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# An overview of carbon capture and storage and its potential role in the energy transition

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## Summary

Carbon capture and storage (CCS) is one of a number of mitigation options and a key component of some proposed negative emissions technologies that can be considered to stabilize atmospheric greenhouse gas concentrations in order to meet the targets set out in the Paris Agreement. CCS involves the capture of $CO_2$ emissions produced from industrial and power generation sources, followed by transport to underground geological storage and long-term isolation from the atmospheric system. Here, we provide a brief introductory review of the steps involved with CCS developments, different options for geological storage, the potential role of CCS in the energy transition, and a discussion of some of the key associated risks and uncertainties. In short, CCS can provide an important avenue for mitigating the increase of greenhouse gases in the atmosphere, particularly during the energy transition.

## Introduction

In August 2021, the Intergovernmental Panel on Climate Change (IPCC) published the Working Group 1 contribution to its Sixth Assessment Report on the Physical Science Basis of climate change (IPCC, 2021). This report concludes that greenhouse gas emissions from human activities are primarily responsible for approximately 1.1°C of warming since 1850-1900. Under current emissions trends, the average global temperature is projected to continue to increase up to and beyond 1.5°C – the target set out in the Paris Agreement – over the next 20 years (Figure 1). Furthermore, the report states that unless there are immediate and significant reductions in the emissions of greenhouse gas, limiting the warming to within 1.5–2°C will be beyond reach (IPCC, 2021). The report is clear that reaching net-zero carbon dioxide is required to stabilise the global temperature (Figure 1).

However, there are a number of mitigation options that can be considered to stabilize atmospheric greenhouse gas concentrations including: carbon capture and storage (CCS), increased energy efficiency, switching to less-carbon intensive fuels, renewable energy, nuclear power, and the enhancement of biological sinks (e.g. Pacala & Socolow, 2004; IPCC, 2005, 2014). Carbon dioxide ($CO_2$) emissions into the Earth's atmosphere are widely accepted to be a dominant contributor to global warming (e.g. IPCC, 2021). CCS is a proven combination of technologies that involves the separation and capture of in excess of 90% of $CO_2$ emissions produced from industrial and electricity generation sources, with capture rates of up to 98% possible at a relatively low marginal cost (Brandl et al., 2021), followed by transport to underground geological storage and hence permanent isolation from the atmospheric system (Figure 2). A recent IPCC report presented four scenarios for limiting global warming to 1.5°C with no or limited overshoot – all scenarios required $CO_2$ removal and three of the scenarios involved significant use of CCS technology in order to achieve this (IPCC, 2018).

In this paper, we provide an introductory review of: (1) the steps involved with CCS developments, (2) different options for geological storage, (3) the potential role of CCS in the energy transition, and (4) a discussion of some of the key associated risks and uncertainties.

## Carbon capture and storage (CCS)

CCS is a well-established technology that has been demonstrated and proven over the past few decades; industrial-scale implementation with disposal in deep saline aquifers dates back to 1996 at the Sleipner project, offshore Norway (Baklid et al., 1996; Eiken et al., 2011). Subsequently, CCS was proposed as a possible solution to stabilize global greenhouse gas emissions (IPCC, 2005; Gibbins & Chalmers, 2008; Haszeldine, 2009). In addition to significantly reducing the $CO_2$ emissions from fossil fuel combustion, CCS can also play a role in decarbonizing hard-to-abate industries such as cement and steel manufacture (Ringrose, 2017, 2020; Global CCS Institute, 2020) and can also be potentially combined with biomass energy to provide a negative emission technology that may be important in future to correct any overshoot of atmospheric greenhouse gas concentration targets (Azar et al., 2010; IPCC, 2014; Kemper, 2015).

