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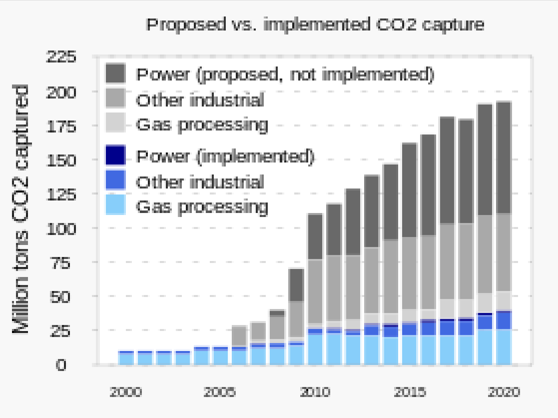
Carbon capture and storage

Carbon capture and storage (**CCS**) is a process in which a relatively pure stream of carbon dioxide (CO_2) from industrial sources is separated, treated and transported to a long-term storage location.[2]:2221 For example, the burning of fossil fuels or biomass results in a stream of CO_2 that could be captured and stored by CCS. Usually the CO_2 is captured from large point sources, such as a chemical plant or a bioenergy plant, and then stored in a suitable geological formation. The aim is to reduce greenhouse gas emissions and thus mitigate climate change.[3][4] For example, CCS retrofits for existing power plants can be one of the ways to limit emissions from the electricity sector and meet the Paris Agreement goals.[5]:16



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.[1]

Carbon dioxide can be captured directly from the gaseous emissions of an industrial source, for example from a cement producing factory (cement kiln). Several technologies are in use: adsorption, chemical looping, membrane gas separation or gas hydration.[6][7][8] However, as of 2022, only about one thousandth of global CO_2 emissions are captured by CCS, and most of those CCS projects are for natural-gas processing.[9]:32 CCS projects generally aim for 90% capture efficiency,[10] but most of the current installations have failed to meet that goal.[11]

Storage of the captured CO_2 is either in deep geological formations or in the form of mineral carbonates. Geological formations are currently the favored option for storage. Pyrogenic carbon capture and storage (PyCCS) is another option.[12] Long-term predictions about submarine or underground storage security are difficult. There is still the risk that some CO_2 might leak into the atmosphere.[13][14][15] A 2018 evaluation estimates the risk of substantial leakage to be fairly low.[16][17] CCS is so far still a relatively expensive process.[18] Carbon capture becomes more economically viable when the carbon price is high, which is the case in much of Europe.[9] Another option is to combine CCS with a utilization process where the captured CO_2 is used to produce high-value chemicals to offset the high costs of capture operations.[19]

Some environmental activists and politicians have criticized CCS as a false solution to the climate crisis. They cite the role of the fossil fuel industry in origins of the technology and in lobbying for CCS focused legislation.[20] Critics also argue that CCS is only a justification for indefinite fossil fuel usage and equate to further investments into the environmental and social harms related to the fossil fuel industry.[21][22] With regards to public support or rejection, communities who have been negatively affected by an industrial activity in the past are less supportive of CCS.[23] Communities that feel inadequately informed about or excluded from project decision-making may also resist CCS development.[24]

Globally, a number of laws and rules have been issued that either support or even mandate the implementation of CCS. In the US, the 2021 Infrastructure Investment and Jobs Act provides support for a variety of CCS projects, and the Inflation Reduction Act of 2022 updates tax credit law to encourage the use of CCS.[25][26] Other countries are also developing programs to support CCS technologies, including Canada, Denmark, China, and the UK.[27][28]

Terminology

The term carbon capture and storage, (CCS) also known as *carbon dioxide capture and storage* refers to a process in which a relatively pure stream of carbon dioxide (CO_2) is separated ("captured"), compressed and transported to a storage location for long-term isolation from the atmosphere.[2]: 2221 Bioenergy with carbon capture and storage (BECCS), is a related technique that involves the application of CCS to bioenergy in order to reduce atmospheric CO2 over the course of time.

