

Carbon Dioxide Capture and Storage: Issues and Prospects

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Abstract

Almost 20 years ago, the first CO₂ capture and storage (CCS) project began injecting CO₂ into a deep geological formation in an offshore aquifer. Relevant science has advanced in areas such as chemical engineering, geophysics, and social psychology. Governments have generously funded demonstrations. As a result, a handful of industrial-scale CCS projects are currently injecting about 15 megatons of CO₂ underground annually that contribute to climate change mitigation. However, CCS is struggling to gain a foothold in the set of options for dealing with climate change. This review explores why and discusses critical conditions for CCS to emerge as a viable mitigation option. Explanations for this struggle include the absence of government action on climate change, economic crisis–induced low carbon prices, public skepticism, increasing costs, and advances in other options including renewables and shale gas. Climate change action is identified as a critical condition for progress in CCS, in addition to community support, safe storage, robust policy support, and favorable CCS market conditions.

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1. INTRODUCTION

In the early to mid-2000s, CO₂ capture and storage (CCS) emerged as an apparently promising option to contribute to climate change mitigation (1, 2). Within a few years, from 1996 to 2004, as many as four industrial-scale CCS projects (1) were initiated, leading to a generally optimistic perspective about the speed and short-term impact of CCS technology on CO₂ emission reductions. Since the late 2000s, however, the pace of deployment of new projects has slowed. Although government and private-sector investments in the science and technology of CCS technology continue to build a strong and broad foundation for it, similar progress has not been made in the legal, social, and financial dimensions of CCS. There is a wide divergence in opinions about the feasibility, long-term risks, and even need for CCS. Whereas some conclude that CCS is an essential tool for reducing emissions sufficiently quickly to avoid the worst consequences of climate change, others believe that it should not and will not ever make a significant contribution to solving the climate problem and, even worse, distracts us from making needed decisions to begin phasing out fossil fuels immediately. Even some in the academic literature go so far as to call for a halt in CCS investment (3).

Knowing whether CCS is part of the climate solution or not will likely take many decades, and the answer will be heterogeneous, with some regions and industries adopting it as the preferred option for reducing emissions and others finding alternatives. Until industry, society, and governments come to grips with the reality that CO₂ emissions must start coming down now—and that it is going to come at a considerable cost—CCS is unlikely to be adopted, particularly in light of the comparatively high cost per tonne of CO₂ emissions and unfamiliar risks. Only when decision makers widely recognize that slow and incremental change will not solve the climate problem will it be clear that every option is needed, including CCS. Here, we address the question of how perceptions have changed about CCS and what can be done to improve its prospects in the years ahead.

This review presents a global narrative of CCS in three fields: technological and scientific developments, milestones in policy and public perception, and the start-up and end of industrial-sized projects. We then examine how development of CCS over the past two decades

has laid the groundwork for CCS going forward. The final section uses these findings to enumerate the conditions that will be critical for CCS to progress, to the extent that the technology can fulfill its potential as a mitigation option.

2. RELEVANT DRIVERS AND THE ROLE OF CCS

The suggestion that climate change mitigation could be achieved by storing CO₂ derived from anthropogenic sources (i.e., human-caused release of CO₂) was made only relatively recently: Marchetti (4) in the 1970s suggested we store CO₂ in oceans, and Horn & Steinberg (5) in the 1980s were among the first to suggest a process used to separate CO₂ from natural gas. Since the 2005 *IPCC Special Report on Carbon Dioxide Capture and Storage* (SRCCS) (1), the option of storing CO₂ in ocean water has largely been abandoned because of high costs, low storage permanence, and considerable ecological impacts. The current discussions revolve around the injection of CO₂ into geological reservoirs, and other storage options—including mineralization—are expected to play a limited role (6).

