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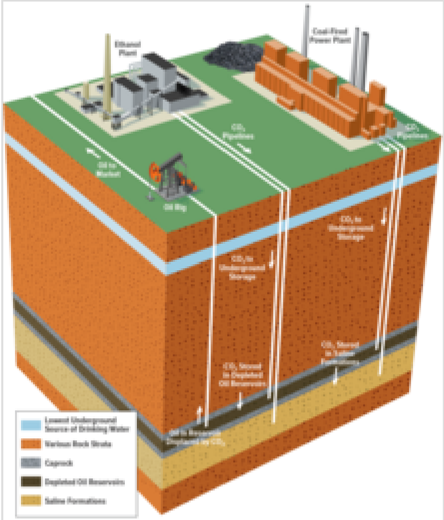
Carbon capture and storage



In CCS, carbon dioxide is captured from point sources such as ethanol plants. It is usually transported via pipelines and then either used to extract oil or stored in dedicated geologic formations.

Carbon capture and storage (**CCS**) is a process in which carbon dioxide (CO_2) from industrial installations is separated before it mixes with the atmosphere, then transported to a long-term storage location.[1]:2221 In CCS, the CO_2 is captured from a large point source, such as a natural gas processing plant and typically is stored in a deep geological formation. Around 80% of the CO_2 captured annually is used for enhanced oil recovery (EOR), a process in which CO_2 is injected into partially-depleted oil reservoirs in order to extract more oil and then is left underground.[2] Since EOR *utilizes* the CO_2 in addition to *storing* it, CCS is also known as **carbon capture, utilization, and storage** (CCUS).[3]

Oil and gas companies first used the processes involved in CCS in the mid 20th century. Early versions of CCS technologies served to purify natural gas and to facilitate oil production. Subsequently, CCS was discussed as a strategy to reduce greenhouse gas emissions.[4][5] Around 70% of announced CCS projects have not materialized.[2] As of 2023, 40 commercial CCS facilities are operational[6] and collectively capture about one thousandth of anthropogenic CO2 emissions.[7] CCS facilities typically require capital investments of up to several billion dollars, and CCS also increases operating costs.[8] Power plants with CCS are expected to require around 15-25% more energy to operate,[9] thus they typically burn additional fossil fuel and increase the pollution from extracting and transporting fuel.

In strategies to mitigate climate change, CCS plays a small but critical role. CCS is expensive compared to other methods of reducing emissions such as renewable energy, electrification, and public transit and is much less effective at reducing air pollution. Given its limitations, CCS is most useful in specific niches, particularly heavy industry, plant retrofits, natural gas processing, and electrofuel production.[10]:21–24 In electricity generation and hydrogen production, CCS is envisioned to complement a broader shift to renewable energy.[10]:21–24 CCS is a component of bioenergy with carbon capture and storage, which can under some conditions remove carbon from the atmosphere.

The effectiveness of CCS in reducing carbon emissions depends on the plant's capture efficiency, the additional energy used for CCS itself, leakage, and business and technical issues that can keep facilities from operating as designed. Many large CCS implementations have sequestered far less CO_2 than originally expected.[11] Additionally, there is controversy over whether CCS is beneficial for the climate if the CO_2 is used to extract more oil.[12] Fossil fuel companies have heavily promoted CCS, framing it as an area of innovation and cost-effectiveness.[13] Some environmental groups regard CCS as an unproven,

expensive technology that will perpetuate dependence on fossil fuels and distract from more effective ways to reduce emissions.[14] Other environmental groups support the use of CCS under certain circumstances.[15]

Almost all CCS projects operating today have benefited from government financial support, usually in the form of grants.[16]:156–160 Countries that are developing programs to support or mandate CCS technologies include the US, Canada, Denmark, China, and the UK.[17][18]

Terminology

The IPCC defines CCS as:

> "A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere."[19]:2221

The terms *carbon capture and storage* (CCS) and *carbon capture, utilization, and storage* (CCUS) are closely related and used interchangeably.[12] Both terms are used predominantly to refer to enhanced oil recovery (EOR) a process in which captured CO_2 is injected into partially-depleted oil reservoirs in order to extract more oil.[12] EOR is both "utilization" and "storage", as the CO_2 left underground is intended to be trapped indefinitely. Prior to 2013, the process was primarily called *CCS*; since then the more valuable-sounding *CCUS* has gained popularity.[12]