The process of using CCS to decarbonise key industries includes the following four steps:

- **Capture:** The combustion of fossil fuels and biofuels leads to the emission of $CO_2$ as a by-product. There are currently three

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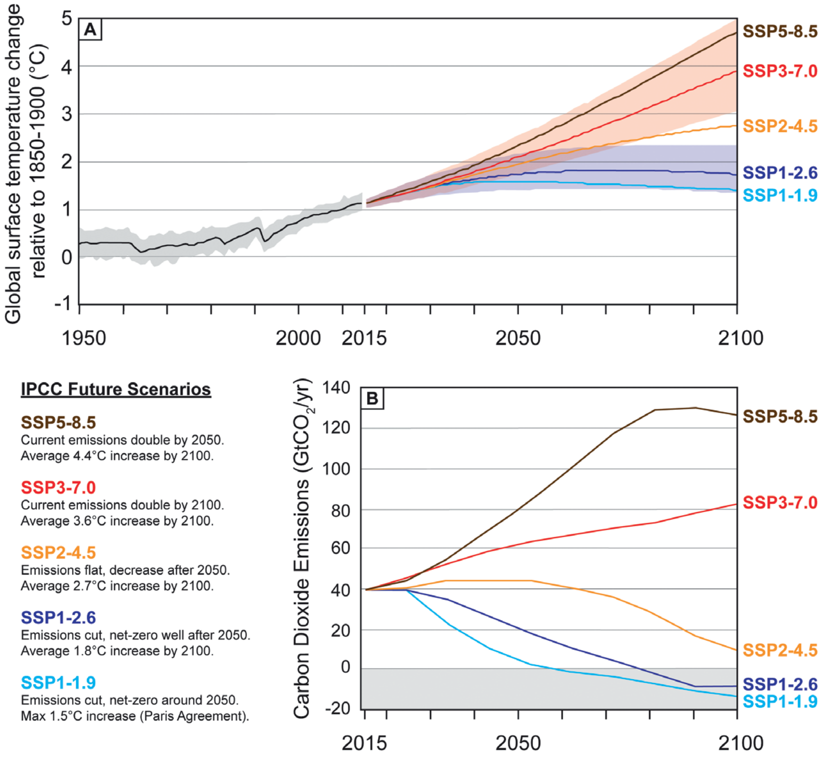

**Figure 1** (A) Historical and modelled future global surface temperature changes relative to 1850–1900 and (B) modelled anthropogenic (human-caused) $CO_2$ emissions over the 2015-2100 period (modified from IPCC, 2021). Five illustrative future scenarios are shown, starting in 2015 and running until 2100. Scenarios with high and very high greenhouse gas emissions (SSP3-7.0 and SSP5-8.5) have $CO_2$ emissions that double from current levels by 2100 and 2050, respectively. The middle scenario with intermediate greenhouse gas emissions (SSP2-4.5) has $CO_2$ emissions remaining around current levels until the middle of the century before decreasing. The scenarios with very low and low greenhouse gas emissions (SSP1-1.9 and SSP1-2.6) have a more rapid cut in $CO_2$ emissions, reducing to net-zero around or after 2050 with varying levels of net negative $CO_2$ emissions in the second half of the century. SSP1-1.9 is the only one of the five scenarios that achieves the target set out in the Paris Agreement. The shaded areas in (A) highlight the very likely ranges for SSP1-2.6 and SSP3-7.0. Additional modelled emissions profiles for methane ($CH_4$), nitrous oxide ($N_2O$) and sulphur dioxide ($SO_2$) can be found in IPCC (2021).

different types of $CO_2$ capture systems: pre-combustion, oxyfuel combustion and post-combustion; all of these utilise a chemical solvent to separate the $CO_2$ from other gases. These capture systems can be implemented at large industrial point source emitters such as coal and natural gas-fired power plants, blue hydrogen gas production, and heavy industries such as cement plants, steel mills, agrichemical and petrochemical plants. In future, these capture systems could also be utilized at direct air capture and bioenergy facilities as a possible negative emission technology. A more detailed review of the main $CO_2$ capture technologies can be found in Herzog et al. (1997), Feron & Henriks (2005) and MacDowell et al. (2010).