The injection of CO₂ underground was not totally new when it was first suggested for climate change mitigation. In the 1970s and 1980s, as production from oil fields in the United States was declining, oil companies started injecting water, natural gas, and CO₂ to recover more oil and extend the productive lifetime of oil reservoirs (1). Thousands of kilometers of CO₂ pipelines were constructed to transport the CO₂ from the natural reservoirs of CO₂, the primary CO₂ source, to the depleting oil fields. CO₂-enhanced oil recovery (EOR) was done almost exclusively using CO₂ from natural underground CO₂ reservoirs, so it was not leading to climate change mitigation. However, it did enable learning and practical experience about, for instance, how the subsurface responds to injection of fluids, which cap rock can sustain the CO₂ best, under which pressures injection can best take place, how wells are best placed, and how to organize pipeline transportation of CO₂ in a safe manner (7). Today, EOR remains a driver for CCS. But in the 1990s and 2000s, climate change mitigation emerged on the policy agenda and temporarily took over as the main driver of CCS. Subsequent IPCC assessment reports (published in 1990, 1996, 2001, and 2007) continued to strengthen the hypothesis that CO₂ and other greenhouse gas (GHG) emissions would lead to harmful and potentially even catastrophic consequences to livelihoods, ecosystems, and the global economy. In 1992, this had already led to the United Nations Framework Convention on Climate Change and in 1997 to the Kyoto Protocol, which included commitments of all developed countries to reduce their GHG emissions (although not all developed countries ratified or complied with the Kyoto provisions). However, despite these international agreements on climate change mitigation, addressing the seemingly unstoppable CO₂ emissions from coal-fired power remained an urgent and challenging problem without a viable solution until CCS emerged as a mitigation option (8).

CCS was given scientific credibility by the SRCCS in 2005 and was supported by influential bodies such as the International Energy Agency (IEA) (9, 10). The failed climate change summit in Copenhagen in 2009, however, seems to have caused a turning point in the perception of CCS. Without a global signal that climate change mitigation must be taken seriously in investment decisions, industry finds little reason to invest in deploying CCS on a large scale because it adds significantly to the cost of generating power and other products that involve the use of fossil fuels, such as cement and steel. Only when CCS makes economic sense in the absence of climate policy, such as in EOR in combination with CO₂ sources that are already of high purity, do decision makers seriously consider capturing, storing, or using anthropogenic CO₂ (7).

Until 2009, CCS seemed to have been affected mainly by EOR or the increasingly prominent climate agenda, but since Copenhagen the factors affecting CCS deployment have become more

diverse and complex. In Europe, the economic crisis and the related low price of CO₂ emission allowance units (EUAs) in the European Emissions Trading Scheme (ETS) have been tremendously important, both for companies' long-term CCS innovations and for the economic viability of demonstration projects. The subsidies for these demonstrations were partly carbon price dependent (in the case of NER300, which involved auctioning EUAs), but even when they were not, the project viability depended on a higher CO₂ price (see, e.g., the discussions on the Dutch ROAD project).

Other factors have also played a role. Since 2005, rising demand for resources such as oil and steel, particularly from fast-growing economies in the developing world, has led to price hikes, which make the cost estimates for CCS in the SRCCS (1) look rosy and highly optimistic (compare Reference 11). Rising oil prices generally lead to higher energy prices, adding even further to the already steep monetary cost of the energy penalty of CO₂ capture. Rising steel prices affect the construction costs of both pipelines and capture installations. So while the push for climate policy and economic incentives through carbon prices weakened, the costs of CCS mounted.

A final factor affecting the implementation of CCS is the availability of other mitigation options. In the 2000s, the rise of coal seemed unstoppable, with no end in the supply of coal reserves. More recently, however, the success of renewables and the availability of shale oil and in particular shale gas in North America have made coal seem less important. Indeed, the noteworthy worldwide drop in costs for solar energy made this technology a viable option for many households. Moreover, the sudden availability of significant quantities of shale gas at low prices in the United States has resulted in the lack of any added capacity for coal-fired power generation in North America and even to an absolute drop in CO₂ emissions (in combination with the effects of the economic crisis).

However, because coal is easily transported and gas generally is not, the drop in coal use in the United States has had other effects: It has led to lower prices and an increased use of coal elsewhere in the world (and even to the planned retiring of gas-fired power capacity in some countries, including in Europe, in favor of new coal-fired capacity) (12). Although the positive news about cost and availability of other mitigation options seems to have negatively affected the perception of CCS necessity, the reasons for CCS—namely the global rise in coal use and the urgency of addressing climate change—have not gone away.

Although the Copenhagen climate conference was a turning point that probably contributed to a drop in attention to CCS, the economic crisis and low carbon prices, increased attractiveness of other mitigation options, and the rise in resource prices also negatively affected the political traction of CCS since 2009. Without a firm climate change–mitigation driver other than the high price of oil, current progress for CCS depends much on the possibility for EOR (13).

