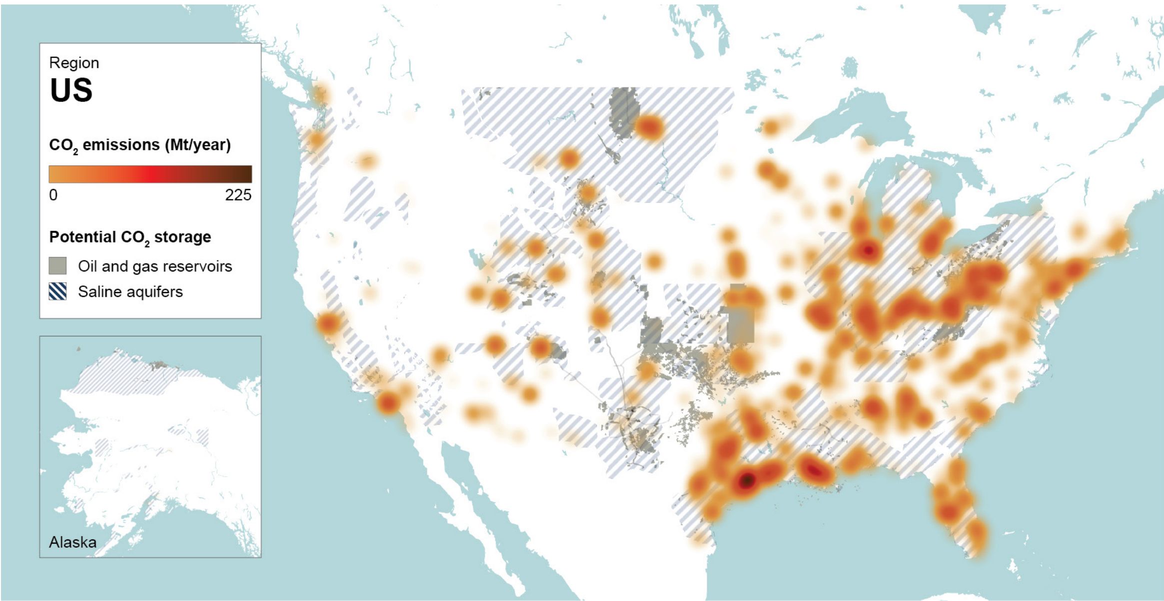
Potential CO_2 storage capacity in the United States is estimated at around 800 Gt – equal to around 160 years of domestic emissions from all sources (see Chapter 3). The availability and likely cost of developing storage sites vary considerably across the country.[2] Around two-thirds of this capacity (550 Gt) is onshore, mostly in saline formations. The Gulf Coast region, home to many large sources of emissions, has the most capacity, followed by Wyoming, Colorado and Montana.

The majority of CO_2 sources in the United States are located close to potential CO_2 storage sites. Around 80% of industrial facilities and power plants, accounting for 85% of emissions, are located within 100 km of a potential storage site and 75% of

[2] Storage estimates for the United States differ among sources (see e.g. the US Department of Energy Carbon Storage Atlas, www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas). The estimated value given here is based on the approach described in the storage section of this chapter and is at the lower end of current storage estimates for the United States.

plants (80% of emissions) within 50 km (Figure 4.4). To put these distances into context, the average distance over which CO_2 is currently transported by pipeline between existing CCUS facilities is around 180 km and the maximum around 375 km (from the Lost Cabin Gas Plant). The United States has the world's largest CO_2 pipeline network (8 000 km), which can provide a basis for developing new capacity to link emissions point sources to dedicated CO_2 storage and EOR sites in the future.[3]

Figure 4.4 Map of CO_2 sources and potential geological storage in the United States



Source: CO_2 storage based on DOE/NETL (2015), NATCARB/ATLAS.

Around 85% of CO_2 emissions from power stations and industry are sourced within a radius of 100 km from potential storage sites and 80% within 50 km.

Near-term opportunities for CCUS

Near-term opportunities for new CCUS facilities in the United States are mainly located in highly industrialised areas where emissions sources are concentrated, CO_2 storage is available and CO_2 is needed for EOR. The 45Q tax credit and California LCFS have improved the investment environment and have already spurred a number of project announcements (Box 4.1).

[3] The CO_2 transported through this pipeline network is a mix of anthropogenic and natural CO_2 used primarily for EOR.

Box 4.1 Driving CCUS deployment: Policy developments in the United States

In the United States, a tax credit known as Section 45Q, named after the relevant section of the US tax code, was expanded in 2018, providing a significant boost to CCUS investment plans. It now provides a credit of up to USD 50/tCO_2 for permanent geological storage, or up to USD 35/t for EOR or other beneficial uses of CO_2. The credits are slated to last for 12 years for projects started within a specified period; to be eligible for the credit, a construction on a new project would need to begin by 1 January 2024. The value of these credits is adjusted over time to take account of inflation. The conditions for projects to qualify for the credit was changed to allow for smaller sources of CO_2 and a cap on the total credit available was removed.

In January 2019, a CCUS protocol was agreed under the Californian LCFS, which allows transport fuels whose life-cycle emissions have been reduced through CCUS to become eligible for additional tax credits. Facilities anywhere in the world capturing CO_2 through DAC for permanent geological storage and projects that produce ethanol for sale in California and store the CO_2 (including through EOR) are also eligible for credits, but must satisfy the requirements of the LCFS CCUS protocol (which includes monitoring for 100 years). The value of these credits, which are tradeable, has risen to more than USD 190/tCO_2 in Q3 2020.

The Gulf Coast and Texas offer opportunities for near-term CCUS deployment: the Denver City hub cluster in Texas has the largest CO_2 pipeline infrastructure in the world and connects CO_2 sources to EOR sites. The Gulf Coast hub emits around 200 MtCO_2 per year, of which around 35 Mt is from highly concentred streams (OGCI, 2019). Another major emission hub is the Rocky Mountain cluster (IEAGHG, 2015). The US Department of Energy has supported a number of front-end engineering design studies for carbon capture.[4] The CarbonSAFE Initiative focuses on the development of geologic storage sites for the storage of more than 50 Mt from industrial sources. These projects could represent potential anchor projects for regional hubs (Table 4.3).

[4] www.energy.gov/articles/us-department-energy-announces-110m-carbon-capture-utilization-and-storage.

Table 4.3 Selection of potential CCUS hubs in the United States

Hub	State	CO_2 sources	Approximate CO_2 emissions (Mt/yr)
Wabash CarbonSAFE	Illinois	Power, refining, (petro)chemicals, fertiliser, hydrogen	2.0
Integrated Midcontinent Stacked Carbon Storage Hub	Nebraska, Kansas	Power, refining, (petro)chemicals, cement, mining, hydrogen	1.9
CarbonSAFE Illinois Macon County	Illinois	Power, refining, (petro)chemicals, cement, iron and steel	2.0-5.0
Project ECO2S: Early CO_2 storage complex in Kemper County	Mississippi	(Petro)chemicals, iron and steel, hydrogen	3.0
Wyoming CarbonSAFE hub	Wyoming	Power	3.0+

Source: Based on DOE/NETL (2020), CarbonSAFE.

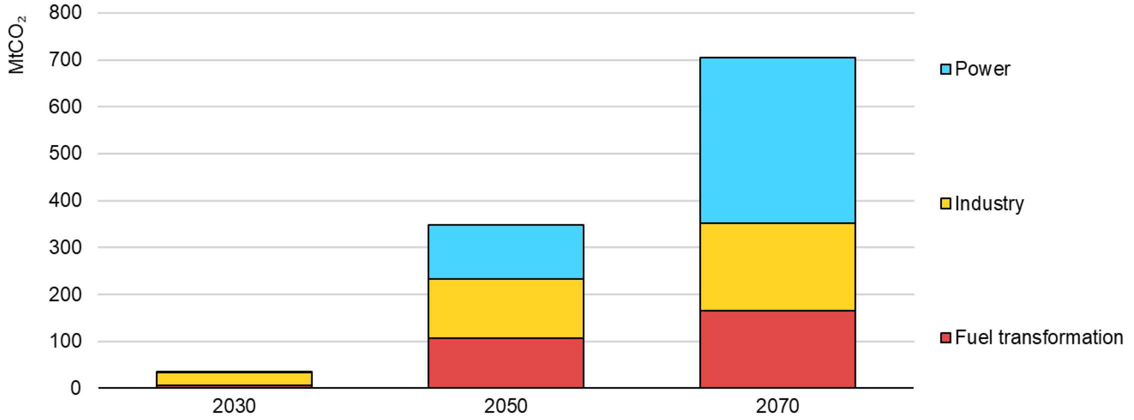
Europe

CCUS today and in the Sustainable Development Scenario

There are two large-scale CCUS projects operating in Europe at present – Sleipner and Snøhvit, both located in Norway and both capturing CO_2 from natural gas processing and reinjecting it into dedicated storage sites. Their combined capacity is 1.7 Mt/year. A number of small pilot and demonstration projects are operating elsewhere in Europe. These include the CarbFix project in Iceland (capturing CO_2 from geothermal fluid and air and storing it in basalts formations), the Drax CCS pilot project in the United Kingdom (currently pilot-testing capture from biomass-based power generation), the STEPWISE Project in Sweden (testing sorption-enhanced water gas shift separation in the iron and steel sector), the CIUDEN project in Spain (focusing mainly on storage technologies) and a geothermal plant with CCS in Croatia (generating electricity from geothermal hot brine).

CO_2 capture is projected to rise to around 35 Mt in 2030, 350 Mt in 2050 and more than 700 Mt in 2070 in Europe in the Sustainable Development Scenario (Figure 4.5). Cumulatively in the time horizon 2019-70, power generation is the main contributor (42%), followed by industry (31%) and fuel refining (26%). Up to 2050, most of the CO_2 captured is associated with the use of fossil fuels. After 2050 BECCS and DAC play a more prominent role, together accounting for almost 330 $MtCO_2$ captured in 2070, compared with almost 380 Mt from fossil fuels. Two-thirds of CO_2 captured from power generation in 2070 is associated with BECCS.