CCS and CCUS (carbon capture, utilization, and storage) are often used interchangeably. The latter involves 'utilization' of the captured carbon for other applications, such as enhanced oil recovery (EOR), liquid fuel production, or the manufacturing of consumer goods, such as plastics. Both approaches capture CO_2 and effectively store it, whether in geological formations or in material products.[29]

Purpose

Early uses

The natural gas industry has used carbon capture technology for decades. Raw natural gas contains CO2 that needs removal to produce a marketable product. The sale of captured CO2, mainly to oil producers for EOR, has enhanced the economic viability of natural gas development projects.[30] CO2 removal for this purpose first occurred at The Terrell Natural Gas Processing Plant, in Terrell, Texas, US, in 1972.[31] The use of CCS as a means of reducing anthropogenic CO2 emissions is more recent. The Sleipner CCS project, which began in 1996, and the Weyburn-Midale Carbon Dioxide Project, which began in 2000, were the first international demonstrations of the large-scale capture, utilization, and storage of anthropogenic CO2 emissions.[32]

Role in climate change mitigation

In the 21st century CCS is employed to contribute to climate change mitigation. For example, CCS retrofits for existing power plants is one way to limit emissions from the electricity sector for meeting Paris Agreement goals.[5]: 16 However, analyses of modeling studies indicate that over-reliance on CCS presents risks, and that global rates of CCS deployment remain far below those depicted in mitigation scenarios of the IPCC Sixth Assessment Report. Total annual CCS capacity was only 45 $MtCO_2$ as of 2021.[33] The implementation of default technology assumptions would cost 29-297% more over the century than efforts without CCS for a 430-480 ppm CO_2/yr scenario.[34][35]

As of 2017, global temperatures had already increased by 1 °C since the beginning of the industrial era.[36] Because of the immediate inability to keep the temperature at the 1 °C target, the next realistic target was 1.5 °C. Scenarios where the degree change is maintained below 1.5 °C were thought to be challenging but not impossible.[37]

As of 2018, for a below 2.0 °C target, Shared socioeconomic pathways (SSPs) had been developed adding a socio-economic dimension to the integrative work started by RCPs models. All SSPs scenarios show a shift away from unabated fossil fuels, that is processes without CCS.[37] It was proposed that bioenergy with carbon capture and storage (BECCS) was necessary to achieve a 1.5 °C, and that with the help of BECCS, between 150 and 12,000 $GtCO_2$ still had to be removed from the atmosphere.[37]

Technology components

Capture

Capturing CO_2 is most cost-effective at point sources, such as large fossil fuel-based energy facilities, industries with major CO_2 emissions (e.g. cement production, steelmaking[38]), natural gas processing, synthetic fuel plants and fossil fuel-based hydrogen production plants. Extracting CO_2 from air is possible,[39] although the lower concentration of CO_2 in air compared to combustion sources complicates the engineering and makes the process therefore more expensive.[40] The net storage efficiency of carbon capture projects is maximally 6–56%.[41]

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, especially with air capture, a scrubbing separation process is needed to initially clean the flue gas.[42]

A wide variety of separation techniques are being pursued, including gas phase separation, absorption into a liquid, and adsorption on a solid, as well as hybrid processes, such as adsorption/membrane systems.[43] There are three ways that this capturing can be carried out: post-combustion capture, pre-combustion capture, and oxy-combustion:[44]

- In *post combustion capture*, the CO_2 is removed after combustion of the fossil fuel—this is the scheme that would apply to fossil-fuel power plants. CO_2 is captured from flue gases at power stations or other point sources. The technology is well understood and is currently used in other industrial applications, although at much smaller scale than required for a commercial operation. Post combustion capture is most popular in research because it is hoped that fossil fuel power plants can be retrofitted with CCS technology in this configuration.[45]
- The technology for *pre-combustion* is widely applied in fertilizer, chemical, gaseous fuel (H_2, CH_4), and power production.[46] 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.[47][48] 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.[49][50]
- In *oxy-fuel combustion*[51] 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. Power plant processes based on oxyfuel combustion are sometimes referred to as "zero emission" cycles, because the CO_2 stored is not a fraction removed from the flue gas stream (as in the cases of pre- and post-combustion capture) but the flue gas stream itself. A fraction of the CO_2 inevitably ends up in the condensed water. To warrant the label "zero emission" the water would thus have to be treated or disposed of appropriately.