3. TECHNICAL UPDATE ON CCS

3.1. The Evolution of CCS-Related Scientific Literature

Figure 1 illustrates an assessment of the number of papers cataloged in the Web of Knowledge databases that concern CCS from the earliest papers in the 1970s through 2012. In the 1990s, a steady stream of 50–100 papers was published annually. After 2005 and 2006, the number increased into the hundreds, reaching approximately 1,000 per year in 2011. The rapid increase highlights that CCS has only recently emerged as a major topic of academic inquiry, resulting from the scale-up of primarily government spending on CCS R&D. The academic community's engagement in the topic has spurred innovation in new materials and approaches for carbon capture and significantly increased the scientific foundation for assessing the potential of CO₂ storage.

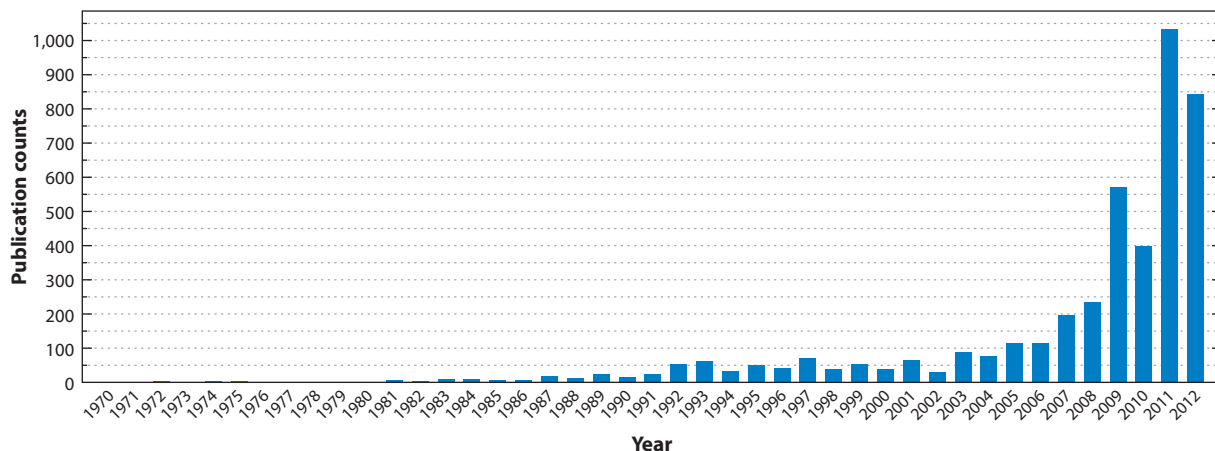


Figure 1

Publication counts related to CCS from the Web of Science 1970–2012 (<http://thomsonreuters.com/thomson-reuters-web-of-science>). The peak figures in 2009 and 2011 are due to conference papers at the Greenhouse Gas Control Technologies (GHGT) conferences in 2008 and 2010, respectively (search terms: CO₂ capture and storage).

3.2. Technology for Capturing and Transporting CO₂

3.2.1. CO₂ sources. Although coal-fired power plants have been the primary focus for CCS efforts and research, CCS can also be applied to other types of stationary emission sources, including industrial sources such as boilers and blast furnaces, steel mills, cement plants, ethanol production facilities, gas-processing units that remove impurities such as CO₂ and H₂S from natural gas, and electricity production from natural gas (8, 14, 15). In fact, CCS from power generation may be among the most challenging from a financial perspective because of the economy-wide implications of increasing costs for power generation. However, of all stationary CO₂ sources, electricity production is the largest single category, accounting for more than two-thirds of global CO₂ emissions from stationary sources. The biggest single sector with potential for CO₂ capture is associated with the over 3,000 coal-fired power plants emitting 1–10 megatons of CO₂ (MtCO₂) each annually, totaling over 10,000 MtCO₂/year, about one-third of global CO₂ emissions (16). The sources are distributed around the world, but two countries stand out in coal-fired power capacity: China and the United States (17).

3.2.2. Physical and chemical processes for CO₂ separation. Several technological options are available for separating CO₂ from a gas stream, and the optimal choice depends on the type of source, the cost, and the ease of deployment. In particular, the choice of technology depends on CO₂ composition of the flue gas, which ranges from 3–4% for natural gas turbines to 10–15% for pulverized coal plants and up to 40–60% for integrated gasification combined cycle (IGCC) plants (14, 18). Options for CO₂ separation include absorption into physical and chemical solvents, adsorption onto solid substrates, cryogenic separation, transport through CO₂ selective membranes, and mineralization (19). For capture using solvents and sorbents, a two-step process is required in which first CO₂ is removed from the gas stream using an absorption tower and, second, CO₂ is released from the media in a separate regeneration tower (so-called solvent or sorbent regeneration). The low concentration of CO₂ in the flue gas of fossil-fuel power plants necessitates large absorption towers for CO₂ separation and related high costs.