- **Transport:** After separation the $CO_2$ is compressed, sometimes into a liquid state, and transported via trucks, ships or pipelines to the ultimate site for geological storage. $CO_2$ transport via pipeline is already a proven and deployed tech-

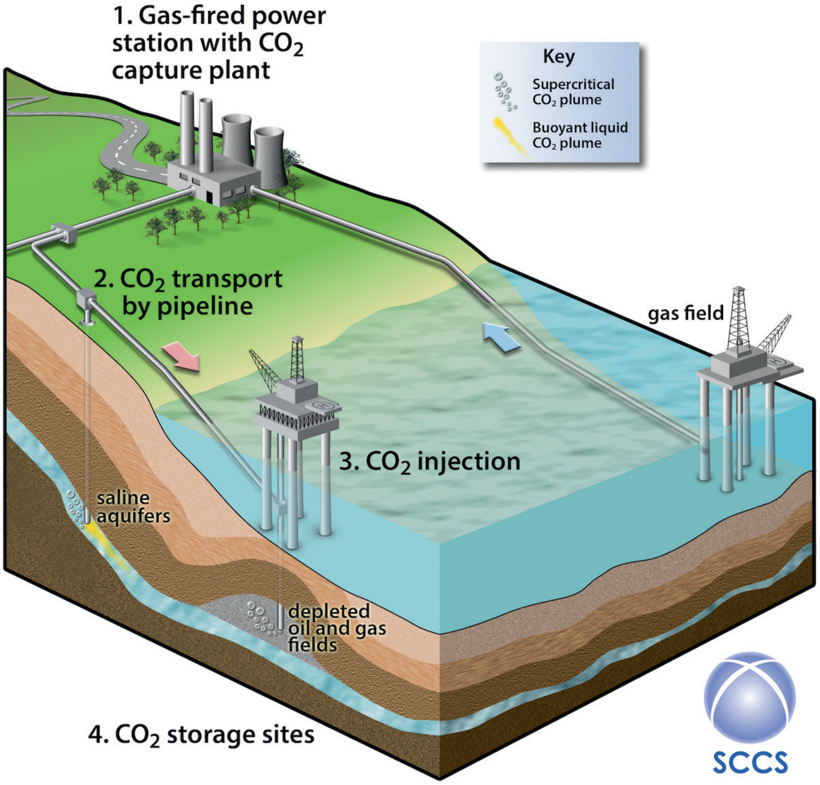

**Figure 2** Carbon Capture and Storage (CCS) is a proven technology that involves the separation and capture of 90-98% of $CO_2$ emissions produced from industrial and electricity generation sources, followed by transport to underground geological storage and hence permanent isolation from the atmospheric system. Image courtesy of SCCS.

nology. After capture, the $CO_2$ can be dehydrated to remove any moisture and ultimately prevent the formation of carbonic acid, the risk of corrosion in the existing pipeline system and also to avoid the additional cost of constructing pipelines with corrosion resistant material.

- **Storage:** Potential storage options for $CO_2$ include geological storage, fixation of $CO_2$ into inorganic carbonates (mineral sequestration), or possible utilisation in industrial processes, although the latter is not anticipated to be a major factor in the reduction of $CO_2$ emissions (IPCC, 2005). Ocean storage (direct onto the deep seafloor or released into the ocean water column) is also possible but is not favoured due to potential negative environmental consequences (OSPAR 2007/1; Directive 2009/31/EC). It has been proposed that subsurface geological storage provides the primary practical solution for the reduction of global $CO_2$ emissions (e.g. Benson & Surles, 2006; Ringrose, 2020). Options for geological storage of $CO_2$ include: (1) deep porous saline aquifers (Bentham & Kirby, 2005; Eiken et al., 2011; Ringrose, 2018; Ringrose et al., 2021); (2) depleted oil and gas fields (Godec et al., 2011; Jenkins et al., 2012); (3) enhanced oil recovery (Harrison & Falcone, 2014; Eide et al., 2019) or enhanced gas recovery (Godec et al., 2014; Rani et al., 2019) projects where the $CO_2$ is injected into partially depleted oil or gas fields to increase the recovery factor; (4) coal beds (Busch et al., 2003); and (5) igneous rocks such as basalt (Gislason & Oelkers, 2014) which may involve mineral reactions to sequester the $CO_2$ in a solid form. Geological storage of $CO_2$ is already a proven technology and effectively takes advantage of the same geological characteristics and processes that have sealed and trapped oil and gas (including in some instances naturally occurring $CO_2$) in the subsurface over geological time periods (i.e. millions of years). Injection of $CO_2$ via wells into deep geological formations, typically at depths below 1 km, is also a proven technology that has been utilised by the oil and gas industry for many years. A more detailed discussion of $CO_2$ storage options can be found in Holloway (1997), Benson & Surles (2006) and Cooper et al. (2009).
- **Monitoring:** Site monitoring is required to ensure safe $CO_2$ storage and containment over long periods of time – i.e. decades (NETL, 2009) – and remedial action may be required to stop or control $CO_2$ releases if they occur. Abrupt leakage could potentially occur through previously abandoned wells that have penetrated the sealing caprock, while more gradual leakage could occur via undetected faults and fractures in the caprock. Remedial action for such scenarios, should they occur, include standard well remediation techniques or, in an extreme case, the re-extraction of $CO_2$ in a controlled manner from potential leakage sites via the injection wells. Under the EU Directive on the Geological Storage of Carbon Dioxide (Directive 2009/31/EC), as an example, the operator of the CCS project would remain liable for site monitoring and any required remedial action until the competent authority determines that the injected $CO_2$ is safely contained for the indefinite future at which point the responsibility is transferred to the authority. The Directive requires that a minimum post-closure monitoring period is determined by the competent authority and that this should normally be no less than 20 years.