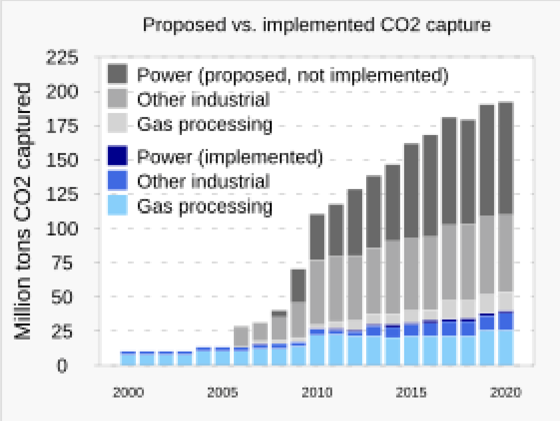
Around 1% of captured CO_2 is used as a feedstock for making products such fertilizer, synthetic fuels, and plastics.[20] These uses are forms of *carbon capture and utilization*.[21] In some cases, the product durably stores the carbon from the CO_2 and thus is also considered to be a form of CCS. To qualify as CCS, carbon storage must be long-term, therefore utilization of CO_2 to produce fertilizer, fuel, or chemicals is not CCS because these substances release CO_2 when burned or consumed.[21]

Some sources use the term *CCS, CCU, or CCUS* more broadly, encompassing methods such as direct air capture or tree-planting which remove CO_2 from the air.[22][23][24] In this article, the term *CCS* is used according to the IPCC's definition, which requires CO_2 to be captured from point-sources such as the flue gas of power plants.

History and current status

In the natural gas industry, technology to remove CO_2 from raw natural gas has been used since 1930.[27] This processing is essential to make natural gas ready for commercial sale and distribution.[16]:25 Usually after CO_2 is removed it is vented to the atmosphere.[16]:25 In 1972, American oil companies discovered that large quantities of CO_2 could be profitably be used for enhanced oil recovery (EOR).[28] Subsequently, natural gas companies in Texas began capturing the CO_2 that was produced by their processing plants, and selling it to local oil producers for EOR.[16]:25

The use of CCS as a means of reducing anthropogenic CO_2 emissions is more recent. In 1977, the Italian physicist Cesare Marchetti proposed that CCS technology could be used to reduce emissions from coal power plants and fuel refineries.[29][30] 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.[16]:25



Global proposed (grey bars) vs. implemented (blue bars) annual CO_2 captured. Both are in million tons of CO_2 per annum (Mtpa). More than 75% of proposed CCS installations for natural-gas processing have been implemented.

In 2005, the IPCC released a report highlighting CCS, leading to increased government support for CCS in several countries.[31] Governments spent an estimated USD $30 billion on subsidies for CCS and for fossil-fuel based hydrogen. [32] Globally, 149 projects were proposed to be operational by 2020, aiming to store 130 million tonnes of CO_2 annually. Of these, around 70% were not implemented.[2] In 2020, the International Energy Agency stated, “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 CO2 emissions.”[16]:18


Plans to add CCS to Bełchatów Power Station were cancelled in 2013.[25] In the power sector, close to 90% of proposed CCS capacity was never built.[26]

As of 2023, 40 commercial CCS facilities are operational.[6] Fifteen of these projects in operation are devoted to separating naturally-occurring CO_2 from raw natural gas. Seven projects are for hydrogen, ammonia, or fertilizer production, six for chemical production, three for electricity and heat, and two for oil refining. CCS is also used in one iron and steel plant.[6] Fourteen projects are in the United States, eleven in China, seven in Canada, and two in Norway. Australia, Brazil, Qatar, Saudi Arabia, and the United Arab Emirates have one project each.[6] North America has more than 8000 km of CO_2 pipelines, and there are two CO_2 pipeline systems in Europe and two in the Middle East.[10]:103–104

Process overview

CCS facilities capture carbon dioxide before it enters the atmosphere. Generally, a chemical solvent or a porous solid material is used to separate the CO2 from other components of a plant’s exhaust stream.[33] Most commonly, flue gas passes through an amine solvent, which binds the CO2 molecule. This CO2-rich solvent is heated in a regeneration unit to release the CO2 from the solvent. The purified CO2 stream is compressed and transported for storage or end-use and the released solvents are recycled to again capture CO2 from flue gas.[34]

After the CO_2 has been captured, it is usually compressed into a supercritical fluid and then injected underground. Pipelines are the cheapest way of transporting CO2 in large quantities onshore and, depending on the distance and volumes, offshore.[10]:103–104 Transport via ship has been researched. CO2

can also be transported by truck or rail, albeit at higher cost per tonne of CO_2.[10]:103–104

Technical components

There are three ways that CO_2 can be separated from a flue gas mixture: post-combustion capture, pre-combustion capture, and oxy-combustion:[35]