An alternative approach for capturing CO₂ is the use of so-called oxygen combustion, which combusts CO₂ into pure oxygen or a mixture of oxygen and CO₂ (18). This requires separation of oxygen from air. The postcombustion waste product is a mixture of CO₂, water, and trace gases, including oxygen, thus avoiding the need to separate CO₂ from nitrogen after combustion. Separation of oxygen from air is a mature, albeit energy-intensive, process using cryogenic separation.

Table 1 provides a summary of the important features of each of these approaches for CO₂ capture and highlights new approaches and materials being developed for CO₂ separation. Vastly different maturity levels exist among the options, and today most CO₂ separation uses absorption-based technology. For natural gas cleanup, cryogenic separation and membrane separation are used, albeit on a limited basis. Fundamental research in this area has grown rapidly, and advances have been made across the board (6, 20–22). Advanced amine solvents (23), chilled ammonia (24), metal organic frameworks (25), ionic liquids (26), phase-change materials, polymer membranes (27), and cryogenic separation have all emerged as potential options for capture. Monoethanolamine solvents are the most mature option and remain the benchmark for cost and technical performance (23).

The energy required for CO₂ capture is one of the biggest challenges for CCS. The minimum energy required, from a thermodynamic perspective, depends on the concentration of CO₂ and ranges from about 3–6 kJ/mol CO₂ for coal plants to 7–9 kJ/mol CO₂ for a natural gas plant (19). This represents only 2–3% of the output of the power plant and suggests that if efficient separation processes could be developed, the energy penalty for capture would be small. However, in practice, the total energy penalty for gas separation is significantly greater, about 5 to 10 times the minimum energy requirement (37). Compression of the purified CO₂ after it is separated requires additional energy, increasing the minimum work requirement of storage-ready CO₂ (~150 bar) to about 8.2 kJ/mol CO₂ for a coal-fired power plant. Optimization of mature technologies can result in energy penalties of 2–3 times the minimum energy; consequently, energy penalties for capture could be reduced to about 10% of the output of the power plant.

Dramatically reducing the energy penalty for capture is one of the largest opportunities for lowering the cost of capture. Energy penalties for CO₂ capture in nonpower industries vary but may be lower. For instance, in the cement sector, given the higher CO₂ concentrations in the exhaust of cement plants compared with coal- or gas-fired power plants, CO₂ capture would add only 3–10% to energy use per tonne of clinker (38, 39).

For absorption using amine-based solvents, significant progress has been made in reducing energy requirements through process innovations and improvements in the characteristics of the solvent (6, 24). Using the most advanced processes and solvents, the amount of energy required to separate and compress CO₂ from a flue gas stream generated by a coal-fired power plant has dropped by nearly a factor of two since 2001 and is now about 2.7 times the theoretical minimum energy needed to separate CO₂ from the flue gas (6). Even more progress is expected from research into new materials, processes, and experience through learning-by-doing from deployment of CCS projects.

3.2.3. The integration of CO₂ capture and power generation. Approaches for integrating CO₂ capture in the process of power generation fall into one of three categories, depending on where in the combustion process the separation occurs: precombustion capture, postcombustion capture, and oxyfuel combustion (18). In postcombustion capture, a separation system is added after the boiler without inherently changing the system. Most demonstration projects in the power sector aim at postcombustion capture. In precombustion, coal or biomass (or a mixture) is gasified, allowing the carbon to be stripped before the resulting hydrogen gas is combusted. This process, for power production, requires an IGCC plant, of which few are operational globally,