Separation technologies

The major technologies proposed for carbon capture are:[6][52][53]

- Membrane
- Oxyfuel combustion
- Absorption
- Multiphase absorption
- Adsorption
- Chemical looping combustion
- Calcium looping
- Cryogenic
- Direct air capture (DAC)

Absorption, or carbon scrubbing with amines is the dominant capture technology. It is the only carbon capture technology so far that has been used industrially.[54] Monoethanolamine (MEA) solutions, the leading amine for capturing CO_2 , have a heat capacity between 3–4 J/g K since they are mostly water.[55][56] Higher heat capacities add to the energy penalty in the solvent regeneration step.

About two thirds of CCS cost is attributed to capture, making it the limit to CCS deployment. Optimizing capture would significantly increase CCS feasibility since the transport and storage steps of CCS are rather mature.[57]

An alternate method is chemical looping combustion (CLC). Looping uses a metal oxide as a solid oxygen carrier. Metal oxide particles react with a solid, liquid or gaseous fuel in a fluidized bed combustor, producing solid metal particles and a mixture of CO_2 and water vapor. The water vapor is condensed, leaving pure CO_2 , which can then be sequestered. The solid metal particles are circulated to another fluidized bed where they react with air, producing heat and regenerating metal oxide particles for return to the combustor. A variant of chemical looping is calcium looping, which uses the alternating carbonation and then calcination of a calcium oxide based carrier.[58]

Under significant study is also adsorption based carbon capture on highly porous materials such as activated carbons, zeolites, or MOFs. Such a process is divided into physical and chemical adsorption or physisorption and chemisorption respectively. The former mitigates the issue of CO_2 regeneration as most of the CO_2 can be regenerated by simply decreasing the pressure. Physisorption capacity is principally determined by the porosity of the adsorbate.[8][59]

A 2019 study found CCS plants to be less effective than renewable electricity.[60] The electrical energy returned on energy invested (EROEI) ratios of both production methods were estimated, accounting for their operational and infrastructural energy costs. Renewable electricity production included solar and wind with sufficient energy storage, plus dispatchable electricity production. Thus, rapid expansion of scalable renewable electricity and storage would be preferable over fossil-fuel with CCS. The study did not consider whether both options could be pursued in parallel.[60]

In sorption enhanced water gas shift (SEWGS) technology a pre-combustion carbon capture process, based on solid adsorption, is combined with the water gas shift reaction (WGS) in order to produce a high pressure hydrogen stream.[61] The CO_2 stream produced can be stored or used for other industrial processes.[62]

Compression

After the CO_2 has been captured, it is usually compressed into a supercritical fluid. The CO_2 is compressed so that it can be more easily transported. Compression is done at the capture site. This process requires its own energy source. Like the capture stage, compression is achieved by increasing the parasitic load. Compression of CO_2 is an energy intensive procedure that involves multi-stage complex compressors and a power-generated cooling process.[63]

Transport

Some highly pressurized CO_2 is already transported via pipelines. For example, approximately 5,800 km of CO_2 pipelines operated in the US in 2008, and a 160 km pipeline in Norway,[64] used to transport CO_2 to oil production sites where it is injected into older fields to extract oil. This injection is used for *enhanced oil recovery*. Pilot programs are in development to test long-term storage in non-oil producing geologic formations. In the United Kingdom, the Parliamentary Office of Science and Technology envisages pipelines as the main UK transport.[64]

In 2021, two companies, namely Navigator CO_2 Ventures and Summit Carbon Solutions were planning pipelines through the Midwestern US from North Dakota to Illinois to connect ethanol companies to sites where liquefied CO_2 is injected into porous rock.[65] The Navigator Heartland Greenway pipeline project was cancelled after encountering significant local resistance to the project.[66] The Summit Carbon pipeline has also been encountering significant headwinds, and is currently forecasting a COD in 2026.[67]

Leakage during transport

Transmission pipelines may leak or rupture. Pipelines can be fitted with remotely controlled valves that can limit the release quantity to one pipe section. A severed 19" pipeline section 8 km long could release its 1,300 tonnes in about 3–4 min.[68]