- In *post combustion capture*, the CO_2 is removed after combustion of the fossil fuel.
- The technology for *pre-combustion* is widely applied in fertilizer, chemical, gaseous fuel (H_2, CH_4), and power production.[36] In these cases, the fossil fuel is partially oxidized, for instance in a gasifier. The CO from the resulting syngas (CO and H_2) reacts with added steam (H_2O) and is shifted into CO_2 and H_2. The resulting CO_2 can be captured from a relatively pure exhaust stream. The H_2 can be used as fuel; the CO_2 is removed before combustion. Several advantages and disadvantages apply versus post combustion capture.[37][38] The CO_2 is removed after combustion, but before the flue gas expands to atmospheric pressure. The capture before expansion, i.e. from pressurized gas, is standard in almost all industrial CO_2 capture processes, at the same scale as required for power plants.[39][40]
- In *oxy-fuel combustion*[41] the fuel is burned in pure oxygen instead of air. To limit the resulting flame temperatures to levels common during conventional combustion, cooled flue gas is recirculated and injected into the combustion chamber. The flue gas consists of mainly CO_2 and water vapor, the latter of which is condensed through cooling. The result is an almost pure CO_2 stream.

Absorption, or carbon scrubbing with amines is the dominant capture technology.[16]:98 Other technologies proposed for carbon capture are membrane gas separation, chemical looping combustion, calcium looping, and use of metal-organic frameworks and other solid sorbents.[42][43][44]

Impurities in CO_2 streams, like sulfurs and water, can have a significant effect on their phase behavior and could cause increased pipeline and well corrosion. In instances where CO_2 impurities exist, a scrubbing separation process is needed to initially clean the flue gas.[45]

Storage and enhanced oil recovery

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.[16]:112 The gas is usually compressed first into a supercritical fluid. When the compressed CO_2 is injected into a reservoir, it flows through it, filling the pore space. The reservoir must be at depths greater than 800 metres to retain the CO_2 in a dense liquid state.[16]:112

As of 2024, around 80% of the CO_2 captured annually is used for enhanced oil recovery (EOR).[2] In EOR, CO_2 is injected into partially depleted oil fields 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.[16] :117 Around 20% of captured CO_2 is injected into dedicated geological storage,[2]

usually deep saline aquifers. These are layers of porous and permeable rocks saturated with salty water.[16]:112 Worldwide, saline formations have higher potential storage capacity than depleted oil wells.[46] Dedicated geologic storage is generally less expensive than EOR because it does not require a high level of CO_2 purity and because suitable sites are more numerous, which means pipelines can be shorter.[47]

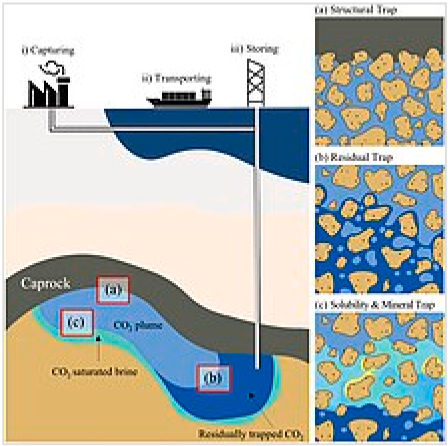


Diagram of mechanisms for trapping carbon dioxide in geologic storage

Various other types of reservoirs for storing captured CO_2 are being researched or piloted as of 2021: CO_2 could be injected into coal beds for enhanced coal bed methane recovery.[48] *Ex-situ mineral carbonation* involves reacting CO_2 with mine tailings or alkaline industrial waste to form stable minerals such as calcium carbonate.[49] *In-situ mineral carbonation* involves injecting CO_2 and water into underground formations that are rich in highly-reactive rocks such as basalt. There, the CO_2 may react with the rock to form stable carbonate minerals relatively quickly.[49][50] Once the mineral carbonation process is complete, there is no risk of CO_2 leakage.[51]

The global capacity for underground CO_2 storage is potentially very large and is unlikely to be a constraint on the development of CCS.[16]:112–115 Total storage capacity has been estimated at between 8,000 and 55,000 gigatonnes.[16]:112–115 However, a smaller fraction will most likely prove to be technically or commercially feasible.[16]:112–115 Global capacity estimates are uncertain, particularly for saline aquifers where more site characterization and exploration is still needed.[16]:112–115

Long-term CO_2 leakage

In geologic storage, the CO_2 is held within the reservoir through several trapping mechanisms: *structural* trapping by the caprock 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.[16]:112 Mineral trapping progresses over time but is extremely slow.[52]:26

Once injected, the CO_2 plume tends to rise since it is less dense than its surroundings. Once it encounters a caprock, it will spread laterally until it encounters a gap. If there are fault planes near the injection zone, CO_2 could migrate along the fault to the surface, leaking into the atmosphere, which would be potentially dangerous to life in the surrounding area. If the injection of CO_2 creates pressures underground that are too high, the formation will fracture, potentially causing an earthquake.[53] While research suggests that earthquakes from injected CO_2 would be too small to endanger property, they could be large enough to cause a leak.[54]