Table 1 Physical and chemical approaches to CO₂ capture

Separation approach	Absorption	Adsorption	Cryogenic	Membranes	Mineralization
Description	CO ₂ from the gas stream dissolves in a fluid. Subsequently, CO ₂ is released (solvent is regenerated) from the fluid by changing pressure or temperature.	CO ₂ from the gas stream adsorbs onto a solid. Subsequently, CO ₂ is released (adsorbent is regenerated) by changing pressure or temperature.	CO ₂ is cooled until it becomes a solid that separates from the gas stream.	CO ₂ from a pressurized gas stream is preferentially transported through a membrane.	CO ₂ reacts with calcium- or magnesium-bearing rocks to form magnesite or calcite.
Example materials (references)	Aqueous amine solutions (6, 23) Chilled ammonia (24) Ionic liquids (26, 28)	Zeolites (29) Metal organic frameworks (22, 25) Activated carbon (20, 30)	No specific material requirements (31)	Polymer membranes (27) Inorganic membranes (32)	Magnesium silicates (33, 34) Alkali-rich (35, 36) waste streams
Advantages	Established technology Numerous solvent options Rapid improvements in energy requirements achieved	Potentially lower energy requirements for regeneration	Avoid need for solvents or sorbents Lower energy requirements	Avoid regeneration energy requirements	CO ₂ is converted to a solid substrate that can be reused as a building material or disposed of in surface facilities.
Technological challenges	Reducing energy for regeneration Solvent degradation	Adsorption capacity and kinetics	Solid separation and handling	Permeability Selectivity	Rate of reactions Mass of reactants (e.g., source of Mg, Ca)
Environmental impacts	Increased water usage if aqueous solvents are used Fugitive emissions of solvents and solvent degradation products Increased fossil-fuel consumption for energy required for capture	Increased fossil-fuel consumption for energy required for capture Disposal or recycling of spent adsorbents	Increased fossil-fuel consumption for energy required for capture	Increased fossil-fuel consumption for energy required for capture	Increased fossil-fuel consumption for energy required for capture Disposal and storage of materials if markets cannot be found Impacts of mining for minerals used in the carbonation reactions
Status	Aqueous amine solvents are available and demonstrated at industrial scale (8 Mt/year). New solvents are being developed and tested at the bench and pilot scale.	Bench and small scale pilot testing in progress	Deployed on a limited basis at an industrial scale for CO ₂ /CH ₄ separation. Bench and small pilot scale testing is under way for flue gas separation.	Deployed on a limited basis at an industrial scale for CO ₂ /CH ₄ separation (7 Mt/year)	Under development

and retrofitting is therefore practically impossible. Hence, prospects for precombustion capture in power generation are less certain than for postcombustion.

In oxyfuel combustion, the fossil fuel is combusted with pure oxygen, resulting in a pure CO₂ stream. The energy penalty is shifted from the CO₂ separation to the oxygen purification. A small-scale demonstration of oxyfuel combustion was built in Germany, but a larger-scale version was abandoned because of economic concerns, public resistance, and the absence of a legal framework in Germany. A potentially promising and low-cost use of oxyfuel combustion is chemical looping, a technology that has made progress in the lab recently (40). However, it has not yet been scaled up for industry, and there are challenges associated with the durability of the chemical-looping materials.

3.2.4. CO₂ capture from industrial processes. CO₂ can also be separated from the flue gases of industrial processes that use carbonaceous fuels, such as cement and steel production, natural gas processing, fertilizer production, and chemical production. Separation of CO₂ is already an integral part of fertilizer production, natural gas production from CO₂-rich fields, hydrogen production at refineries, and synfuel production. In cement, industry decision makers are considering postcombustion and oxyfuel combustion as options (6, 15). In steel production, depending on the production process, industry is considering different systems, including using oxy-firing and regular chemical absorption for top-gas recycling processes (currently the most common) and, if natural gas is affordable, direct reduced iron, which uses a precombustion type of conversion to convert iron ore to iron (41).

3.2.5. CO₂ transport. After the CO₂ is separated and compressed to a liquid, CO₂ can be transported on land via pipelines, motor carriers, railway, ships, or barges. Due to the large scale of existing and prospective storage projects, land-based transport will likely require pipelines. For pipeline transport, CO₂ is compressed to a liquid at ambient temperature (CO₂ pressure above ~8 MPa, temperatures varying by location). Key operational issues include pipeline pressure, corrosion, hydrate formation, temperature, and impurities (8). CO₂ transport by pipeline is a mature technology, and today the capacity exists to transport over 150 MtCO₂/year for CO₂-EOR in North America in over 6,560 km of operational CO₂ pipelines (42). Large-scale deployment of CCS would require significant scale-up in such infrastructure; 37,000 km of CO₂ pipelines will be needed in the United States between 2010 and 2050 (42), and the IEA estimates that about 150,000 km of dedicated CO₂ pipelines will be needed in the European Union.