In 2020 a pipeline exploded near Satartia, Mississippi, causing cars to stop and people to go unconscious; 45 were hospitalized, and some experienced longer term effects on their health.[69][70]

Sequestration (storage)

Various approaches have been conceived for permanent storage. These include gaseous storage in deep geological formations (including saline formations and exhausted gas fields), and solid storage by reaction of CO_2 with metal oxides to produce stable carbonates. Storage capacity, containment efficiency and injectivity are the three factors that require major pre-assessment to decide the feasibility of CO2 storage in a candidate geological formation.[71] Geo-sequestration, involves injecting CO_2, generally in supercritical form, into underground geological formations. Oil fields, gas fields, saline formations, unmineable coal seams, and saline-filled basalt formations have been suggested as alternatives. At the molecular level, carbon dioxide is shown to affect the mechanical properties of the formation where it has been injected.[72] Physical (e.g., highly impermeable caprock) and geochemical trapping mechanisms prevent the CO_2 from escaping to the surface.[73]

Unmineable coal seams can be used because CO_2 molecules attach to the coal surface. Technical feasibility depends on the coal bed's permeability. In the process of absorption the coal releases previously absorbed methane, and the methane can be recovered (enhanced coal bed methane recovery). Methane revenues can offset a portion of the cost, although burning the resultant methane, however, produces another stream of CO_2 to be sequestered.

Saline formations contain mineralized brines and have yet to produce benefit to humans. Saline aquifers have occasionally been used for storage of chemical waste in a few cases. The main advantage of saline aquifers is their large potential storage volume and their ubiquity. The major disadvantage of saline aquifers is that relatively little is known about them. To keep the cost of storage acceptable, geophysical exploration may be limited, resulting in larger uncertainty about the aquifer structure. Unlike storage in oil fields or coal beds, no side product offsets the storage cost. *Trapping mechanisms* such as structural trapping, residual trapping, solubility trapping and mineral trapping may immobilize the CO_2 underground and reduce leakage risks.[73] [74]

Enhanced oil recovery

CO_2 is occasionally injected into an oil field as an enhanced oil recovery technique,[75] but because CO_2 is released when the oil is burned,[76] it is not carbon neutral.[77]

CO_2 has been injected into geological formations for several decades for enhanced oil recovery and after separation from natural gas, but this has been criticised for producing more emissions when the gas or oil is burned.[9]

Leakage risks during storage

Long-term retention

IPCC estimates that leakage risks at properly managed sites are comparable to those associated with current hydrocarbon activity. It recommends that limits be set to the amount of leakage that can take place.[78] However, this finding is contested given the lack of experience.[79][80] CO_2 could be trapped for millions of years, and although some leakage may occur, appropriate storage sites are likely to retain over 99% for over 1000 years.[81]

Mineral storage is not regarded as presenting any leakage risks.[82]

Norway's Sleipner gas field is the oldest industrial scale retention project. An environmental assessment conducted after ten years of operation concluded that geosequestration was the most definite form of permanent geological storage method:

> Available geological information shows absence of major tectonic events after the deposition of the Utsira formation [saline reservoir]. This implies that the geological environment is tectonically stable and a site suitable for CO_2 storage. The solubility trapping [is] the most permanent and secure form of geological storage.[83]

In March 2009, the national Norwegian oil company StatoilHydro (later renamed Equinor) issued a study documenting the slow spread of CO_2 in the formation after more than 10 years operation.[84]

Gas leakage into the atmosphere may be detected via atmospheric gas monitoring, and can be quantified directly via eddy covariance flux measurements.[85][86][87]

Sudden leakage hazards

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.