The IPCC estimates that at appropriately-selected and well-managed storage sites, it is likely that over 99% of CO_2 will remain in place for more than 1000 years, with "likely" meaning a probability of 66% to 90%.[4]:14,12 Estimates of long-term leakage rates rely on complex simulations since field data is limited.[55] If very large amounts of CO_2 are sequestered, even a 1% leakage rate over 1000 years could cause significant impact on the climate for future generations.[56]

Social and environmental impacts

Energy and water requirements

The construction of pipelines adversely affects wildlife.[57]

In general, facilities with CCS require 15-25% more energy.[9] The energy consumed by CCS is called an "energy penalty". It has been estimated that about 60% of the penalty originates from the capture process, 30% comes from compression of the extracted CO_2, while the remaining 10% comes from pumps and fans.[58] CCS technology is expected to use between 10 and 40 percent of the energy produced by a power station.[59][60] CCS would increase the fuel requirement of a gas plant with CCS by about 15%.[61]

For super-critical pulverized coal (PC) plants, CCS' energy requirements range from 24 to 40%, while for coal-based gasification combined cycle (IGCC) systems it is 14–25%.[62] Using CCS for natural gas combined cycle (NGCC) plants can decrease operating efficiency from 11 to 22%.[62]

Depending on the technology used, CCS can require large amounts of water. For instance, coal- fired power plants with CCS may need to use 50% more water.[63]:668

Pollution

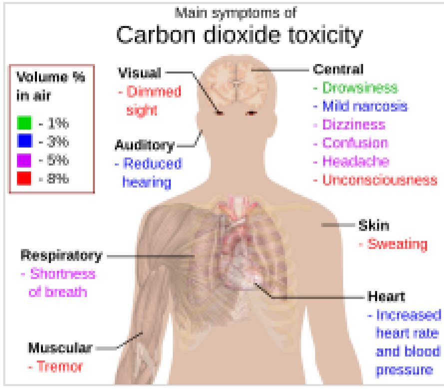
Since plants with CCS require more fuel to produce the same amount of electricity or heat, the use of CCS increases the "upstream" environmental problems of fossil fuels. Upstream impacts include pollution caused by coal mining, emissions from the fuel used to transport coal and gas, emissions from gas flaring, and fugitive methane emissions.

Since CCS facilities require more fossil fuel to be burned, this could cause a net increase of non-GHG pollutants from those facilities. Some of these pollutants are controlled by pollution control equipment,[64] however no equipment can eliminate all pollutants.[7] Since liquid amine solutions are used to capture CO_2 in many CCS systems, these types of chemicals can also be released as air pollutants if not adequately controlled. Among the chemicals of concern are volatile nitrosamines which are carcinogenic when inhaled or drunk in water.[65][66]

Studies that consider both upstream and downstream impacts indicate that adding CCS to power plants increases overall negative impacts on human health.[67] The health impacts of adding CCS in the industrial sector are less well-understood.[67] Health impacts vary significantly depending on the fuel used and the capture technology.[67]

Sudden CO_2 leakage

CO_2 is a colorless and odorless gas that accumulates near the ground because it is heavier than air. In humans, exposure to CO_2 at concentrations greater than 5% causes the development of hypercapnia and respiratory acidosis. Concentrations of more than 10% may cause convulsions, coma, and death. CO_2 levels of more than 30% act rapidly leading to loss of consciousness in seconds.[68]



Main symptoms of carbon dioxide toxicity

Pipelines and storage sites can be sources of large accidental releases of CO_2 that can endanger local communities. A 2005 IPCC report stated that "existing CO2 pipelines, mostly in areas of low population density, accident numbers reported per kilometre of pipeline are very low and are comparable to those for hydrocarbon pipelines."[4]:12 The report also stated that the local health and safety risks of geologic CO_2 storage were "comparable" to the risks of underground storage of natural gas if good site selection processes, regulatory oversight, monitoring, and incident remediation plans are in place.[4]:12

While infrequent, accidents can be serious. In 2020 a CO_2 pipeline ruptured following a mudslide near Satartia, Mississippi, causing people nearby to lose consciousness.[69] 200 people were evacuated and 45 were hospitalized, and some experienced longer term effects on their health.[70][71] High concentrations CO_2 in the air also caused vehicle engines to stop running, hampering the rescue effort.[72]