## Geological storage of $CO_2$

As noted above, the entrapment of gas in the subsurface over geological time periods is a well understood natural process and this has been studied and developed by the oil and gas industry for more than a century. Any porous and permeable rock formation at a depth in excess of ~ 1 km is a potential candidate for the storage of $CO_2$ as long as there is an overlying impermeable caprock to prevent the upward migration and leakage of the gas. The minimum depth for storage in any given location is determined by the critical pressure and temperature required to maintain the $CO_2$ in a dense form (i.e. a liquid phase or a supercritical phase; Figure 3).

**Depleted oil and gas fields:** Oil and gas fields are proven natural reservoirs for storing buoyant fluids in the subsurface over geological time and therefore represent obvious candidates for CCS. There is usually a large amount of available data and a good understanding of the subsurface in these areas due to historical investment by the oil and gas industry. The geological traps are well imaged by

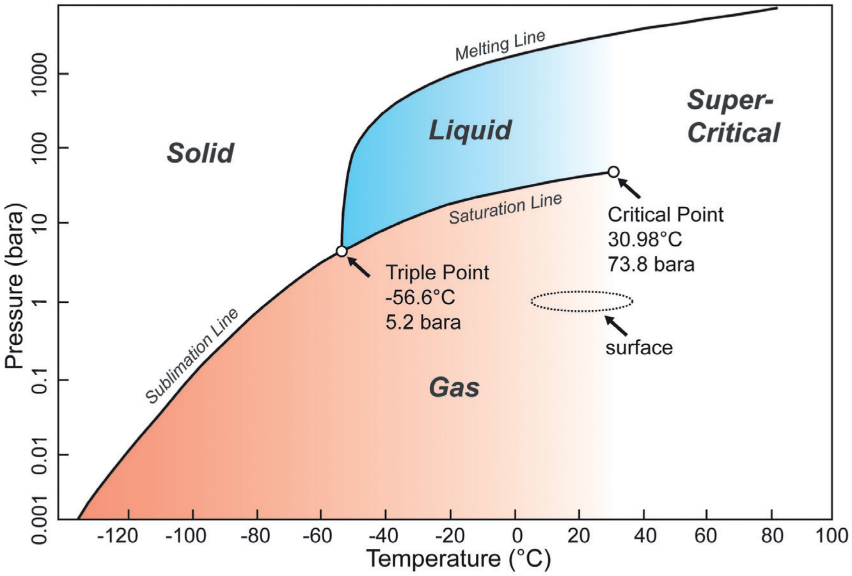

**Figure 3** Phase diagram for $CO_2$ (modified from Ringrose, 2020; Wu et al., 2021). The minimum depth for a CCS storage site at any given location is governed by the pressure and temperature required to maintain the $CO_2$ in a dense form (i.e. a liquid phase or a supercritical phase). Supercritical fluids are substances that are above their critical temperature and pressure, where distinct liquid and gas phases no longer exist, but are still below the pressure required to compress it into a solid.

geophysical data including seismic surveys, and the rock properties of the target reservoirs and caprocks are calibrated by numerous wells and their associated petrophysical and core data. Additionally, the production history of the oil and gas fields can provide a strong indication of the rate at which $CO_2$ can be injected into the same formations, and the total amount of previously produced oil or gas can provide a good initial estimate for the $CO_2$ storage capacity of the trap. CCS projects in depleted oil and gas fields may also be able to utilise the presence of existing infrastructure including wells and pipelines. However, legacy well penetrations can also be a potential leakage risk that needs to be evaluated.