Large-scale CO_2 releases present asphyxiation risks. For example, in the 1953 Menzengraben mining accident, several thousand tonnes were released and asphyxiated a person 300 meters away.[68] Malfunction of a CO_2 industrial fire suppression system in a large warehouse released 50 t CO_2 after which 14 people collapsed on the nearby public road.[68]

Scale

Worldwide storage capacity in oil and gas reservoirs is estimated to be 675–900 Gt CO_2, and in un-minable coal seams is estimated to be 15–200 Gt CO_2. Deep saline formations have the largest capacity, which is estimated to be 1,000–10,000 Gt CO_2.[88] In the US, there is estimated to be at least 2,600 Gt and at most 22,000 Gt total CO_2 storage capacity.[89]

According to the Global CCS Institute, in 2020 there was about 40 million tons CO_2 per year capacity of CCS in operation and 50 million tons per year in development.[90] In contrast, the world emits about 38 billion tonnes of CO_2 every year,[91] so CCS captured about one thousandth of the 2020 CO_2 emissions. Iron and steel is expected to dominate industrial CCS in Europe,[18] although there are alternative ways of decarbonizing steel.[92]

Example projects

There are a number of large-scale carbon capture and sequestration projects that have demonstrated the viability and safety of this method of carbon storage, which are summarized by the Global CCS Institute.[93]

In September 2020, the US Department of Energy awarded $72 million in federal funding to support the development and advancement of carbon capture technologies.[94]

One of the most well-known failures is the FutureGen program, partnerships between the US federal government and coal energy production companies which were intended to demonstrate "clean coal", but never succeeded in producing any carbon-free electricity from coal.[95][96]

Cost

Cost is a significant factor affecting CCS. The cost of CCS, plus any subsidies, must be less than the expected cost of emitting CO_2 for a project to be considered economically favorable.

CCS technology is expected to use between 10 and 40 percent of the energy produced by a power station.[97][98] 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.[99] CCS would increase the fuel requirement of a plant with CCS by about 15% (gas plant).[100] The cost of this extra fuel, as well as storage and other system costs, are estimated to increase the costs of energy from a power plant with CCS by 30–60%. This makes it more 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.

Constructing CCS units is capital intensive. The additional costs of a large-scale CCS demonstration project are estimated to be €0.5–1.1 billion per project over the project lifetime. Other applications are possible. CCS trials for coal-fired plants in the early 21st century were economically unviable in most countries,[101] including China,[102] in part because revenue from enhanced oil recovery collapsed with the 2020 oil price collapse.[103] A carbon price of at least 100 euros per tonne CO_2 is estimated to be needed to make industrial CCS viable,[104] together with carbon tariffs.[105] But, as of mid-2022, the EU Allowance had never reached that price and the Carbon Border Adjustment Mechanism had not yet been implemented.[106] However, a company making small modules claims it can get well below that price by mass production by 2022.[107]

According to UK government estimates made in the late 2010s, carbon capture (without storage) is estimated to add 7 GBP per MWh by 2025 to the cost of electricity from a gas-fired power plant. However, the CO_2 will need to be stored, so in total the increase in cost for gas or biomass generated electricity is around 50%.[108]

A 2020 study concluded that half as much CCS might be installed in coal-fired plants as in gas-fired: these would be mainly in China and India.[109] However a 2022 study concluded that it would be too expensive for coal power in China.[110]

Bill Gates said in 2023 that in his view CCS was unlikely to be economically viable for mass-scale use in the long term, and that "for most cases, you should use an alternative technique rather than emitting and then paying for capturing.... For everything you can, you want to solve it by never generating the carbon dioxide."[111][112]

Related impacts

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.[113] CCS systems also reduce the efficiency of the power plants that use them to control CO_2. 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%.[114] Using CCS for natural gas combined cycle (NGCC) plants can decrease operating efficiency from 11 to 22%.[114] This in turn could cause a net increase of non-GHG pollutants from those facilities. However, most of these impacts are controlled by the pollution control equipment already installed at these plants to meet air pollution regulations.[115] CCS technology also has operational impacts. These impacts increase as the capacity factor decreases (the plant is used less - for example only for times of highest demand or in emergencies).[9]: 42

Other impacts occur outside the facility. As a result of efficiency losses at coal plants, fuel use and environmental problems arising from coal extraction increase. Plants equipped with flue-gas desulfurization (FGD) systems for sulfur dioxide control require proportionally greater amounts of limestone, and systems equipped with selective catalytic reduction systems for nitrogen oxides produced during combustion require proportionally greater amounts of ammonia. Limiting the use of CCS would also bring near-term benefits from reduced air and water pollution, human rights violations, and biodiversity loss.[33]

Monitoring

Monitoring allows leak detection with enough warning to minimize the amount lost, and to quantify the leak size. Monitoring can be done at both the surface and subsurface levels.[116] The dominant monitoring technique is seismic imaging, where vibrations are generated that propagate through the subsurface. The geologic structure can be imaged from the refracted/reflected waves.[116]

Subsurface

Subsurface monitoring can directly and/or indirectly track the reservoir's status. One direct method involves drilling deep enough to collect a sample. This drilling can be expensive due to the rock's physical properties. It also provides data only at a specific location.