Figure 4.5 CCUS in Europe in the Sustainable Development Scenario



Early deployment of CCUS in Europe is focused on industrial applications, with a growing role for CCUS in power generation – particularly BECCS – in the Sustainable Development Scenario to 2070.

Tackling emissions from existing plants

Energy sector CO_2 emissions totalled 3.9 Gt in Europe in 2019. The power sector was the main source (32%), followed by the transport sector (25%), manufacturing industries (20%), and buildings and agriculture (18%). Industry emissions of around 800 $MtCO_2$ came largely from energy-intensive industries, including iron and steel (26%), cement (19%) and chemicals (18%). Around 32% of the emissions from these three sectors were from industrial processes rather than fuel combustion (Table 4.4).

Table 4.4 Stationary sources of energy sector CO_2 emissions in Europe, 2019

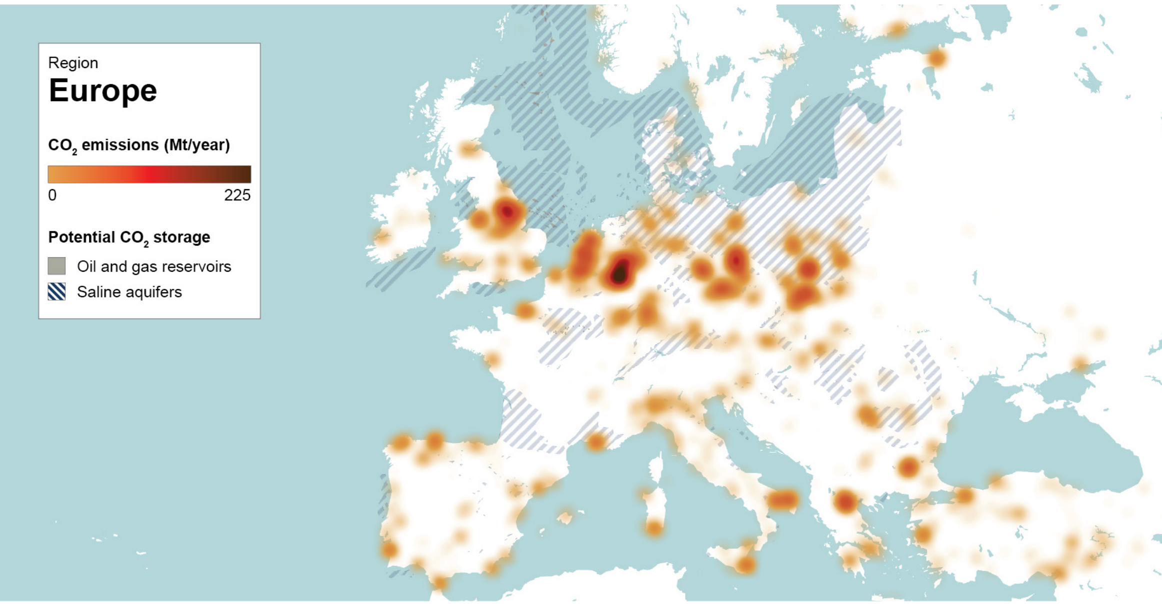
Sources	CO_2 emissions (Mt/yr)	Number of units
Power and heat generation	1 242	3 550
Chemicals	141	6 200
Iron and steel	204	40
Cement	154	250
Fuel refining	166	600
Total	**1 907**	**10 640**

Notes: The number of units is based on estimations. The number of units for chemicals, which excludes Turkey, is a subset of the total fleet of chemical plants in Europe. It includes naphtha crackers and plants manufacturing HVCs.

Many of the plants responsible for CO_2 emissions could be operating for decades to come. For instance, the average age of a European fossil-based power plant is 28 years (33 for coal-fired plants and 17 for natural gas plants) against an average technical lifetime of around 50 years. Those plants and others under construction or planned could emit cumulatively more than 25 Gt between 2019 and 2070 unless they are retrofitted with CCUS or retired early. For industrial plants, the average lifetime is around 25 years, while the average age in Europe depends on the subsector: 15 years for chemical and cement plants, around 12 for blast furnaces, and 17 for DRI production. The cumulative emissions from these plants could amount to 10 Gt over the next 30 years or so.

The bulk of Europe's energy sector emissions are from sources located in relatively close proximity to potential storage sites. This report calculates that around 68% of all the emissions from power plants and factories in Europe are located within 100 km of potential storage.[5] This includes 54% of emissions from iron and steel plants, 56% of emissions from refineries, 52% from cement, 72% from power, and 79% from chemical plants. However, much of the European storage capacity – around 160 Gt – is onshore, where storage projects are likely to face public opposition; offshore storage – roughly 140 Gt – is expected to be more feasible, particularly in the near term. An estimated 19% of industrial plants in Europe are located within 100 km of a suitable offshore storage site, with oil refineries accounting for 25% of these emissions, followed by chemical plants (20%), power plants (19%), iron and steel plants (17%) and cement plants (10%) (Figure 4.6).

Figure 4.6 Map of CO_2 sources and potential geological storage in Europe



Source: CO_2 storage data based on CO2StoP (2020), European CO_2 storage database, CO_2 Storage Potential in Europe (CO2StoP).

In Europe, 50% of the CO_2 emissions from power and energy-intensive industries is within 50 km of potential CO_2 storage, and 68% of emissions within 100 km.

[5] Given the wide range of plant sizes, not all plants will be suitable for CO_2 capture.

Many of these plants are found in industrial hubs, notably in Germany, France, Belgium, the Netherlands and the United Kingdom (Table 4.5).

In **Germany**, North Rhine-Westphalia produces around a quarter of Germany's electricity (WIRTSCHAFT.NRW, 2020), hosting as well a large number of manufacturing industries, while the Ruhr region, a very large industrial cluster, includes Europe's largest steel production complex alongside cement industries, refineries and several waste-to-energy facilities (Bellona, 2016).

The two main industrial hubs in **France** are located in close proximity of the coasts. They are in the south at Fos-Berre/Marseille, with a number of emissions-intensive areas between 2.5 Mt and 17.7 $MtCO_2$/year (IEAGHG, 2015), and in the west at Le Havre, where assessments have been made on the feasibility of a shared transport and storage system, with captured CO_2 coming from around 13 facilities (Decarre, 2012).

In **Belgium**, geological storage options are limited, therefore transportation links to nearby collection hubs are required to ensure the deep decarbonisation of the Antwerp region (Bellona, 2016).

In **Scandinavia**, the Skagerrak/Kattegat region, which lies between southern Norway, Sweden and northern Denmark, includes several industrial and energy-related smaller clusters (IEAGHG, 2015), with potential capture estimated to be equivalent to 14 $MtCO_2$ per year (Tel-tek, 2012).

In the **United Kingdom**, there are a number of industrial clusters with the Humber region the most carbon-intensive (12.4 $MtCO_2$ emitted per year), including more than 100 chemical and refining plants and a number of manufacturing facilities and power stations (Zero Carbon Humber, 2019).

Table 4.5 Selection of potential CCUS hubs in Europe

Hub	Country	CO_2 sources	Approximate CO_2 emissions (Mt/yr)
North Rhine-Westphalia/Ruhr	Germany	Refining, (petro)chemicals, cement, iron and steel, waste incineration	35
Fos-Berre/Marseille	France	Refining, (petro)chemicals, cement, iron and steel	31
Rotterdam	Netherlands	Refining, (petro)chemicals, cement, iron and steel, waste incineration, bio-based industries	28

Hub	Country	CO_2 sources	Approximate CO_2 emissions (Mt/yr)
Antwerp	Belgium	Refinery, (petro)chemicals, iron and steel, waste incineration	20
Le Havre	France	Power, refining, (petro)chemicals, cement, iron and steel	14
Skagerrak/Kattegat	Scandinavia	(Petro)chemicals, fertilisers, refinery, cement, pulp and paper	14
Humberside	United Kingdom	Refinery, (petro)chemicals, cement, iron and steel	12.4
South Wales	United Kingdom	Refining, (petro)chemicals, cement, iron and steel, waste incineration, bio-based industries	8.2
Grangemouth/Fifth of Forth	United Kingdom	Power, refining, (petro)chemicals	4.3
Teesside	United Kingdom	Refining, (petro)chemicals	3.1
Merseyside	United Kingdom	Refining, (petro)chemicals, pulp and paper, glass	2.6
Southampton	United Kingdom	Refining, (petro)chemicals, cement	2.6

Sources: Bellona (2016); Decarre (2012); GCCSI (2019); IEAGHG (2015); OGCI (2019); Tel-tek (2012).

Most of Europe's potential offshore CO_2 storage capacity is located in the North Sea, where there are a number of depleted oil and gas fields and saline aquifers that could provide suitable storage. These sites are in close proximity to a number of industrial clusters in Belgium, Denmark, Netherlands, Norway, United Kingdom and Sweden. The Utsira formation (an offshore saline formation) in Norway is considered the largest potential sink for CO_2 in Europe, with a storage capacity up to 16 $GtCO_2$ (The Norwegian Petroleum Directorate, 2020a, 2020b). Other Norwegian offshore saline aquifers and depleted oil and gas fields might be able store as much as 40 Gt. As in Norway, CO_2 storage capacity in the United Kingdom (around 78 Gt) is mostly located offshore, including in deep saline formations and depleted oil and gas fields (The ETI, 2016). Germany has an estimated storage capacity of around 20 Gt, mainly offshore in the North Sea. Onshore CO_2 storage in Germany, which is currently prohibited, has faced considerable public opposition in the past. Storage capacity in the Netherlands is estimated at between 2.7 Gt and 3.2 Gt (mostly onshore, with only 1.2 Gt offshore), most of it in depleted gas fields (Noordzeeloket UK, 2020).