**Deep saline aquifers:** One issue with depleted oil and gas fields is that their distribution may be relatively limited, and they may not necessarily be situated in close proximity to major industrial point source emitters of $CO_2$. An alternative option for geological storage is to target deep porous and permeable formations saturated with high-salinity brine as opposed to oil and gas. These targets will have a much broader distribution across sedimentary basins and have the potential to store huge volumes of $CO_2$ and may, therefore, provide a more significant option for CCS globally (Ringrose & Meckel, 2019; Ringrose et al., 2021). As with oil and gas fields, deep saline aquifers also require an effective overlying caprock to ensure that the $CO_2$ does not leak and escape up into the shallow subsurface and ultimately back into the atmosphere.

## Role of CCS in the energy transition

In order to achieve net-zero $CO_2$ emissions and the target set out in the Paris Agreement, CCS projects can assist in four key ways (Global CCS Institute, 2020):

- **Decarbonising (dispatchable) power generation:** A dispatchable source of electricity is where the power supply to the grid can be adjusted in order to match the demand. The most common types currently are plants run on fossil fuel or hydro power. While power generation from wind and solar photovoltaics (PV) is likely to become an increasingly important source of low-carbon electricity, in the absence of grid-scale battery storage in the short-term, the associated power supply is intermittent in nature. Gas-fired power plants with CCS are one option to provide dispatchable and low-carbon electricity to complement renewables and ensure the electrical grid remains reliable and resilient throughout the energy transition.
- **Decarbonising heavy industry:** Several industries including the iron and steel, cement and chemical sectors are significant emitters of carbon due in part to the need for high-temperature heat generation and process emissions of $CO_2$ (e.g. carbonate rock is broken down under high temperature to produce lime in the cement production process and $CO_2$ is released as a by-product). These hard-to-abate industries represent a major challenge in trying to reduce global $CO_2$ emissions. Achieving net-zero emissions in these sectors may be impossible without associated CCS projects.
- **Facilitating the production of low-carbon hydrogen at scale:** Hydrogen may become an important low-carbon energy carrier that can be utilised in residential heating, transport, dispatchable power generation and also help to decarbonise the hard-to-abate industrial sectors. Currently, most hydrogen is produced via Steam Methane Reforming (SMR) or Autothermal Reforming (ATR). SMR or ATR can be combined with CCS to capture and store the associated $CO_2$ emissions (Antonini et al., 2020), producing what is referred to as 'blue hydrogen'. SMR and ATR are mature technologies and currently the most cost-effective way to produce hydrogen. In future, hydrogen production may occur via electrolysis which is the decomposition of water to produce 'green hydrogen' and oxygen; this process is currently the focus of significant research and development to try to increase efficiency and reduce input-energy demand and cost.
- **Delivering negative emissions:** Negative emissions will be required to compensate for residual emissions in sectors that will be difficult to get to zero-emissions (e.g. aviation, agriculture, heavy industry), or indeed to correct an overshoot of the targeted limit of global warming. New technologies such as bioenergy with CCS (BECCS) and direct air capture with carbon storage (DACCS) may provide a means to achieve this.