One indirect method sends sound or electromagnetic waves into the reservoir which reflects back for interpretation. This approach provides data over a much larger region; although with less precision.

Both direct and indirect monitoring can be done intermittently or continuously.[117]

Seismic

Seismic monitoring is a type of indirect monitoring. It is done by creating seismic waves either at the surface using a seismic vibrator, or inside a well using a spinning eccentric mass. These waves propagate through geological layers and reflect back, creating patterns that are recorded by seismic sensors placed on the surface or in boreholes.[118] It can identify migration pathways of the CO_2 plume.[119]

Examples of seismic monitoring of geological sequestration are the Sleipner sequestration project, the Frio CO_2 injection test and the CO2CRC Otway Project.[120] Seismic monitoring can confirm the presence of CO_2 in a given region and map its lateral distribution, but is not sensitive to the concentration.

Zoback and Gorelick (2012) identified the need for further study into how low to moderate intensity seismic events can impact the seal integrity of any prospective reservoirs for geologic carbon storage. Induced seismicity due to wastewater injection is widely documented; however these discussions are typically not in the context of nearby CCS storage sites. This prompts the need for a greater understanding of the risks of local and regional seismic impacts of storage integrity over time.[121]

Tracer

Organic chemical tracers, using no radioactive or Cadmium components, can be used during the injection phase in a CCS project where CO_2 is injected into an existing oil or gas field, either for EOR, pressure support or storage. Tracers and methodologies are compatible with CO_2 – and at the same time unique and distinguishable from the CO_2 itself or other molecules present in the sub-surface. Using laboratory methodology with an extreme detectability for tracer, regular samples at the producing wells will detect if injected CO_2 has migrated from the injection point to the producing well. Therefore, a small tracer amount is sufficient to monitor large scale subsurface flow patterns. For this reason, tracer methodology is well-suited to monitor the state and possible movements of CO_2 in CCS projects. Tracers can therefore be an aid in CCS projects by acting as an assurance that CO_2 is contained in the desired location sub-surface. In the past, this technology has been used to monitor and study movements in CCS projects in Algeria,[122] the Netherlands[123] and Norway (Snøhvit).

Surface

Eddy covariance is a surface monitoring technique that measures the flux of CO_2 from the ground's surface. It involves measuring CO_2 concentrations as well as vertical wind velocities using an anemometer.[124] This provides a measure of the vertical CO_2 flux. Eddy covariance towers could potentially detect leaks, after accounting for the natural carbon cycle, such as photosynthesis and plant respiration. An example of eddy covariance techniques is the Shallow Release test.[125] Another similar approach is to use accumulation chambers for spot monitoring. These chambers are sealed to the ground with an inlet and outlet flow stream connected to a gas analyzer.[117] They also measure vertical flux. Monitoring a large site would require a network of chambers.

InSAR

InSAR monitoring involves a satellite sending signals down to the Earth's surface where it is reflected back to the satellite's receiver. The satellite is thereby able to measure the distance to that point.[126] CO_2 injection into deep sublayers of geological sites creates high pressures. These layers affect layers above and below them, change the surface landscape. In areas of stored CO_2 , the ground's surface often rises due to the high pressures. These changes correspond to a measurable change in the distance from the satellite.[126]

Society and culture

Social acceptance

Multiple studies indicate that risk and benefit perception are the most essential components of social acceptance.[23]

Risk perception is mostly related to the concerns on its safety issues in terms of hazards from its operations and the possibility of CO_2 leakage which may endanger communities, commodities, and the environment in the vicinity of the infrastructure.[127] Other perceived risks relate to tourism and property values.[23] CCS public perceptions appear among other controversial technologies to tackle climate change such as nuclear power, wind, and geoengineering[128]