Near-term opportunities for CCUS

The investment environment for CCUS in Europe has been improving, in particular due to the adoption of more ambitious climate goals and increased policy support for clean energy technologies. The European Commission has set a net-zero emissions target within its 2050 long-term climate strategy, which is part of the recently announced European Green Deal – a set of policy initiatives drawn by the Commission to achieve that target. The United Kingdom has also adopted a goal of net-zero emissions by 2050, following the advice of the Committee on Climate Change. The committee suggested a number of decarbonisation options, including resource and energy efficiency, extensive electrification, development of a hydrogen economy, and CCUS (Committee on Climate Change, 2019). The European Commission and also a number of European countries (including Austria, Belgium, France, Germany, Italy and the Netherlands) have included hydrogen in their long-term decarbonisation strategies and roadmaps (IEA, 2019).

Recent policy measures include the EU Innovation Fund, which makes available up to EUR 10 billion (USD 11.9 billion) to support the demonstration of low-carbon innovative technologies, and the EU Horizon 2020 (EUR 70.2 billion/ USD 83 billion) dedicated to research and innovation covering a number of topics including energy system decarbonisation. National policies include the Dutch SDE++ programme – an operating grant intended to support the deployment of sustainable energy and CO_2 reducing technologies and practices – and CCUS funding in the United Kingdom. The UK government announced the establishment of a CCS Infrastructure Fund of at least GBP 800 million (USD 1 billion) to support CCUS in at least two sites, one by 2025 and one by 2030 (UK Government, 2020).

This improved investment environment has contributed to a growing number of CCUS projects under development in Europe, including several targeting industrial hubs:

Porthos, the Netherlands: The Port of Rotterdam currently emits around 28 $MtCO_2$ per year (OGCI, 2019). Within the Porthos Project, the Port of Rotterdam Authority and two state-owned energy companies, Gasunie and EBN, have joined forces to develop CO_2 storage of 2 Mt to 5 Mt per year below the North Sea. The storage capacity could be increased to up to 10 Mt/year or more, enabling the site to store CO_2 coming from other European countries (OGCI, 2019; Rotterdam CCUS, 2020).

Longship CCS project, Norway: This project consists of two CO_2 capture facilities and a CO_2 transport and storage hub. Fortum Oslo Varme (waste-to-energy) and Norcem (cement production) are planning to build CO_2 capture facilities at their plants, delivering the gas to the Northern Lights consortium (Equinor, Shell and Total), which will handle the transport and permanent storage of the CO_2 in the North

Sea. Although this project does not focus on an existing industrial hub (it is currently planning to capture 0.8 Mt per year), it has the potential to increase the transport and storage capacity up to 5 Mt/year (total storage capacity around 100 Mt) and provide a storage solution for industrial facilities around Europe[6] (Northern Lights, 2019).

Zero Carbon Humber, United Kingdom: This project is currently aiming to convert the gas grid in the Humber region to hydrogen, while capturing CO_2 from the hydrogen facility and also from a number of emissions sources (including a proposed BECCS project from Drax) and storing it offshore in the North Sea (initial capture capacity equivalent to 10 $MtCO_2$/year).

Net Zero Teesside, United Kingdom: This project is an integrated CCUS project aiming to store up to 6 Mt/year of CO_2 from a number of energy-intensive industries located in Teesside. The region is home to five of the United Kingdom's top 25 CO_2 emitters and accounts for 5.6% of total UK industrial emissions. The storage site, with capacity of at least 1 Gt, would be located offshore in the North Sea (Net Zero Teesside, 2019).

Ervia Cork, Ireland: The aim of this project is to reduce CO_2 emissions from the electricity, heating, industry, agriculture and transport sectors in Ireland (Ervia, 2020). It will initially capture 2.5 $MtCO_2$ from two combined-cycle gas turbine power plants (440 MW each) and one oil refinery (with a capacity of 75 000 bbl per day).

In addition to the above, a number of projects in the United Kingdom are developing CCUS infrastructure for low-carbon hydrogen production. This includes H21 North of England, which aims to decarbonise homes and business (Northern Gas Networks, 2018), and HyNet, an integrated low-carbon hydrogen production, distribution and CCUS project (HyNet, 2020).

Several of the proposed offshore CO_2 storage projects in Europe are planning to use shipping rather than pipelines as the primary form of transport. This could provide valuable flexibility in linking storage to sources of CO_2 and reduce initial integration risks. A major legal barrier to the development of CCUS hubs in Europe and elsewhere was resolved in 2019, with Norway and the Netherlands securing Provisional Application of the CCS export amendment to the London Protocol (Box 4.2).

[6] In September 2019, Equinor signed a memorandum of understanding with seven companies (Air Liquide, Arcelor Mittal, Ervia, Fortum Oyj, HeidelbergCement AG, Preem and Stockholm Exergi) interested in developing value chains in CCUS.

Box 4.2 The London Protocol is amended to allow cross-border transportation of CO_2

A major hurdle to the development of regional CO_2 transport infrastructure was removed in 2019, when the Parties to the London Protocol – an international agreement on preventing marine pollution – approved a resolution to allow countries who have ratified a 2009 amendment to export and receive CO_2 for offshore geological storage. The London Protocol effectively prohibits the transport of CO_2 across national boundaries for the purposes of sub-seabed storage. The Protocol was amended in 2009 to remove this barrier, but for the amendment to come into force, it must be ratified by two-thirds of the Parties. There has been little progress in reaching this share.

In October 2019, Norway and the Netherlands, with the endorsement of the United Kingdom, agreed on an interim solution in the form of a Resolution for Provisional Application of the 2009 CCS Export Amendment. The resolution highlights the role of CCUS technology as a means to reduce levels of atmospheric concentrations of CO_2 and provides for the provisional adoption of the 2009 amendment in the absence of full ratification. With the support of several countries, the proposal was accepted (IMO, 2019).

China

CCUS today and in the Sustainable Development Scenario

There is one large-scale CCUS project currently operating in China – the China National Petroleum Corporation (CNPC) Jilin project, which captures some 600 $ktCO_2$ per year from a natural gas processing plant for transportation via a 50 km pipeline to an oil reservoir for EOR (GCCSI, 2020). Two other large-scale projects are under construction, both of which involve capturing around 400 kt/year of CO_2 from chemicals production facilities and transporting it over 75-150 km for use in EOR. Several smaller capture and storage demonstration projects, mainly related to coal-fired power plants and chemical facilities, have operated successfully over the last decade. China's interest in CCUS is reflected in government documents highlighting the importance of the technology for the country's decarbonisation strategy (Box 4.3).

Box 4.3 Policy framework for CCUS in China

Since the 12th Five-Year Plan (2011-15), China has included CCUS in its national carbon mitigation strategies. The National Climate Change Plan for 2014-20 defines CCUS as a key breakthrough technology. Since the plan came into effect, the government has issued guidance documents, such as the Notice on Promoting Demonstration of Carbon Capture, Utilisation and Storage, Industrial Green Development Plan (2016-2020) and 13th Five-Year (2016-2020) Work Scheme on Greenhouse Gas Emissions Reduction, which aim to support and advance the development of CCUS technologies. CCUS was also included in China's catalogue of strategic emerging technologies and was a major focus of the national technological innovation project, Clean and Efficient Use of Coal (Wei et al., 2020).

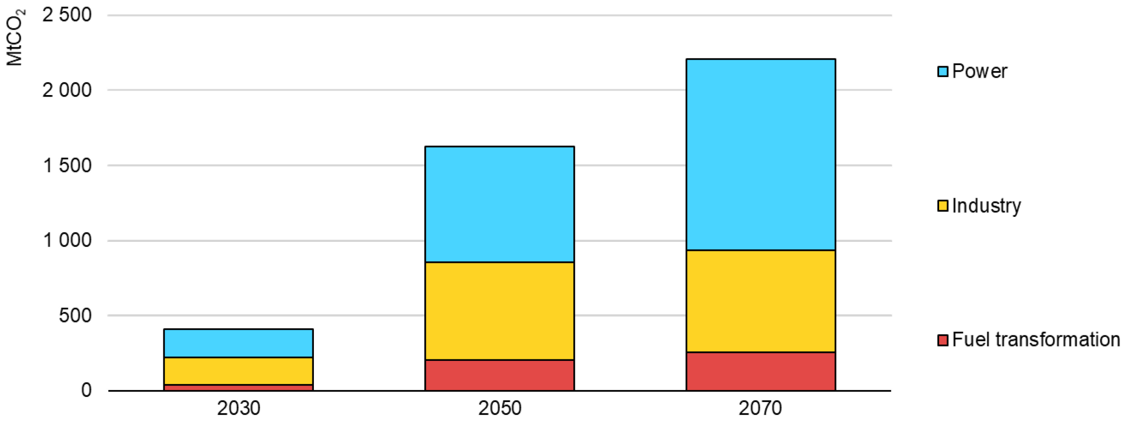
In May 2019, the Ministry of Science and Technology, and the Administrative Centre for China's Agenda 21 (ACCA21) jointly issued an updated version of the Roadmap for Development of CCUS Technology in China. The roadmap sets out an overall vision of the development of CCUS technology in China (ACCA21, 2019). It defines several phase goals in five-year increments to 2050. By 2030, CCUS should be ready for industrial applications, and long-distance onshore pipelines with capacities of 2 $MtCO_2$ should be available. It also aims to reduce the cost and energy consumption of CO_2 capture by 10-15% in 2030 and 40-50% in 2040. By 2050, CCUS technology is to be deployed extensively, supported by multiple industrial CCUS hubs across the country. The roadmap earmarks several regions as suitable candidates for CCUS hubs (see Table 4.7).

Hurdles to faster CCUS deployment in China include the lack of a legal and policy framework, limited market stimulus and inadequate subsidies (Jiang et al., 2020). Public understanding and awareness of CCUS technologies is relatively low.

China is committed to achieving a peak in CO_2 emissions by 2030 or before. In 2017, China implemented a national ETS to limit and reduce CO_2 emissions in a cost-effective manner. The ETS, which is due to start operating in 2020, will strengthen commercial incentives to invest in CCUS and other low-carbon technologies. It will initially cover coal- and gas-fired power plants and will later be expanded to seven other sectors, including iron and steel, cement, and petrochemicals. The scheme will be the world's largest to date, covering one-seventh of global CO_2 emissions from fossil fuel combustion.