A severed 19" pipeline section 8 km long could release its 1,300 tonnes in about 3–4 min.[73] At the storage site, the injection pipe can be fitted with non-return valves to prevent an uncontrolled release from the reservoir in case of upstream pipeline damage. Pipelines can be fitted with remotely controlled valves that can limit the release quantity to one pipe section, however, operators in the United States have not been required to retrofit older pipes because of the nonapplication clause found at 49 U.S.C. § 60104(b), which prohibits the Pipeline and Hazardous Materials Safety Administration (PHMSA) from promulgating regulations to existing facilities.[74] The US Pipeline and Hazardous Materials Safety Administration, the agency in charge of pipeline safety, has been criticized as being underfunded and understaffed.[74]

Equity

In the United States, the types of facilities that could be retrofitted with CCS are often located in communities that have already borne the negative environmental and health impacts of living near power or industrial facilities.[7] These facilities are disproportionately located in poor and/or minority communities.[75] While there is evidence that CCS can help reduce non-CO2 pollutants along with capturing CO2, many environmental justice groups are concerned that CCS will be used as a way to

prolong a facility's lifetime and continue the local harms it causes.[7] Often, community-based organizations and other advocates would prefer a facility is shut down and investment is focused instead on cleaner production processes, such as renewable energy sources in the power sector.[7]

Cost

Project cost, low technology readiness levels in capture technologies, and a lack of revenue streams are among the main reasons for CCS projects to stop.[2] A commercial-scale project typically requires an upfront capital investment of up to several billion dollars.[8] According to the U.S. Environmental Protection Agency, CCS would the cost of electricity generation from coal plants by $7 to $12/ MWh.[76]

Costs can vary greatly by CO2 source, from a range of USD 15-25/tonne of CO2 for industrial processes producing highly concentrated CO2 streams (such as ethanol production or natural gas processing) to USD 40-120/tonne CO2 for processes with dilute gas streams, such as cement production and power generation. [77] In the United States, the cost of onshore pipeline transport is in the range of USD 2-14/t CO2, and more than half of onshore storage capacity is estimated to be available below USD 10/t CO2.[77]

CCS trials for coal-fired plants in the early 21st century were economically unviable in most countries,[78][79] in part because revenue from enhanced oil recovery collapsed with the 2020 oil price collapse,[80] and the falling cost of alternative electricity generation, such as solar and wind.[81]

Role in climate change mitigation

Comparison with other mitigation options

Compared to other options for reducing emissions, CCS is very expensive. For instance, removing CO_2 from the flue gas of fossil fuel power plants increases costs by USD $50 - $200 per tonne of CO_2 removed.[82]:38 There are many ways to reduce emissions that cost less than USD $20 per tonne of avoided CO_2 emissions.[83] Options to reduce emissions that have far more potential to reduce emissions at lower cost include public transit, electric vehicles, and various other energy efficiency measures.[82]:38 Wind and solar power are often the lowest-cost ways to produce electricity, even when compared to power plants that do *not* use CCS.[82]:38 Since CCS always adds costs, it is difficult for fossil fuel plants with CCS to compete with renewable energy combined with energy storage, especially as the cost of renewable energy and batteries continues to decline.

Priority uses

In the literature on climate change mitigation, CCS is described as having a small but critical role in reducing greenhouse gas emissions.[7][63]:28 The IPCC estimated in 2014 that forgoing CCS altogether would make it 138% more expensive to keep global warming within 2 degrees Celsius.[84] Excessive reliance on CCS as a mitigation tool would also be costly and technically unfeasible. According to the IEA, attempting to abate oil and gas consumption only through CCS and direct air capture would cost

USD 3.5 trillion per year, which is about the same as the annual revenue of the entire oil and gas industry.[85] Emissions are relatively difficult or expensive to abate without CCS in the following niches:[10]:13–14

Retrofitting cement plants with CCS is one of the few options to reduce their emissions. However, carbon capture technology for cement is still at the demonstration stage.

- **Heavy Industry:** CCS is one of the few few available technologies that can significantly reduce emissions associated with the production of steel, cement, and various chemicals.[10]:21–24 The CO_2 emissions from these processes come from chemical reactions, in addition to emissions from burning fuels for heat. Cleaner industrial processes are in development but are far from being widely-deployed.[63]:29
- **Retrofits:** CCS can be retrofitted to existing coal and natural gas power plants and industrial facilities to enable the continued operation of existing plants while reducing their emissions.[10]:21–24
- **Natural gas processing:** CCUS is the only solution to reduce the CO_2 emissions from natural gas processing.[10]:21–24 This does not reduce the emissions released when the gas is burned.[7]
- **Hydrogen:** Nearly all hydrogen today is produced from natural gas or coal. Facilities can incorporate CCS to capture the CO_2 released in these processes.[10]:21–24
- **Complement to renewable electricity:** In the IEA's scenario for net zero emissions, 251 GW of electricity worldwide are produced by coal and gas plants equipped with CCS by 2050, while 54,679 GW of electricity are produced by solar PV and wind.[86]:91–92 Although solar and wind energy are typically cheaper, power plants that burn natural gas, biomass, or coal have the advantage of being able to produce electricity in any season and any time of day, and can be dispatched at times of high demand.[10]:51–52 A small amount of power plant capacity can help to meet the growing need for system flexibility as the share of wind and solar increases.[10]:51–52 The potential for a robust power grid using 100% renewable energy has been modelled as a feasible option for many regions, which would make fossil CCS in the electricity sector unnecessary.[87] However, this approach may be more expensive.[63]:676
- **Electrofuel production:** According to the IEA, 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. 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 direct air capture to be carbon-neutral.[10]:21–24
- **Bioenergy with carbon capture and storage:** Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the CO_2 that is produced. Under some conditions, BECCS can remove carbon dioxide from the atmosphere.[88]