CO₂ transport costs depend on pipeline length, diameter, construction material, route of the pipeline, and safety-related codes, regulations, and standards (43). Transport of CO₂ by pipeline benefits from economies of scale and favors collaborative hub-and-spoke transport systems rather than point-to-point systems. Innovative financing schemes will likely be required to build pipelines shared by multiple users (44). For industrial-scale storage projects, costs of CO₂ transport are expected to be several US dollars per tonne of CO₂ (43) and are a small fraction of the overall cost of CCS.

Several studies conclude that CO₂ transport by pipeline does not pose a higher risk of accident than is already tolerated for transporting hydrocarbons (see, e.g., 45). For instance, cumulative failures reported in the literature for CO₂ pipelines range from 0.7 to 6.1 failures per 10,000 km per year, which is in the same range of failures reported for hydrocarbon pipelines (46). Although most pipelines currently in use run through sparsely populated areas, broader-scale deployment of pipelines, particularly from existing power plants in densely populated areas, will require modifications to existing standards and risk assessment models: sectioning valves to reduce the quantity of CO₂ that could leak out, shorter distances between valves near populated areas, safety zones

on both sides of the pipeline, increased pipe wall thickness near populated areas, and protection from damage (e.g., burying the pipeline) (46).

3.2.6. Cost of CO₂ capture. Cost estimates for CO₂ capture in power plants and industrial production processes vary greatly and have high uncertainties. A recent review conducted for the Global CCS Institute (11) indicates that CCS would add approximately 40% to the cost of power production in IGCC and natural gas combined cycle power plants and between 50% and 80% for coal-fired power plants with postcombustion or oxyfuel combustion. Added costs are estimated at 10–15% for steel production and 39–52% for cement production. To high-purity CO₂ sources, it would add only 1–3% to production costs.

Capture costs are also estimated on the basis of CO₂ emissions avoided (47). For retrofitting existing coal plants in the United States, costs range from \$73 to \$107 per tonne of CO₂ avoided (48). For new coal plants with low-rank coal, cost of capture is estimated to be \$60–70 per tonne (49). Costs of capture with natural gas plants are higher on a cost-per-tonne-avoided basis (~\$125 per tonne avoided) because the CO₂ concentration in the fluid gas is only about 25% that of a coal plant (e.g., 50). First-of-a-kind plants are expected to cost significantly more, perhaps doubling or even tripling these costs (51). Costs will remain highly uncertain until more industrial-scale projects are under way.

3.3. Storage of CO₂

3.3.1. CO₂ storage overview. Over the years, several options for storage have been assessed, including ex situ mineralization, ocean storage in a dissolved or liquid form, reuse in the chemical industry, and sequestration in deep geological formations (1). Of these options, today only storage in geological formations is considered to have the capacity, permanence, and environmental performance necessary for CO₂ storage at the gigatonne (Gt) scale needed to materially reduce CO₂ emissions (1, 8). This may change in the future as technological advances open up more options.

Deep geological formations suitable for CO₂ storage typically occur in sedimentary basins and include depleted or depleting oil and gas reservoirs and saltwater-filled rocks (so-called saline formations). Sedimentary basins underlie much of the continents and are colocated with many large CO₂ emission sources (52). In these geological formations, CO₂ is injected at depths of 800 m or more where, under typical conditions, CO₂ has a liquid-like density in the range of 500 to 700 kg/m³. The liquid-like density is important from the perspectives of efficiently using the underground storage space and of minimizing the buoyancy forces that would cause leakage back to the atmosphere. Sedimentary basins often contain many thousands of meters of sediments where 10⁻³–10² μm pore spaces that occupy about 20% of the rock volume provide storage space for CO₂. They typically consist of alternating layers. Sand layers provide storage space for oil, water, and natural gas. Silt, clay, and evaporite (rock formations composed of salt deposited from evaporating water) layers provide seals that can trap these fluids underground for millions of years and longer (53, 54). The presence of an overlying, thick, and continuous layer of shale, silt, clay, or evaporite is essential to making a geological formation suitable for storage of CO₂. For oil and gas reservoirs, which are found under such fine-textured rocks, the mere presence of oil and gas demonstrates the presence of a reservoir seal. For saline formations, a significant site characterization effort is required to demonstrate the presence of a satisfactory seal. Important attributes of the seal include low permeability (10⁻¹⁸ m² or less) and a high capillary entry pressure (1 MPa or more).