CCUS capacity is projected to grow rapidly in China, seeing the largest increase of any country or region through to 2070, in the Sustainable Development Scenario. By 2030, the amount of CO_2 captured reaches 0.4 Gt, or around half of the global total, and more than 2 Gt in 2070 (Figure 4.7). CO_2 capture is applied mainly to coal-fired power plants, followed by chemicals, cement, and iron and steel production facilities. These sectors together make up the vast majority of the CO_2 captured in both 2030 and 2050. The role of BECCS and DAC becomes more important over time, accounting for one-third of the CO_2 captured in 2070.

Figure 4.7 CCUS in China in the Sustainable Development Scenario



The importance of CCUS in China grows steadily in the Sustainable Development Scenario, reaching more than 2 Gt in 2070.

Tackling emissions from existing plants

China's energy sector CO_2 emissions totalled 11.1 Gt in 2019 – close to one-third of the world total. Coal-fired power generation was responsible for 45% of Chinese emissions, followed by iron and steel (12%), cement (11%), chemicals (5%), and oil refineries (2%) (Table 4.6).

Table 4.6 Stationary sources of energy sector CO_2 emissions in China, 2019

Sources	CO_2 emissions (Mt/yr)	Number of units
Power and heat generation	5 000	450
Chemicals	600	60
Iron and steel	1 390	650
Cement	1 210	800
Fuel refining	270	120
Total	**8 470**	**2 080**

Notes: The number of plants is based on estimations. The number of chemical plants in the table is a subset of the total fleet of chemical plants in China. It includes naphtha crackers and plants manufacturing HVCs.

The majority of CO_2 sources are concentrated along the coast (Figure 4.8). In recent years, the government has started relocating some coal-fired power plants and energy-intensive industry (cement, iron and steel, and refineries) to neighbouring provinces to reduce air pollution in major population centres, such as the Beijing-Tianjin-Hebei Circle and Yangtze River Delta Region.

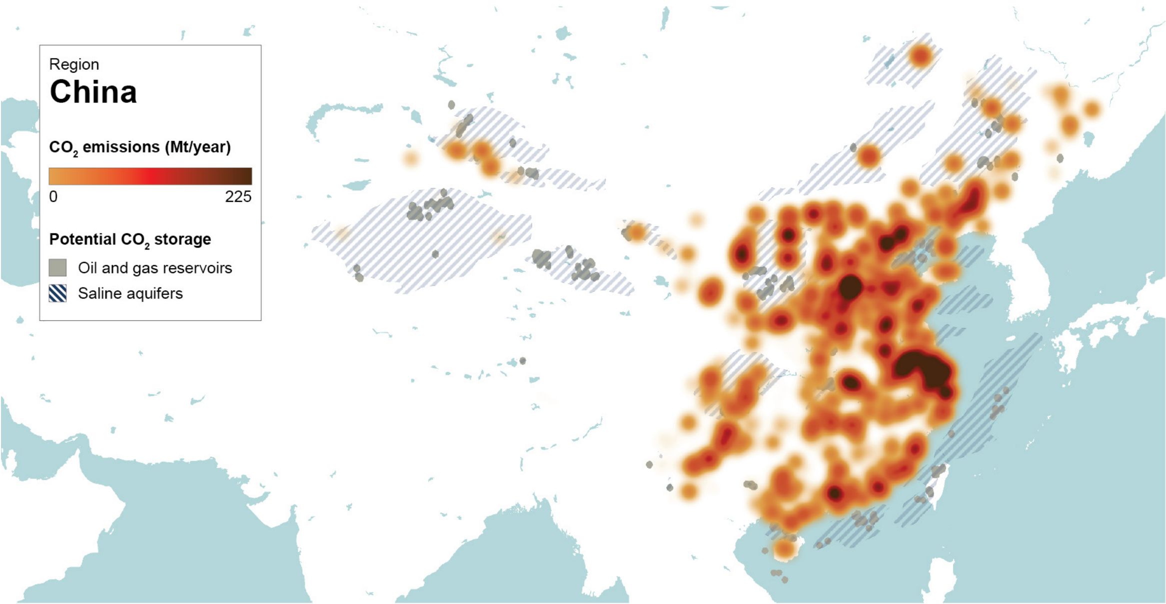
The young average age of the coal-fired power and industrial assets presents a risk of CO_2 emissions being locked in for decades to come. Unlike in Europe and the United States, most of the investment in those assets occurred over the past two decades when China's economy grew most rapidly. Nearly half of the global coal-fired power capacity of 2 100 GW in operation today is in China, where the average age of coal-fired power stations is less than 13 years. Of the currently installed capacity in China, around 900 GW could still be operating in 2050. The country also hosts close to 60% of global capacity to make primary steel, just over half the world's kiln capacity in cement production and 30% of total production capacity for ammonia, methanol and high-value chemicals. The majority of this industrial capacity is at the younger end of the global age range in each asset class, averaging between 10 and 15 years. The potential cumulative emission lock-in to 2070 amounts to nearly 180 Gt for power stations and around 90 Gt for industry. CCUS can help avoid a large share of these emissions while minimising the cost of early retirement of power and industrial assets.

As in other countries, the competitiveness of CCUS in China as a mitigation option is specific to each sector and location. The economic viability of power and industrial plants with CCUS depends on several factors, including the plant's age and layout, raw material and energy prices, proximity to CO_2 storage resources or large-scale opportunities for making use of the CO_2 (including EOR), and competing low-carbon technologies. In regions with favourable solar and wind resources, renewable electricity generation coupled with electrolytic hydrogen production may be cheaper than power plants retrofitted with CCUS. For example, compared with coal-fired power generation with CCUS, wind power currently has a cost advantage in 16 out of the country's 23 provinces, while solar PV is cheaper in the central province Qinghai and the southern island Hainan (Fan et al., 2019). Planned high-voltage direct current (HVDC) transmission lines would enable huge amounts of renewables-based electricity to flow from resource-rich inland provinces to population centres near the coast.

China has large theoretical geological storage capacity in excess of 325 $GtCO_2$ in onshore basins and 100 Gt in offshore basins (Kearns et al., 2017). Most of the onshore sedimentary formations are located in the northern, western and central-eastern parts of the country, while offshore basins are available along most of the coastal area. In its 2019 CCUS roadmap, the Chinese government expressed interest in exploiting early opportunities associated with CO_2-EOR (ACCA21, 2019). Most of these opportunities are in the north-western (Xinjiang), central (Gansu, Ningxia, Shaanxi) and north-eastern areas (Heilongjiang, Jilin) (Wei et al., 2015).

A considerable share of the stationary sources of CO_2 in China are in relatively close proximity to at least one geological CO_2 storage reservoir. In China, 45% of existing power and industrial facilities (2.8 $GtCO_2$) have at least one storage formation within 50 km, and 65% of the sources (4.1 $GtCO_2$) are located within 100 km of a potential storage site. This means that all of the CO_2 captured in the period to 2070 in the Sustainable Development Scenario could come from plants that are within 50 km of a storage site based on the current location of emissions sources. Further assessments would be required to determine the suitability of potential reservoirs, their exact technical capacity and their economic feasibility. The South Central and Eastern provinces, which have high CO_2 emissions, are farthest from potential onshore CO_2 storage reservoirs. In these areas, offshore storage may be cheaper than the development of long-distance CO_2 pipeline infrastructure to inland onshore reservoirs. Offshore storage may also be the preferred option for populous areas along the coast where high land prices and public opposition could hamper the development of onshore storage resources.

Figure 4.8 Map of CO_2 sources and potential geological storage in China



Source: CO_2 storage based on data provided to IEA by Chinese Academy of Sciences.

In China, 45% of the CO_2 emissions from power and energy-intensive industries is within 50 km of potential CO_2 storage, and 65% of emissions within 100 km.

Near-term opportunities for CCUS

Prime locations for early development of CCUS hubs are centred on areas with good CO_2-EOR opportunities. The revenue stream from CO_2-EOR can help support investment in CO_2 capture facilities and be a bridge towards more widespread geological storage of CO_2. CO_2-EOR can contribute to emissions reductions (see Chapter 3). Locations for CCUS hubs include those where CO_2-EOR is already in use today, in particular in the northern provinces (Xinjiang, Heilongjiang, Jilin and Shaanxi) (Table 4.7). While the CO_2 emissions density in some of these provinces is lower than in the coastal areas, supply of CO_2 is unlikely to be a constraint.

Regions with a high concentration of coal-based chemicals and hydrogen production facilities provide other near-term opportunities for CCUS. CHN Energy, China's largest power company, is also the world's largest hydrogen production company. Its 80 coal gasifiers can produce around 8 Mt/year of hydrogen – equivalent to 12% of global dedicated hydrogen production today. Applying CCUS to this existing capacity could deliver CO_2 emissions reductions of up to 145 Mt per year, while providing a major boost to the development of both CCUS and low-carbon hydrogen. The majority of the coal-based hydrogen production facilities are located in the northern provinces of Shanxi, Shaanxi and Inner Mongolia, all of which have CO_2 storage resources in relative close proximity. In recent years, the Chinese government indicated that hydrogen energy is a vital element in China's energy technology development strategy. Coal gasification with CCUS could be a springboard for hydrogen to fulfil its longer-term decarbonisation potential across the Chinese energy sector.

Other opportunities for CCUS hubs are in large industrial ports on the east coast. Of the ten largest ports in the world, seven are in China. The development of industrial CCUS hubs with associated infrastructure in these ports presents an attractive opportunity to reduce a significant amount of China's CO_2 emissions.