The IPCC stated in 2022 that "implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers."[63]:28 Since CCS can only be used with large, stationary emission sources, it cannot reduce the emissions from burning fossil fuels in

vehicles and homes. The IEA describes "excessive expectations and reliance" on CCS and direct air capture as a common misconception.[85] To reach targets set in the Paris Agreement, CCS must be accompanied by a steep decline in the production and use of fossil fuels.[7][63]:672

Effectiveness in reducing emissions

Coal plants with CCS usually burn more coal to provide the energy needed for CCS processes. This increases the environmental effects of coal mining.

When CCS is used for electricity generation, most studies assume that 85-90% of the CO_2 in the flue gas is captured.[89] However, industry representatives say actual capture rates are closer to 75%, and have lobbied for government programs to accept this lower target.[90] The potential for a CCS project to reduce emissions depends on several factors in addition to the capture rate. These factors include the amount of additional energy needed to power CCS processes, the source of the additional energy used, and post-capture leakage. The energy needed for CCS usually comes from fossil fuels whose mining, processing, and transport produce emissions. Some studies indicate that under certain circumstances the overall emissions reduction from CCS can be very low, or that adding CCS can even increase emissions relative to no capture.[91][92] For instance, one study found that in the Petra Nova CCS retrofit of a coal power plant, the actual rate of emissions reduction was so low that it would average only 10.8% over a 20-year time frame.[93]

Many CCS implementations have not sequestered carbon at their designed capacity, either for business or technical reasons. For instance, in the Shute Creek Gas Processing Facility, around half of the CO2 that has been captured has been sold for EOR, and the other half vented to the atmosphere because it could not be profitably sold.[94]:19 In the first year after CCS was added to the Boundary Dam Power Station in Canada, the capture rate was 90% when the capture system was operating, but due to technical problems it operated only 40% of the time.[95] A 2022 analysis of 13 major CCS projects found that most had sequestered far less CO2 than originally expected.[11][94]

Additionally, there is controversy over whether carbon capture followed by EOR is beneficial for the climate. When the oil that is extracted using EOR is subsequently burned, CO_2 is released. If these emissions are included in calculations, carbon capture with EOR is usually found to *increase* overall emissions compared to not using carbon capture at all.[3] If the emissions from burning extracted oil are excluded from calculations, carbon capture with EOR is found to *decrease* emissions. In arguments for excluding these emissions, it is assumed that oil produced by EOR displaces conventionally-produced oil instead of adding to the global consumption of oil.[3] A 2020 review found that scientific papers were roughly evenly split on the question of whether carbon capture with EOR increased or decreased emissions.[3]

Pace of implementation

As of 2023 CCS captures around 0.1% of global emissions — around 45 million tonnes of CO_2.[7] Climate models from the IPCC and the IEA show it capturing around 1 billion tonnes of CO_2 by 2030 and several billions of tons by 2050.[7] Technologies for CCS in high-priority niches, such as cement

production, are still immature. The IEA notes "a disconnect between the level of maturity of individual CO2 capture technologies and the areas in which they are most needed."[10]:92

CCS implementations involve long approval and construction times and the overall pace of implementation has historically been slow.[96] As a result of the lack of progress, authors of climate change mitigation strategies have repeatedly reduced the role of CCS.[97]:132 Some observers such as the IEA call for increased commitment to CCS in order to meet targets.[96]:16 Other observers see the slow pace of implementation as an indication that the technology is fundamentally unlikely to succeed, and call for efforts to be redirected to other mitigation tools such as renewable energy.[98]

Political debate

Protest against CCS in 2021 in Torquay, England

Protest against CCS at the same event as above

CCS has been discussed by political actors at least since the start of the UNFCCC[99] negotiations in the beginning of the 1990s, and remains a very divisive issue.[100]

Fossil fuel companies have heavily promoted CCS, framing it as an area of innovation and cost-effectiveness.[13] Public statements from fossil fuel companies and fossil-based electric utilities ask for “recognition” that fossil fuel usage will increase in the future and suggest that CCS will allow the fossil fuel era to be extended.[13] Their statements typically position CCS as a necessary way to tackle climate change, while not mentioning options for reducing fossil fuel use.[13]