In addition to CO₂ storage via trapping below a seal, CO₂ may be retained through secondary trapping mechanisms such as solubility, residual gas trapping, and mineral trapping. Researchers

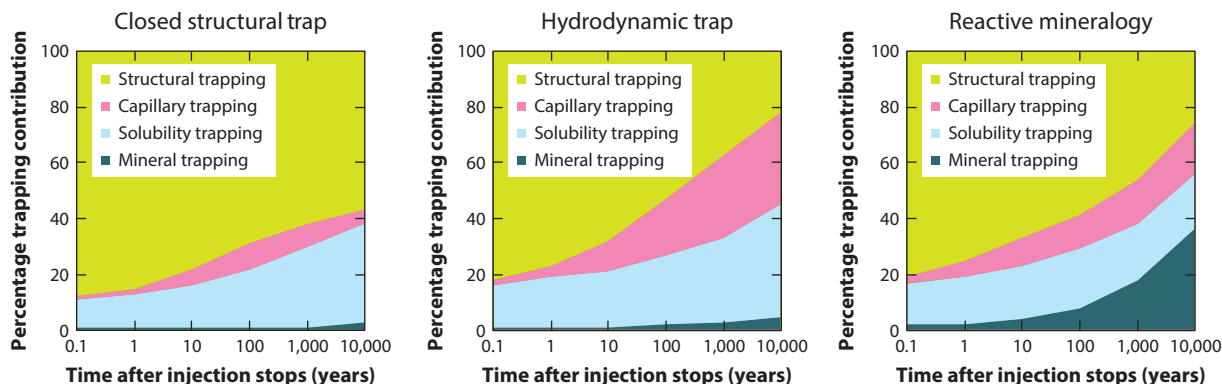


Figure 2

Schematic showing the relative importance of the trapping mechanisms and their evolution over a 10,000-year period, expressed as a percentage of the total trapping contribution (modified with permission from 62).

have made significant progress in the past decade in assessing the necessary conditions and contributions to CO₂ retention of secondary trapping mechanism (55–61). Although secondary trapping mechanisms are not a substitute for a high-quality seal, they do act over decadal to millennial timescales and thus increase storage security over time. As illustrated in **Figure 2**, the relative importance of each of these trapping mechanisms will change over time and depend on hydrogeological attributes of the storage site, such as mineralogy, multiphase fluid flow properties, stratigraphy, and structure of the formation (from 8).

To increase the diversity of options for geological storage of CO₂, several ongoing studies are evaluating the potential of CO₂ storage in basalt formations, which rely on geochemical reactions between the CO₂ and basalt to store CO₂ underground as a mineral such as calcite or magnesite (63–65) and coal beds where CO₂ is adsorbed to the solids (66). These potential options require additional research and large-scale testing, however.

3.3.2. Current issues in CO₂ storage. If CCS is to be implemented on the Gt scale needed to have an impact on emissions reduction, a 20-fold increase will be required in the amount injected underground annually for CO₂-EOR today. Moreover, it will require an infrastructure on the scale of today's oil industry. The ability to scale up the existing operations is central among the issues to be resolved before CCS emerges as a viable option for global emissions reduction. Achieving such a scale-up relies on several critical factors that we discuss below, including storage capacity; injectivity; risk management to avoid detrimental environmental impacts such as groundwater pollution, induced seismicity, and ecosystem degradation; and the availability of intervention methods to effectively remediate unanticipated leakage of CO₂ or other unplanned events. **Table 2** lists these risks, potential impacts, and management approaches for dealing with them. Of these, several have received scrutiny in recent years and are discussed in greater depth below.

3.3.2.1. Storage capacity. Since 2005, numerous governments worldwide have assessed regional storage resources. Significant advances have been made to harmonize highly diverse approaches to capacity estimation (67–69). Storage resource estimates typically provide an upper bound on the storage capacity of sedimentary basins and globally range from about 5,000 to 25,000 GtCO₂. Oil and gas reservoirs are anticipated to have on the order of 1,000 GtCO₂ storage capacity (8). But they are geographically limited to hydrocarbon-rich regions of the world, and they may not

Table 2 Summary of key risks of storage, environmental impacts, and management approaches