Table 4.7 Selection of potential CCUS hubs in China

Hub	Province	CO_2 sources	Approximate CO_2 emissions (Mt/yr)
Junggar and Turpan-Hami basins	Xinjiang (Northwest China)	Power, refining, chemicals, cement, iron and steel	65
Ordos basin	Shanxi, Shaanxi (North China)	Power, refining, chemicals, cement, iron and steel	300
Songliao basin	Heilongjiang, Jilin (Northeast China)	Power, refining, chemicals, cement, iron and steel	100
Sichuan basin	Sichuan (Central China)	Power, refining, cement, iron and steel	200

Notes: The hubs include CO_2 sources within a distance of 50 km from the basin(s).
Sources: IEA analysis based on in-house data and ACCA21 (2019).

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Chapter 5: Accelerating deployment

HIGHLIGHTS

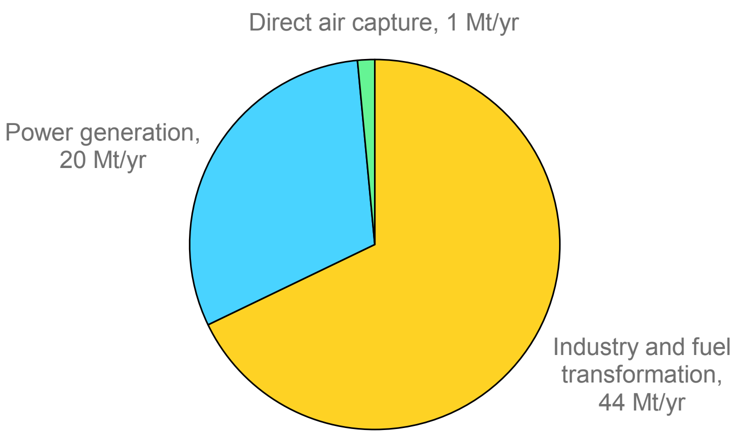
- The next decade will be critical to the prospects for CCUS and for putting the global energy system on a path to net-zero emissions. A significant scaling-up of CCUS is needed to provide the momentum for further technology development and cost reductions, and to foster progress across a broader range of applications in the longer term.
- Delays in investment and innovation in CCUS technologies would have a lasting impact on future emissions trajectories and could slow the pace at which net-zero emissions can be achieved. A five-year delay in developing and deploying CCUS technologies would halve the CO_2 emissions being captured worldwide in 2030 compared to the Sustainable Development Scenario.
- The required rate of CCUS rollout is challenging. It can only be achieved if near-term policy action establishes the conditions for investment along the CCUS value chain. Economic recovery packages are a unique window of opportunity for governments to support CCUS alongside other clean energy technologies.
- The key to successful policy is designing a framework that supports the creation of a sustainable and viable market for CCUS. There is no one-size-fits-all policy template: the appropriate choice or mix of instruments for each country depends on local market conditions and institutional factors. On their own, technology-neutral measures such as carbon pricing are generally not sufficient. Measures targeted at specific CCUS applications, including capital grants and operational support, can help build a business case for investment and drive widespread deployment in the near term.
- There are four high-level priorities for governments and industry to support a rapid scaling-up of CCUS over the next decade: create the conditions to stimulate private investment; target the development of industrial hubs with shared CO_2 infrastructure; identify and encourage the development of CO_2 storage; and boost innovation to reduce costs and ensure that critical technologies and applications are available, including in sectors where emissions are hard to abate and for carbon removal.

The importance of the next decade

The next decade will be critical to the prospects for CCUS and for putting the global energy system on a path to net-zero emissions. A significant scale-up of deployment is needed to provide the momentum for further technological progress, cost reductions and more widespread application in the longer term. Without a sharp acceleration in CCUS innovation and deployment over the next few years, meeting net-zero emissions targets will be all but impossible.

The introduction of stimulus packages to counter the economic impact of the Covid-19 pandemic presents a unique opportunity for governments to support the needed acceleration in CCUS development and deployment. As discussed in Chapter 1, CCUS is well placed to contribute to near-term economic recovery plans in some regions, with a growing number of projects that are close to a FID but that will require government support. In particular, industrial applications with highly concentrated CO_2 emission streams could be brought online relatively quickly in response to new policy incentives. Support for CO_2 storage development as well as innovation is also urgently needed to lay the foundations for future large-scale CCUS deployment.

Figure 5.1 World CO_2 capture capacity average annual additions to 2030 by sector in the Sustainable Development Scenario



CO_2 capture grows by a factor of 20 in the period to 2030, mainly driven by retrofits at existing plants and the scaling-up of clean hydrogen production.

The rate of acceleration in CCUS deployment over the next decade that is required for the world to be on track for net-zero emissions is a major challenge. In the Sustainable Development Scenario, the amount of CO_2 captured grows by a factor of 20 from around 40 Mt today[1] to over 800 Mt in 2030, requiring a significant ramp-up in average annual additions of CO_2 capture capacity (Figure 5.1). The projected rollout is ambitious – as it is for many other emerging low-carbon technologies in the Sustainable Development Scenario – but there are historic precedents for the rapid deployment of similar technologies, notably flue gas desulphurisation (Box 5.1).

Most of the growth in CCUS deployment takes place in the second half of the decade. The projected expansion in deployment after 2025 reflects the lead times in developing new CO_2 transport and storage infrastructure, which can be as long as ten years, as well as in planning and building capture facilities. Virtually all the capacity that comes online in the next four to five years will already be in advanced development today and/or will have access to existing CO_2 transport and storage infrastructure (see Chapter 1). This highlights the importance of securing a massive increase in investment in the coming months and years for the projected expansion of capacity later in the decade to be achieved.

Box 5.1 An analogue to the rapid scaling-up of CO_2 capture technology: Flue gas desulphurisation

The near-term growth in CCUS projected in the Sustainable Development Scenario is ambitious, but not without comparable precedent. In the 1970s and 1980s, several countries, including Germany and the United States, introduced regulations to address the problem of acid rain pollution caused in particular by sulphur dioxide emissions from power stations and industrial facilities. These measures led to a rapid expansion of flue gas desulphurisation technology, often known as "scrubbers". These technologies are comparable to CO_2 capture (notably post-combustion capture) in terms of their complexity, sectors of application and technological characteristics.

Over the period 1972-2000, an average of 6.6 GW of coal-fired power generation capacity was equipped with scrubbers each year globally. In Germany alone, the rate of deployment reached an annual average of 9 GW from 1985-88 (IEAGHG, 2012). In China, the installation of scrubbers accelerated in the 2000s, contributing significantly to overall global deployment of the technology. At its peak (around 2002-12), an annual average of 73 GW of capacity was equipped with scrubbers

[1] Includes CO_2 captured from large-scale CCUS facilities where the CO_2 is stored or used for EOR (see Chapter 1) but not CO_2 that is generated in ammonia production and used on-site to manufacture fertiliser (as this use of CO_2 is not associated with a climate benefit).

worldwide (van Ewijk and McDowall, 2020). In the Sustainable Development Scenario, CO_2 capture facilities come online at much lower rates in the power sector, averaging 23 GW/year over the entire projection horizon. Deployment peaks at around 40 GW/year in the 2060s, driven mainly by increasing capture from bioenergy power stations – 45% less than the peak in scrubbers and 90% less adjusted for the size of the economy.

This suggests that the increase in CO_2 capture equipment projected in the Sustainable Development Scenario over the next decade and beyond is technologically achievable – if effective policy or regulatory frameworks are in place and if transport and storage infrastructure are scaled at a similar rate. In practice, a significant and sustained boost in innovation to demonstrate and commercialise CO_2 capture in heavy industry, in addition to significant public support, will also be needed.

The projected growth in CO_2 capture over the next decade in the Sustainable Development Scenario is characterised by three important trends:

- Retrofitting of large numbers of existing power and industrial facilities that significantly reduces lock-in of emissions. An annual average of around 20 coal power plants are retrofitted with capture equipment between 2025 and 2030, primarily in Asia.[2] In 2030, over 450 Mt of CO_2 is captured from retrofitted fossil fuel-based power and industrial facilities, of which the majority is permanently stored. These retrofits result in the avoidance of over 70 Gt of cumulative emissions over the lifetime of the plants – more than double the level of global annual energy-sector emissions today.[3]
- The scale-up of low-carbon hydrogen production with CCUS. With a relatively concentrated CO_2 stream, hydrogen represents a lower-cost opportunity for CCUS deployment compared with power generation, for example. By 2030, 18 Mt of hydrogen is produced from CCUS-equipped facilities in the Sustainable Development Scenario.
- The rapid adoption of CCUS technologies and applications that are not yet widely used. Around half of the CO_2 captured in the period to 2030 is from technologies and applications that are currently in the prototype or demonstration phase, including capture technologies in heavy industry where alternative low-carbon technologies are more costly or difficult to adopt. Between 2025 and 2030, an

[2] Based on coal-fired power plants with an average CO_2 capture capacity of 2 Mt.
[3] Assuming a typical operating life for coal-fired power plant of 50 years.

average of 90 cement plants are equipped with CCUS each year.[4] DAC also starts to be deployed commercially, primarily for synthetic fuel production, with capacity growing from around 9 000 t today to 10 Mt in 2030.

Delays in investment and innovation in CCUS technologies would have a lasting impact on future emissions trajectories and affect the pace at which net-zero emissions can be achieved. The IEA calculates that a five-year delay in completing demonstration projects for pre-commercial CCUS technologies, together with a slowdown in the deployment of CCUS technologies at early adoption stage, would result in 50% less CO_2 emissions being captured worldwide in 2030 and 35% less in 2040 than in the Sustainable Development Scenario (IEA, 2020). CO_2 captured from cement production and power generation would be the areas most affected, accounting for almost 80% of the reduction in CCUS deployment through to 2040. The delay in deploying CO_2 capture technologies would also hold up the rate of decline in costs over time, due to the missed opportunity for learning-by-doing.

Policy considerations

Supporting accelerated deployment

The rapid deployment hinges critically on a massive increase in government support, as well as new approaches to public and private investment. CCUS is not unique in this respect: the future of many of the clean energy technologies needed in the global energy transition depends on rigorous and sustained policy action.