Protest against CCS in 2021 in Torquay, England

People who are already affected by climate change, such as drought,[129] tend to be more supportive of CCS. Locally, communities are sensitive to economic factors, including job creation, tourism or related investment.[23]

Experience is another relevant feature. Several field studies concluded that people already involved or used to industry are likely to accept the technology. In the same way, communities who have been negatively affected by any industrial activity are also less supportive of CCS.[23]

Protest against CCS at the same event as above

Perception of CCS as a viable technology has a strong geographic component. Public perception of the risks and benefits of CSS can depend on the available information about pilot projects, trust in the government entities and developers involved, and awareness of successes and failures of CCS projects both locally and globally. These considerations vary by country and by community.[130]

If only considering technical feasibility, countries with no known viable storage sites may dismiss CCS as an option in national emissions reduction strategies. In contrast, countries with several, or an abundance of viable storage sites may consider CCS as essential to reducing emissions.[131]

Few members of the public know about CCS. This can allow misconceptions that lead to less approval. No strong evidence links knowledge of CCS and public acceptance. However, one study found that communicating information about monitoring tends to have a negative impact on attitudes.[132] Conversely, approval seems to be reinforced when CCS is compared to natural phenomena.[23]

Connected to how public perception influences the success or failure of a CCS project is consideration for how decision-making processes are implemented equitably and meaningfully for impacted communities at all stages of the project. Public participation alone does not encompass all aspects of procedural justice needed for CCS projects to receive the "social license" to operate.[133]

Due to the lack of knowledge, people rely on organizations that they trust. In general, non-governmental organizations and researchers experience higher trust than stakeholders and governments. Opinions amongst NGOs are mixed.[134][135] Moreover, the link between trust and acceptance is at best indirect. Instead, trust has an influence on the perception of risks and benefits.[23]

CCS is embraced by the Shallow ecology worldview,[136] which promotes the search for solutions to the effects of climate change in lieu of/in addition to addressing the causes. This involves the use of advancing technology and CCS acceptance is common among techno-optimists. CCS is an "end-of-pipe" solution[23] that reduces atmospheric CO_2, instead of minimizing the use of fossil fuel.[23][136]

On 21 January 2021, Elon Musk announced he was donating $100m for a prize for best carbon capture technology.[137]

Political debate

CCS has been discussed by political actors at least since the start of the UNFCCC[138] negotiations in the beginning of the 1990s, and remains a very divisive issue.

Some environmental groups raised concerns over leakage given the long storage time required, comparing CCS to storing radioactive waste from nuclear power stations.[139]

Other controversies arose from the use of CCS by policy makers as a tool to fight climate change. In the IPCC's Sixth Assessment Report in 2022, most pathways to keep the increase of global temperature below 2 °C include the use of negative emission technologies (NETs).[140]

Some environmental activists and politicians have criticized CCS as a false solution to the climate crisis. They cite the role of the fossil fuel industry in origins of the technology and in lobbying for CCS focused legislation and argue that it would allow the industry to "greenwash" itself by funding and engaging in things such as tree planting campaigns without significantly cutting their carbon emissions.[141][20]

A review of studies by the Stanford Solutions Project concluded that relying on Carbon capture and storage/utilization (CCS/U) is a dangerous distraction, with it (in most and large-scale cases) being expensive, increasing air pollution and mining, inefficient and unlikely to be deployable at the scale required in time.[142]

Government programs

In the US, a number of laws and rules have been issued to either support or require the use of CCS technologies. 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.[25] 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 are $85/tonne for CO_2 capture and storage in saline geologic formations from industrial and power plants. Incentives for CO_2 capture and utilization from these plants are $60/tonne. Thresholds for the total amount of CO_2 needing to be captured are also lower, and so more facilities will be able to make use of the credits.[26]

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.[143] 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. In that rule EPA identified CCS as a viable technology for controlling CO2 emissions.[143] Costs of using CCS technology were estimated to be, on average, $14/ton of CO2 reduced for coal plants. The impact on the cost of electricity generation from coal plants was estimated as $12/ MWh. These are considered by EPA to be reasonable air pollution control costs.[144]

Other countries are also developing programs to support CCS technologies. Canada has established a C$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. In Europe, Denmark has recently announced €5 billion in subsidies for CCS. 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.[27] 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.[28]

Carbon emission status-quo

Opponents claimed that CCS could legitimize the continued use of fossil fuels, as well obviate commitments on emission reduction.