Many environmental NGOs such as Greenpeace hold strongly negative views on CCS, whereas others such as the Bellona Foundation consider it to be a useful tool.[15] In surveys, environmental NGOs' importance ratings for fossil energy with CCS have been around as low as their ratings for nuclear energy.[101] Critics see CCS as an unproven, expensive technology that will perpetuate dependence on fossil fuels.[14] They would rather see government funds go to initiatives that are not connected to the fossil fuel industry.[14] Environmental NGOs that do support CCS often do so conditionally, depending on factors such as effects on local ecosystems and whether CCS competes for funding with other climate initiatives.[102]

Social acceptance

The public has generally low awareness of CCS.[103]:642–643 Public support among those who are aware of CCS has tended to be low, especially compared to public support for other emission-reduction options.[103]:642–643 Local opposition has sometimes been a major factor in the cancellation of CCS projects.[103]:642–643

A frequent concern for the public is transparency, e.g. around issues such as safety, costs, and impacts.[104] Another factor in acceptance is whether uncertainties are acknowledged, including uncertainties around potentially negative impacts on the natural environment and public health.[104] Research indicates that engaging comprehensively with communities increases the likelihood of project success compared to projects that do not engage the public.[104] Some studies indicate that community collaboration can contribute to the avoidance of harm within communities impacted by the project.[104]

Government programs

Almost all CCS projects operating today have benefited from government financial support, largely in the form of capital grants and – to a lesser extent – operational subsidies. 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 million (CAD 865 million) for Quest in Canada. An explicit carbon price has supported CCS investment in only two cases to date: the Sleipner and Snøhvit projects in Norway.[16]:156–160

North America

As a means to help boost domestic oil production, the US federal tax code has had some sort of incentive for enhanced oil recovery since 1979, when crude oil was still under federal price controls. A 15 percent tax credit was codified with the U.S. Federal EOR Tax Incentive in 1986, and oil production from CO2-EOR subsequently grew rapidly.[105]

In the U.S., the 2021 Infrastructure Investment and Jobs Act designates over $3 billion for a variety of CCS demonstration projects. A similar amount is provided for regional CCS hubs that focus on the broader capture, transport, and either storage or use of captured CO_2. Hundreds of millions more are dedicated annually to loan guarantees supporting CO_2 transport infrastructure.[106]

The Inflation Reduction Act of 2022 (IRA) updates tax credit law to encourage the use of carbon capture and storage. Tax incentives under the law provide up to $85/tonne for CO_2 capture and storage in saline geologic formations or up to $60/tonne for CO_2 used for enhanced oil recovery.[107] The Internal Revenue Service relies on documentation from the corporation to substantiate claims on how much CO_2 is being sequestered, and does not perform independent investigations.[108] In 2020, a federal investigation found that claimants for the 45Q tax credit failed to document successful geological storage for nearly $900 million of the $1 billion they had claimed.[3]

In 2023 the US EPA issued a rule proposing that CCS be required in order to achieve a 90% emission reduction for existing coal-fired and natural gas power plants. That rule would become effective in the 2035-2040 time period.[109] For natural gas power plants, the rule would require 90 percent capture of CO2 using CCS by 2035, or co-firing of 30% low-GHG hydrogen beginning in 2032 and co-firing 96% low-GHG hydrogen beginning in 2038.[109] Within the US, although the federal government may fully or partially fund CCS pilot projects, local or community jurisdictions would likely administer CCS project siting and construction.[110]

Canada has established a CAD $2.6 billion tax credit for CCS projects and Saskatchewan extended its 20 per cent tax credit under the province's Oil Infrastructure Investment Program to pipelines carrying CO2.

Europe

In Norway, CCS gained traction because it allowed the country to pursue its interests regarding the petroleum industry.[111] Its two major CCS projects were enabled through a CO2 tax on offshore oil and gas production introduced in 1991.[16]:156–160

Denmark has recently announced €5 billion in subsidies for CCS.