CCUS faces some specific challenges in the initial scaling-up phase, which policies must recognise and address. These include the need for co-ordination across multiple sectors and stakeholders; high capital investment requirements for CO_2 capture and related infrastructure; uncertainty surrounding long-term ownership and liability for stored CO_2; untested insurance and finance markets; and public opposition to storage (particularly onshore) in some regions.

The key to successful policy is designing a framework that supports the creation of a sustainable and viable market for CCUS. That framework needs to recognise that the private sector is unlikely to invest in the technology unless it is obliged to do so, or unless it can make a profit from the sale of the CO_2 or by earning credits from the emissions avoided under carbon pricing arrangements.

A range of policy instruments are at policy makers' disposal to support the establishment of a market for CCUS and address the investment challenges. In practice, a mix of measures is likely to be needed. These measures include direct capital grants, tax credits, carbon pricing mechanisms, operational subsidies,

[4] Based on cement plants with annual average CO_2 emissions of 0.5.

regulatory requirements and public procurement of low-carbon products from CCUS-equipped plants. Continuous support for innovation is also needed to drive down costs, and develop and commercialise new technologies (Table 5.1).

Table 5.1 Main policy instruments for CCUS development and deployment

Category	Types	Examples
Grant support	Capital funding provided directly to targeted projects or through competitive programmes to overcome high upfront costs.	• UK CCUS infrastructure fund • EU Innovation Fund
Operational subsidies	• **Tax credits** based on CO_2 captured/stored/used. • **Contracts-for-difference** (CfD) mechanisms covering the cost differentials between production costs and a market price. • **Feed-in tariff** mechanisms with long-term contracts with low-carbon electricity producers. • **Cost-plus open book** mechanisms in which governments reimburse some costs as they are incurred, reducing risk for the contractor.	• US 45Q and 48A tax credits • Netherlands' SDE++ scheme • UK power sector CfD arrangements
Carbon pricing	• **Carbon taxes,** which impose a financial penalty on emissions. • **ETSs** involving a cap on emissions from large stationary sources and trading of emissions certificates.	• Norway carbon tax on offshore oil and gas • European ETS • China ETS • Canada federal Output-Based Pricing System
Demand-side measures	• **Public procurement** of low-CO_2 building materials, transport fuels and power, including those produced with CCUS. • **Border adjustments,** adding a carbon tariff on imported goods to prevent competition from those with higher CO_2 and a lower price.	• Canada and the Netherlands rules favouring low-CO_2 material inputs for construction projects • Several jurisdictions (including in the US, Canada and EU plan to purchase concrete cured using CO_2 • EU carbon border tax (proposed)
CCUS-specific market mechanisms	• **Tradeable certificates or obligations,** such as fuel standards favouring low-carbon fuels for transport or stationary applications. • **Carbon storage units** based on a verified record of CO_2 securely stored, which could be purchased by emitters from those storing carbon (proposed).	

Category	Types	Examples
Regulatory standards and obligations	• **Mandates** on manufacturers to meet emissions criteria, or oblige firms to purchase a minimum share of products with low life-cycle CO_2 emissions. • **Regulated asset base,** a model for investment recovery through a regulated product price passed on to consumers. • **Emissions standards** establishing limits on unabated CO_2 emissions.	• EU Renewable Energy Directive II • Australia – Gorgon LNG project CCS requirement • UK energy and infrastructure markets employ a regulated asset base model • Limits on allowable CO_2 intensity from coal and natural gas power generation in Canada
Risk mitigation measures	• **Loan guarantees** covering project developers' debt should they default on loans. • **Pain-gain risk-sharing mechanisms** whereby partners share some projects risks. • **CO_2 liability ownership,** in which governments take a share of liability for stored CO_2, in particular after project closure.	• Australian legislation allowing the transfer of CO_2 liability to the state.
Innovation and RD&D	• **Funding** for RD&D, either directly in state-run research institutions or indirectly through grants and other types of subsidy for private activities. • **Competitive approaches** to support RD&D for low-carbon technology.	• Canada/US Carbon XPRIZE • EU Horizon 2020 • US Department of Energy CCUS R&D programmes

Almost all CCUS projects operating today have benefited from some form of public support, largely in the form of capital grants and – to a lesser extent – operational subsidies (Table 5.2). Grant funding has played a particularly important role in projects coming online since 2010, with 8 out of 15 projects receiving grants ranging from around USD 55 million (AUD 60 million) in the case of Gorgon in Australia to USD 840 billion (CAD 865 million) for Quest in Canada. Seven projects have had access to operational support in the form of tax credits or subsidies, including US projects developed since 2009, which can access the original[5] 45Q tax credit of USD 20/tCO_2 for geological storage and USD 10/tCO_2 used in EOR. Of the seven projects that that have not received a direct capital subsidy, four are owned and operated by a state-owned enterprise.

[5] The 45Q tax credit was expanded and increased in 2018, to reach USD 50/tCO_2 for geological storage and USD 35/tCO_2 for CO_2 used in EOR (or for other beneficial uses). The original tax credit was capped at 75 000 tCO_2, cumulative, and it is not clear if all eligible US projects have accessed this. The cap was removed in 2018.

Table 5.2 Policy support for large-scale CCUS projects in operation today

Country	Project (Operational date)	Sector	Policy/support measure:				
			Carbon tax	Grant support	Operational support	Regulatory requirement	State-owned enterprise
US	Terrell natural gas plants (1972)	Fuel transformation					
US	Enid Fertilizer (1982)	Industry (chemicals)					
US	Shute Creek gas processing (1986)	Fuel transformation				●	
Norway	Sleipner CO_2 storage (1996)	Fuel transformation	●				●
US/ Canada	Great Plains Synfuels (2000)	Fuel transformation					
Norway	Snøhvit CO_2 storage (2008)	Fuel transformation	●				●
US	Century Plant (2010)	Fuel transformation			●		
US	Air Products steam methane reformer (2013)	Fuel transformation		●	●		
US	Lost Cabin Gas Plant (2013)	Fuel transformation			●		
US	Coffeyville Gasification (2013)	Industry (chemicals)			●		
Brazil	Petrobras Santos Basin pre-Salt oilfield (2013)	Fuel transformation					●
Canada	Boundary Dam (2014)	Power generation		●		●	●
Saudi Arabia	Uthmaniyah CO_2-EOR (2015)	Fuel transformation					●
Canada	Quest (2015)	Fuel transformation		●	●		
UAE	Abu Dhabi (2016)	Industry (steel)					●
US	Petra Nova (2017)	Power generation		●	●		
US	Illinois Industrial (2017)	Fuel transformation		●	●		
China	Jilin oilfield CO_2-EOR (2018)	Fuel transformation					●
Australia	Gorgon CO_2 Injection (2019)	Fuel transformation		●		●	
Canada	ACTL – Agrium (2020)	Industry (Chemicals)		●			
Canada	ACTL – North West Sturgeon Refinery (2020)	Fuel transformation		●			

Source: Global CCS institute (GCCSI) (2019), The Global Status of CCS 2019.

An explicit carbon price or tax has supported CCUS investment in only two cases to date: the Sleipner and Snøhvit projects in Norway, which were subject to a CO_2 tax on offshore oil and gas production introduced in 1991. In both cases, there was a technical need to separate the CO_2 from the natural gas to meet market requirements, strong subsurface expertise and knowledge within Equinor, [6] favourable geology, relatively high product margins, and a lack of alternative abatement options.

There is no one-size-fits-all policy for CCUS

There is no one-size-fits-all policy template for CCUS. The appropriate choice or mix of instruments for each country depends on local market conditions and institutional factors, including the current stage of CCUS infrastructure development, emissions targets, domestic energy resources, and the availability and cost of alternative approaches to cutting emissions. These factors vary markedly across regions:

- In the United States, CCUS has been supported through grant funding and an extensive R&D programme. The expanded 45Q tax credits are proving effective in stimulating plans for new projects. Tax credits are a familiar and well-established policy mechanism in the country, having been extensively used to support the development of renewable energy technology. They may not be as effective in other regions where CCUS is at an earlier stage of development or if higher-cost industrial applications are being targeted.
- Europe has only two operational CCUS projects but a rich pipeline of planned projects concentrated around industrial clusters with shared CO_2 storage infrastructure and applications that include cement, gas-fired power generation, waste-to-energy and hydrogen production (see Chapter 4). A combination of competitive grant funding (for example, through the EUR 10 billion Innovation Fund and the GBP 800 million UK CCS Infrastructure Fund), direct government funding with risk-sharing arrangements (Norway's Longship CCS project) and operational support (for example the Dutch SDE++ scheme) are the main measures currently in place to support the expansion of CCUS.
- In countries or regions with large state-owned enterprises, including China and the Middle East, direct investment has been used to support early CCUS projects. State-owned enterprises could lead the more widespread application of CCUS and in some cases help to create a low-carbon market through procurement policies.

[6] Formerly Statoil, the state oil company and project operator.

The suitability of each type of policy instrument also varies according to the specific application of CCUS (Table 5.3). Some capture applications, such as natural gas processing, are mature and relatively less expensive, requiring relatively limited policy intervention. Other applications, including in heavy industry, are currently at an earlier stage of development, and the higher costs of CO_2 capture and its potential impact on competitiveness – particularly in the case of internationally traded commodities, such as steel – are a major barrier to the adoption of CCUS. Transport and storage infrastructure is capital-intensive and future demand from capture facilities can be uncertain, creating considerable risk for project developers and investors. Government support and co-ordination will be very important in developing new transport and storage infrastructure as CCUS scales up.