## CCS risks and uncertainties

As discussed above, CCS is a well-established and proven technology that could play a significant role in the energy transition and assist in efforts to achieve the targets set out in the Paris Agreement. However, there are some key risks and uncertainties that need to be evaluated and assessed for any proposed future CCS development. Pawar et al. (2015) reviewed recent advances in risk assessment and risk management of CCS projects and proposed that the primary risks can be divided into four different categories:

- **Site performance risks:** This category relates to risks to the successful operation of a CCS project. The two primary site-specific performance risks are insufficient capacity or injectivity during the appraisal and injection stages. Capacity describes the volume of $CO_2$ that can be geologically stored in a storage formation and injectivity describes the ability of injection wells to deliver $CO_2$ into that formation. Injectivity, and the number of injection wells, controls the achievable injection rate at the CCS site while capacity controls the cumulative volume that can be injected over the life of the project.
- **Containment risks:** This category relates to risks to effective containment of $CO_2$ and brine in the subsurface storage formation during the injection and the post-injection (storage) phases. The two primary containment risks are leakage pathways and induced seismicity. Potential leakage pathways can be provided by: (1) discontinuous or breached caprocks, (2) transmissive faults, and (3) imperfectly sealed wells, particularly old legacy wells that were not constructed and abandoned with $CO_2$ storage in mind. Leakage of $CO_2$ and brine into the shallow subsurface, or to the surface, has the potential to impact on groundwater resources (e.g. Keating et al., 2013) and the biosphere (e.g. Bowden et al., 2013), and ultimately undermine the primary purpose of the CCS project to isolate the $CO_2$ from the atmosphere. The risks associated with induced seismicity range from potential structural damage to buildings and infrastructure down to a general nuisance from smaller non-damaging events (e.g. Pawar et al., 2015).

All of these containment risks need to be assessed as part of an upfront CCS site characterisation and selection process (e.g. see Annex 1 of Directive 2009/31/EC).

- **Public perception risks:** This category relates to risks to public acceptance of CCS projects. Some arguments raised against CCS include concerns about induced seismicity, that the technology is too costly, that it prolongs the use of fossil fuels, and that public money should instead be invested in renewable energy (Parmiter and Bell, 2020). Effective communication is required to address various stakeholder concerns, explain how the key project risks are managed via monitoring and mitigation actions, and also explain the overall benefits of CCS in terms of the large-scale decarbonisation of energy and industry as part of the energy transition.
- **Market failure risks:** This category relates to financial risks to the execution of CCS projects. Aside from the technical and public perception risks, a CCS developer needs to have confidence that the future revenue stream will be sufficient to cover all of the investment in the upfront drilling and infrastructure, the injection phase operations and the continuance of monitoring during the post-injection phase. Market risks relate to the demand for $CO_2$ storage, to ultimately fill the site capacity, and also to the market price for $CO_2$.

Pawar et al. (2015) noted that all CCS projects should have significant characterization and regulatory scrutiny as part of the permitting process. Monitoring should be utilised to address residual areas of risk and the parameters of the injection operations should be defined on the basis of reducing the containment risks to an acceptable level. Pawar et al. (2015) also noted the Snøhvit project in offshore Norway as an example where the injection pressures were monitored and adjusted as a result of observing increased pressure build-up. Ringrose (2020) concluded that site performance and containment risks are continuing to reduce as project experience grows, but that public perception and market risks remain the key barriers at this moment in time.

## Conclusion

CCS is one of a number of mitigation options, and a key component of some proposed negative emissions technologies that can be considered to stabilize atmospheric greenhouse gas concentrations in order to meet the targets set out in the Paris Agreement. CCS involves the separation and capture of 90-98% of $CO_2$ emissions produced from industrial and electricity generation sources, followed by transport to underground geological storage and hence permanent isolation from the atmospheric system. In spite of the positives, progress with the implementation of CCS has been slow, partially due to high cost and partially because of the view that CCS will facilitate the continued use of fossil fuels (Ringrose, 2017, 2020). However, multiple studies have shown that CCS is needed as one of the solutions to tackle and mitigate global warming (IPCC, 2014, 2018; Peters et al., 2017). Ultimately, new technologies will be developed in future to get to net-zero emissions globally, but CCS can provide an important avenue for mitigation during the transitional period. Implementing proven technologies to utilise existing infrastructure and reduce $CO_2$ emissions in the near term is preferrable to continuing on the current business-as-usual trajectory while awaiting the development and deployment of new technologies to fully decarbonise (dispatchable) power generation and the hard-to-abate industries. Finally, CCS also forms a key component of potential future negative emissions technologies such as BECCS and DACCS that may be deployed in the second half of this century.

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