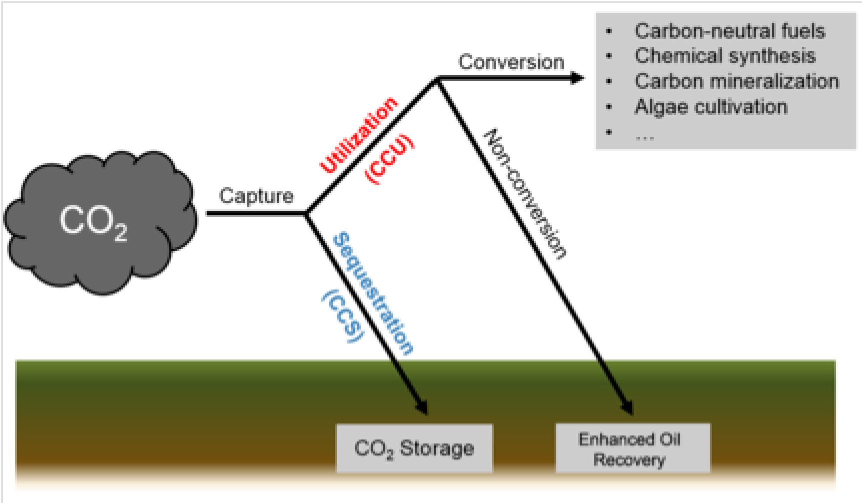
In the UK the CCUS roadmap outlines joint government and industry commitments to the deployment of CCUS and sets out an approach to delivering four CCUS low carbon industrial clusters, capturing 20-30 $MtCO_2$ per year by 2030.[18]

Asia

The Chinese State Council has now issued more than 10 national policies and guidelines promoting CCS, including the Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Vision 2035 of China.[17]

Related concepts

CO_2 utilization in products



Carbon dioxide is mostly used for enhanced oil recovery. It can also be used as a feedstock for products.

While nearly all utilization of CO_2 is for enhanced oil recovery, CO_2 can be used as a feedstock for making various types of products. As of 2022, usage in products consumes around 1% of the CO_2 captured each year.[112] As of 2023, it is commercially feasible to produce the following products from captured CO_2: methanol, urea, polycarbonates, polyols, polyurethane, and salicylic acids.[113] Methanol is currently primarily used to produce other chemicals, with potential for more widespread future use as a fuel.[114] Urea is used in the production of fertilizers.[16]:55

Technologies for sequestering CO_2 in mineral carbonate products have been demonstrated, but are not ready for commercial deployment as of 2023.[113] Research is ongoing into processes to incorporate CO_2 into concrete or building aggregate. The utilization of CO_2 in construction materials holds promise for

deployment at large scale,[115] and is the only foreseeable CO_2 use that is permanent enough to qualify as *storage*.[116] Other potential uses for captured CO_2 that are being researched include the creation of synthetic fuels, various chemicals and plastics, and the cultivation of algae.[113] The production of fuels and chemicals from CO_2 is highly energy-intensive.[116]

Capturing CO_2 for use in products does not necessarily reduce emissions.[16]:111 The climate benefits associated with CO_2 use primarily arise from displacing products that have higher life-cycle emissions.:111 The amount of climate benefit varies depending on how long the product lasts before it re-releases the CO_2, the amount and source of energy used in production, whether the product would otherwise be produced using fossil fuels, and the source of the captured CO2.[16]:111 Higher emissions reductions are achieved if CO_2 is captured from bioenergy as opposed to fossil fuels.[16]:111

The potential for CO_2 utilization in products is small compared to the total volume of CO_2 that could foreseeably be captured. For instance, in the International Energy Agency (IEA) scenario for achieving net zero emissions by 2050, over 95% of captured CO_2 is geologically sequestered and less than 5% is used in products.[116] According to the IEA, products created from captured CO_2 are likely to cost a lot more than conventional and alternative low-carbon products.[16]:110

Direct air carbon capture and sequestration (DACCS)

Direct air capture (DAC) is the use of chemical or physical processes to extract carbon dioxide directly from the ambient air.[117] If the extracted CO_2 is then sequestered in safe long-term storage (called direct air carbon capture and sequestration (DACCS), the overall process will achieve carbon dioxide removal and be a "negative emissions technology" (NET).

The carbon dioxide (CO_2) is captured directly from the ambient air; this is contrast to carbon capture and storage (CCS) which captures CO_2 from point sources, such as a cement factory or a bioenergy plant.[118] After the capture, DAC generates a concentrated stream of CO_2 for sequestration or utilization. Carbon dioxide removal is achieved when ambient air makes contact with chemical media, typically an aqueous alkaline solvent[119] or sorbents.[120] These chemical media are subsequently stripped of CO_2 through the application of energy (namely heat), resulting in a CO_2 stream that can undergo dehydration and compression, while simultaneously regenerating the chemical media for reuse.

See also

Energy portal

- List of carbon capture and storage projects
- Timeline of carbon capture and storage
- Coal pollution mitigation
- Carbon sink
- Carbon storage in the North Sea
- Greenwashing
- Life-cycle greenhouse gas emissions of energy sources
- Methane pyrolysis

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- Media related to Carbon capture and storage at Wikimedia Commons
- Zero Emissions Platform - technical adviser to the EU Commission on the deployment of CCS and CCU (https://zeroemissionsplatform.eu/)