Table 5.3 Policy implications of CCUS deployment by sector

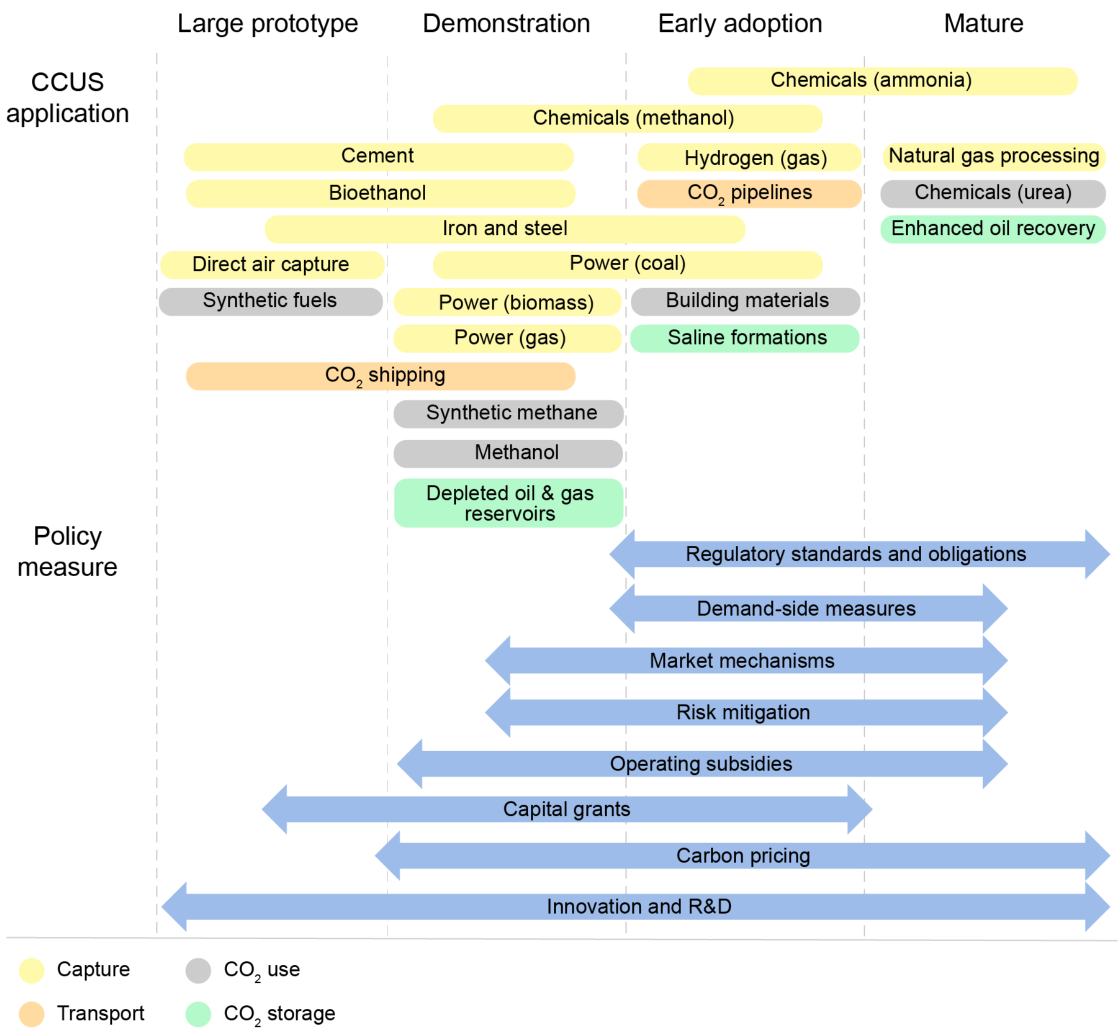
	Sector characteristics	Implications for policy
Transport and storage	Likely monopolistic market for CO_2 transport	Transport and storage assets may need to be regulated or owned/operated by governments
	High capital costs of transport and storage infrastructure	Grant funding or financing support may be needed
	Co-ordination and alignment of timelines with capture development needed	Targeted funding of integrated projects (e.g. around industrial hubs) or volume guarantees
	Uncertainties over long-term ownership and liability for stored CO_2	May require public liability cap or transfer of ownership to governments post-closure
Industry	International competiveness for traded commodities with low profit margins	Compensate for additional cost; mitigate additional cost along the value chain; consider border adjustments; create demand for low-carbon products
	Range of applications, technologies and scale	Policies and implementation models must be flexible
	Current high cost of capture in many applications	RD&D required
	High credit risk, uncertain markets and expected short payback	Capital financing and operational support may be required
Hydrogen production	Low cost of CO_2 capture	Smaller financial incentive for CO_2 capture than in other sectors may be needed
	Uncertainty over future demand	Policy support to stimulate demand for low-carbon hydrogen in heat, industry and/or transport
	End use may be in clusters of high energy demand and/or production	Focus on early opportunities by incentivising production in industrial clusters with CCUS infrastructure

	Sector characteristics	Implications for policy
Power generation	High capital cost of retrofits	Capital support or guaranteed operational revenue
	Power markets vary significantly among regions and countries	Different policies required nationally; experience in other regions not always transferable
	Load factors for plants equipped with CCUS may fall over time as more renewables are integrated	Flexibility to accommodate a potential transition from baseload to flexible generation
CO_2 use	Uncertain climate benefits	Policy incentives need to be linked to robust life-cycle assessments of emissions savings
	Uncertain demand for CO_2 use	Public procurement measures to consider CO_2-derived products
	High energy needs and costs for CO_2 conversion to fuels and chemicals	RD&D support to reduce costs and prove feasibility of technology at scale
Carbon removal	Immature application with uncertain costs and demand	Focus on proving feasibility at scale and lowering costs; stimulate demand through targets or CO_2 certificate trading
	No recognition of value of negative emissions	Include carbon removal in emissions trading frameworks or other tradeable credits
	Measurement and verification of carbon removal	Policy incentives need to be linked to robust life-cycle assessments of emissions savings

Policy action also needs to be tailored to the stage of CCUS technology development in the sector or application in which it is being deployed. As deployment increases, the market for CCUS should become progressively more independent, requiring less government intervention. Targeted subsidies could be phased out and economy-wide measures such as carbon pricing could become the primary measure to support investment.

Today, CCUS is at an early stage of commercialisation, with most applications classified as demonstration and early adoption in this report (see Chapter 3) (Figure 5.2). On their own, technology-neutral measures such as carbon pricing are generally not sufficient to overcome the barriers to commercialising these or other emerging technologies. Measures targeted at specific CCUS applications, including (initially) capital grants and operating subsidies, would likely be required to build a business case for early investment and to drive widespread deployment.

Figure 5.2 CCUS policy measures by stage of technology development



Notes: See chapter 3 for description of stage of technology development. Policy measures by technology development are indicative only, and they will vary by technology and regional factors.

The appropriate mix of policies will depend on the level of technology development.

Priorities for accelerated deployment

Recognising that policy responses will need to be tailored to national and sector-specific circumstances, there are four high-level priorities for governments to support a rapid scaling-up of CCUS over the next decade:

- Create the conditions to stimulate private investment.
- Target the development of industrial hubs with shared CO_2 infrastructure.
- Identify and encourage the development of CO_2 storage.
- Boost innovation to reduce costs and ensure that critical technologies are available this decade.

Create the conditions for investment

Bringing forth the investment needed to deploy CCUS on the scale envisioned in the Sustainable Development Scenario requires measures to make such investment commercially attractive. An estimated USD 160 billion of cumulative investment in CCUS is needed to 2030 in that scenario, a tenfold increase from the decade to 2020. While a range of specific policy measures could be employed to support this investment depending on national circumstances or preferences, their overall effectiveness would be improved by three key approaches: placing a value on emissions reductions, provide funding to support capital and operating costs, and allocating risks between the public and private sector.

Place a value on reducing emissions

A major barrier to CCUS deployment today in many regions is the low value or absence of a value attached to CO_2 emissions reductions, such that there may be no commercial driver for industrial or power facilities to capture CO_2 as an alternative to emitting it, even where this can be done at relatively low cost. Placing a value on reducing emissions does not necessarily require explicit carbon pricing through emissions trading or explicit taxation of emissions; though these can play an important role. It can also take the form of public procurement programmes that favour lower-emissions commodities or products, or tax credits associated with CO_2 storage.

Provide funding to support capital and operating costs for early projects

Grant funding programmes can play an important role in supporting early CCUS deployment, particularly first-of-a-kind projects and CO_2 transport and storage infrastructure. They can alleviate the high capital costs and commercial and technical risks associated with such projects. However, they can be a heavy burden on public budgets, limiting their use to a small number of individual facilities. A rapid scale-up of CCUS will necessitate a shift towards market-based measures that can complement grant funding and provide a stable and ongoing framework for CCUS facilities to operate over the long term.

Allocate risks across the public and private sector

The private sector can manage the majority of risks associated with CCUS projects, but some may need to be shared initially with governments. These include low-probability but high-impact risks, such as the long-term liability associated with CO_2 storage, including the risk that the CO_2 could migrate or leak out many years or decades after the site has closed. This risk is difficult to quantify and hard to insure against, in part because the financial cost to the project would depend on the prevailing carbon price at the time of the leakage. Policy or legislative frameworks should consider the option to transfer the ownership of the stored CO_2 back to governments after a specified period and with appropriate assurances, including evidence that the injected CO_2 behaving in a stable and predictable manner. Other risks that can inhibit investment include cross-chain risk – that a failure of one of the components in the CCUS supply chain affects operations in other parts of the chain – and stranded assets, such as when storage capacity is built but no CO_2 is available due to a lack of investment in capture facilities. Governments can play a critical role in co-ordinating and orchestrating CCUS deployment in its early stages to alleviate these risks (e.g. the Norwegian government with its Longship CCS project).

Target industrial hubs with shared CO_2 infrastructure

The development of CCUS hubs with shared CO_2 transport and storage infrastructure could play a critical role in accelerating the scale-up of CCUS by exploiting economies of scale and making it feasible to capture CO_2 at smaller industrial facilities, for which dedicated CO_2 transport and storage infrastructure may be both impractical and uneconomic. It can allow continued operation of existing infrastructure and supply chains in industrial regions, retaining employment and boosting the potential to attract new investment, including in energy-intensive industries or low-carbon hydrogen production.

To drive the development of hubs, governments first need to identify opportunities in partnership with potential investors and then establish business models that encourage their development.