Some examples such as in Norway shows that CCS and other carbon removal technologies gained traction because it allowed the country to pursue its interests regarding the petroleum industry. Norway was a pioneer in emission mitigation, and established a CO_2 tax in 1991.[145]

Maintaining the use of fossil fuels as the energy status quo extends beyond the climate impacts of their emissions. Implementing CCS to capture carbon emissions from an industrial point source can also enable the negative environmental or social impacts "upstream" of a storage site. This is particularly evident where energy resources lie in or near areas home to indigenous communities, such as the regions overlying the Bakken Formation or the Athabasca Oil Sands. Power imbalances persist between the extractive industry corporations, state, provincial, or federal governments, and the "host" communities. As a result, the impacted populations are often displaced or criminalized when seeking to defend their ancestral lands from ecological harm (*see Resource Extraction in Environmental Justice*).[146]

In some circumstances, promoting and implementing CCS projects for industrial operations that refine, distribute, or convert raw energy resources from these lands can be viewed as investing in displacement processes, delegitimizing indigenous rights, and furthering ecological harm.[147]

Another aspect of CCS that could concern project opponents is that projects only remove carbon dioxide from flue gas. Particulate matter and other toxic gas emissions would continue, which is of particular concern in places in the US where industries are in poor and/or minority communities. In many cases, CCS would not markedly improve the public or environmental health of these communities.[148]

Because CCS is an "end of pipe" technology, part of the key to its viability as a climate change solution stems from wholistically evaluating the sustainability of the energy resource pipeline tied to a project. 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.[149]

The communities targeted for hosting CCS projects may meet the geologic and technical siting criteria; however, non-technical social characterizations are equally important factors in the success of an individual project and the global deployment of this technology. Failing to provide meaningful engagement with local communities can drive resistance to CCS projects and enable feelings of mistrust and injustice from project developers and supporting government entities.[150]

Environmental NGOs

Environmental NGOs are not in widespread agreement about CCS as a potential climate mitigation tool. The main disagreement amid NGOs is whether CCS will reduce CO_2 emissions or just perpetuate the use of fossil fuels.[151]

For instance, Greenpeace is strongly against CCS. According to the organization, the use of the technology will keep the world dependent on fossil fuels.[152]

On the other hand, BECCS is used in some IPCC scenarios to help meet mitigation targets.[153] Adopting the IPCC argument that CO_2 emissions need to be reduced by 2050 to avoid dramatic consequences, the Bellona Foundation justified CCS as a mitigation action.[152] They claimed fossil fuels are unavoidable for the near term and consequently, CCS is the quickest way to reduce CO_2 emissions.[127]

Related concepts

Carbon capture and utilization (CCU)

Carbon capture and utilization (CCU) is the process of capturing carbon dioxide (CO_2) from industrial processes and transporting it via pipelines to where one intends to use it in industrial processes.[154]

Bioenergy with carbon capture and storage (BECCS)

Bioenergy with carbon capture and storage (BECCS) is the process of extracting bioenergy from biomass and capturing and storing the carbon, thereby removing it from the atmosphere.[155] BECCS can theoretically be a "negative emissions technology" (NET),[156] although its deployment at the scale considered by many governments and industries can "also pose major economic, technological, and social feasibility challenges; threaten food security and human rights; and risk overstepping multiple planetary boundaries, with potentially irreversible consequences".[157] The carbon in the biomass comes from the greenhouse gas carbon dioxide (CO_2) which is extracted from the atmosphere by the biomass when it grows. Energy ("bioenergy") is extracted in useful forms (electricity, heat, biofuels, etc.) as the biomass is utilized through combustion, fermentation, pyrolysis or other conversion methods.

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.[158] 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.[159]