Identify opportunities for CCUS deployment in industrial regions

A national or regional audit of the emissions associated with industrial clusters – including the age and type of facilities – together with an assessment of CO_2 storage options and opportunities for using the CO_2 is needed to inform the planning and development of infrastructure. Early planning and co-ordination can promote more efficient investment decisions in the long term, including the identification of opportunities for economies of scale through "oversizing" of infrastructure to accommodate future demand. Governments can play a leading role in this planning and co-ordination across regions and industries (e.g. the Alberta Carbon Trunk Line in Canada).

Establish a business model for CO_2 transport and storage infrastructure

Like electricity and natural gas networks, CO_2 infrastructure may be considered a natural monopoly, whereby high start-up costs and economies of scale make it economically more efficient to have a single owner and operator rather than competing providers. A number of business models have been proposed for the development of industrial CCUS hubs (in CCUS Cost Challenge Taskforce, 2018; IEAGHG, 2018; Element Energy 2018). Virtually all involve the CO_2 transport and storage infrastructure being owned and operated by a dedicated entity that is publicly owned (wholly or partly) or regulated. An exception involves hubs built around an "anchor" capture facility (often a power plant) providing sufficient scale for the initial transport and storage infrastructure development, with third-party access being granted to neighbouring CO_2 capture facilities.

Identify and encourage the development of CO_2 storage

Confidence in the availability of safe, secure and adequate CO_2 storage is a prerequisite for investment in both transport and storage infrastructure and capture facilities. Global CO_2 storage resources are considered to be well in excess of likely future requirements. In many regions, however, significant further assessment work is required to convert theoretical storage capacity into "bankable" storage, whereby the maximum amount of CO_2 that can ultimately be stored, the maximum rate of injection, how the gas is contained in the formation and the risk of leakage are well understood. The identification and development of CO_2 storage will also need to be supported by a robust legal and regulatory framework, as well as effective communication with local communities and the broader public.

Develop a geological CO_2 storage atlas

The process of characterising and assessing CO_2 storage can be lengthy – up to ten years depending on existing data (see Chapter 3). This underscores the need for early action. Government geological surveys should start by undertaking pre-commercial CO_2 storage assessments in order to develop an atlas of CO_2 storage resources (as with other natural resources, the knowledge obtained can be considered a public good). Oil and gas companies will be important partners in this work in countries where they have been active, as they will already hold large amounts of data, notably on depleted oil and gas reservoirs. Storage atlases have already been developed in several regions, and the OGCI and Global CCS Institute recently released a global CO_2 storage resource database that covers 13 countries and regions (OGCI, 2020). Beyond the pre-competitive assessment stage, policy measures will be needed to support investment in the detailed characterisation and assessment of storage sites.

Establish a legal and regulatory framework for safe and secure storage

The development of CO_2 storage resources must be underpinned by a robust legal and regulatory framework. This should ensure appropriate site selection and safe operation of CO_2 storage, providing a framework to mitigate and manage risks across all stages of site development, operation and closure. It should also provide a legal basis for CO_2 storage, allocating property rights, managing competition for resources (for example, with oil and gas development), and defining roles and responsibilities, including ownership and liability for stored CO_2. International standards that have already been developed for CO_2 storage (e.g. ISO/TC 265, ISO 27914) can inform national efforts to establish such a framework.

Support public awareness and education

Successful deployment of CCUS will involve a concerted effort to ensure that local communities and the general public understand and accept the technology. Geological storage of CO_2 can raise legitimate concerns about safety and risks, since it is a relatively new concept for many people. Communication and engagement should be initiated at the earliest possible stage of project development to secure community support – as was the case for Shell's Quest project in Canada and the Tomakomai project in Japan. Governments, alongside non-governmental organisations and the scientific community, will also have an important role to play in communicating the value of CCUS in the portfolio of technologies needed to meet climate goals.

Boost technology innovation

Innovation will be key to scaling up CCUS in both the short and long term. In the Sustainable Development Scenario, around 60% of the cumulative emissions reductions through to 2070 hinge on technologies that are currently at the prototype or demonstration phase, including carbon removal (BECCS and DAC), new ways of using CO_2 (particularly to make fuels and chemicals), and CO_2 capture in cement and iron and steel production. Governments and industry can drive their deployment through accelerated innovation, collaborative RD&D and direct support for emerging technologies.

Private-sector entrepreneurs, companies and financiers are expected to play a critical role for innovation in clean energy technologies such as CCUS. Private-sector participants in the innovation system greatly outnumber those from the public sector, with public-sector employees representing just 5-25% of R&D researchers in most member countries of the Organisation for Economic Co-operation and Development (OECD) (OECD, 2020). Success will depend upon the public and private sectors working closely together to agree on the way ahead, identify projects and metrics, and learn together from past successes and failures.

Reduce CO_2 capture costs and support new technologies through RD&D

CO_2 capture typically accounts for almost 75% of the cost of CCUS and can range from USD 15-25/t to more than USD 120/t, depending on the application and the concentration of CO_2. Although capture costs have already declined substantially in the past decade, RD&D will play a critical role in supporting further cost reductions.

RD&D efforts should focus on developing and demonstrating the technical performance and costs of each element of the CCUS value chain (capture, transport, use and storage), as well as their successful integration. Technological development is critical to prepare various CCUS applications – ranging from cement and iron and steelmaking to synthetic fuels and DAC – for large-scale deployment. RD&D programs should aim to further improve mature capture technologies, in particular chemical absorption through better solvent design and automated operating systems to optimise capture processes, but also technologies and applications that are still at earlier stages of development. Focus RD&D areas for these novel applications include designing better separation materials, lowering energy consumption, and integration with the core process. Transport and storage technologies would benefit from developments in digitalisation, including advanced modelling, sensing and real-time monitoring technologies to accelerate site appraisals and improve tracking of CO_2.

Accelerate the availability of CCUS in key applications

Several CCUS technologies and applications will need to rapidly progress from the prototype or demonstration stage to being commercially available within the next decade. There is an urgent need to scale-up key applications, particularly in heavy industry (cement, steel and chemicals), CO_2 use (for synthetic fuels) and for carbon removal, where the technologies are generally at an earlier stage of development but where CCUS plays a critical role in the transition to net zero.

Targeted and tailored support for innovation in these applications will be needed, and could also be a focus for international collaboration. Where budgets allow, governments should increase funding for these technologies given their long-term strategic importance and the need to improve understanding of their technical potential and cost. For industrial applications, including cement and steel production, the availability of shared CO_2 transport and storage infrastructure will be important to improve the economics of CO_2 capture given the relatively smaller quantities of CO_2.

Collaborate to support CCUS innovation

Risks from being a first mover can sometimes be too high for a single country to fund if the market players are multinational, the outlook uncertain and the project requires significant upfront capital – as is currently the case for CCUS, including for low-carbon hydrogen and industrial processes. Countries with smaller R&D budgets and companies with weaker balance sheets are likely to find collaboration especially attractive. International partnerships and initiatives, such as the Clean Energy Ministerial CCUS Initiative, Mission Innovation, IEA Greenhouse Gas Technologies Programme (IEAGHG) and the Accelerating CCUS Technologies (ACT) programme are providing an important foundation for collaboration on CCUS development and deployment.

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Annexes

Acronyms and abbreviations

ACCA21	Administrative Centre for China's Agenda 21
ACTL	Alberta Carbon Trunk Line
ADNOC	Abu Dhabi National Oil Company
ATR	autothermal reforming
BECCS	bioenergy with carbon capture and storage
BF-BOF	blast furnace basic oxygen furnace
BTL	biomass-to-liquids
$CaCO_3$	calcium carbonate
CaO	lime
capex	capital expenditures
CarbonSAFE	Carbon Storage Assurance Facility Enterprise
CCS	carbon capture and storage
CCU	carbon capture and use
CCUS	carbon capture, utilisation and storage
CES	Clean Energy Systems
CESA	Central and South America
CfD	contracts-for-difference
CO	carbon monoxide
CO_2	carbon dioxide
CTSCo	Carbon Transport and Storage Company
DAC	direct air capture
DACS	direct air capture with storage
DRI	direct reduced iron
EAF	electric arc furnace
EFTA	European Free Trade Association
elec	electrolytic
EOR	enhanced oil recovery
ESA-DAC	electro swing adsorption
ETP	Energy Technology Perspectives

ETS	emissions trading system
EU	European Union
FID	final investment decision
gas DRI	natural gas-based direct reduced iron/electric arc furnace route
GDP	gross domestic product
GHG	greenhouse gas
H_2 DRI	100% electrolytic hydrogen-based direct reduced iron
H_2	hydrogen
HVC	high-value chemical
HVDC	high-voltage direct current
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISR	innovative smelting reduction
L-DAC	liquid DAC
LCFS	Low Carbon Fuel Standard
LCOE	levelised cost of electricity
LEILAC	Low Emissions Intensity Lime and Cement
Li-ion	lithium-ion
LNG	liquefied natural gas
LPG	liquefied petroleum gas
NASA	National Aeronautics and Space Administration
NG	natural gas
OGCI	Oil and Gas Climate Initiative
opex	operating expenditures
PSA	pressure swing adsorption
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
S-DAC	solid DAC
SDG	Sustainable Development Goal
SDS	Sustainable Development Scenario
SMR	steam methane reforming
SR1.5	Special Report on Global Warming of 1.5°C
SRMS	Storage Resource Management System
STEPS	Stated Policies Scenario

TRL	technology readiness level
TSA	temperature swing adsorption
UK	United Kingdom
US	United States
USDOE	United States Department of Energy
VSA	vacuum swing adsorption
WACC	weighted average cost of capital
ZEP	Zero Emissions Platform

Units of measure

bbl	barrel
EJ	exajoule
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
kg	kilogramme
km_2	square kilometre
kt	kilotonne
kW	kilowatt
kWe	kilowatt electrical capacity
kWh	kilowatt-hour
mb/d	million barrels per day
MBtu	million British thermal units
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
Mtpa	million tonnes per annum
MW	megawatt
MWh	megawatt-hour
t	tonne
toe	tonne of oil equivalent
TWh	terawatt-hour
Wh/kg	watt-hours per kilogramme

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