Environmental Risk	Impacts	Management Approaches
Leakage of CO ₂ into the atmosphere	Ineffectiveness of CCS	Effective site selection and monitoring Remediation of leakage pathways
Accumulation of elevated CO ₂ concentrations in ecosystems	Damage to CO ₂ -sensitive habitats	Effective site selection and monitoring Remediation of leakage pathways and ecosystem cleanup
Accumulation of elevated CO ₂ concentrations where humans can be exposed	Chronic or acute health concerns from CO ₂ exposure	Effective site selection and monitoring Administrative controls to restrict access Remediation of leakage pathways
Leakage of CO ₂ to groundwater	Acidification of groundwater and potential dissolution of toxic minerals	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways and groundwater cleanup
Leakage of hydrocarbons to groundwater	Contamination of groundwater with organic compounds	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways and groundwater cleanup
Displacement of saline brine into drinking water aquifers or surface water	Contamination of groundwater or surface water with dissolved salts	Effective site selection and monitoring Administrative controls to restrict groundwater use Remediation of leakage pathways and groundwater cleanup
Induced seismicity	Potentially felt ground motion and structural damage	Effective site selection and monitoring Regulatory limits on pressure buildup and consequent induced seismicity

be available for storage until the oil and gas reservoirs are fully depleted or until market conditions favor CO₂-enhanced oil or gas recovery. Saline aquifers are assessed to have the largest storage capacity, global estimates ranging from 4,000 to 23,000 GtCO₂. However, for storage in saline aquifers, there is still very limited experience from which to assess the safety and effectiveness of this option, and uncertainty persists about how much this large storage capacity can be utilized (70–72). A 500-fold scale-up of the existing saline aquifer storage projects would be required for Gt-scale storage. Storage in unminable coal beds is considered to have a low storage potential. See **Figure 3** for a regional overview.

3.3.2.2. Pressure buildup, injectivity, and induced seismicity. When CO₂ is injected into a storage reservoir, the pressure increases (so-called pressure buildup) due to a combination of viscous forces associated with multiphase flow of CO₂ within the plume and displacement of in situ fluids (73). The magnitude of pressure buildup depends primarily on the permeability and thickness of the storage reservoir and the injection rate. In the case of a sealed reservoir (sealed on the top, bottom, and sides), pressure also increases due to compression of the pore-filling fluids (74). Careful consideration and monitoring of pressure buildup and associated geomechanical effects are needed for CO₂ storage projects (75).

Recently, researchers have raised concerns over how much excessive pressure buildup limits storage capacity in saline aquifers (71) and causes induced seismicity (76). Both topics are the subject of considerable debate. Although excessively large pressure increases are indeed expected for Mt/year storage in small and completely closed reservoirs, some researchers argue that concerns

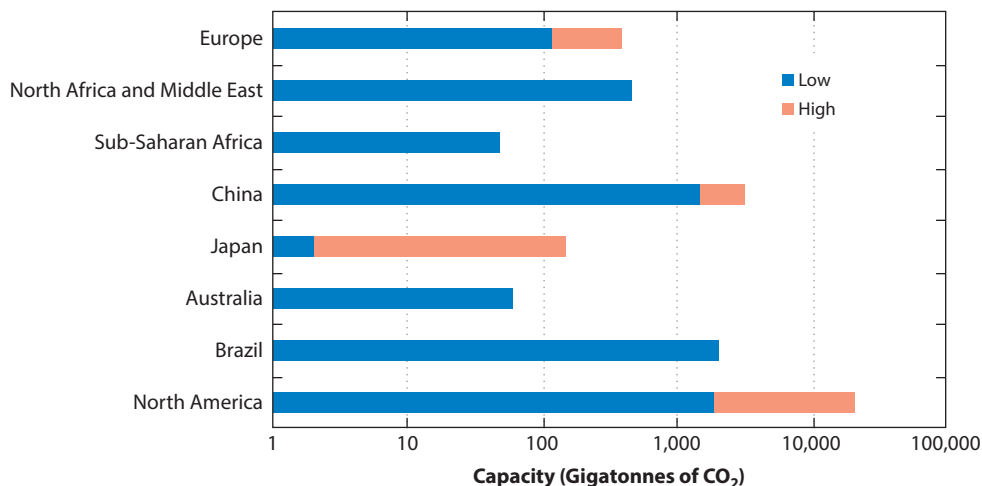


Figure 3

Regional assessment of CO₂ storage capacity as compiled by the Global Energy Assessment (8). Blue bars represent the minimum estimate and red bars the maximum. Notably, these estimates represent the total size of the storage resource, only some fraction of which is expected to be economically and technically viable (70).

are misplaced because existing projects have not experienced such problems (77), most storage reservoirs are not completely sealed (78), pressure management techniques such as injection rate control (79) and brine extraction (80) could mitigate this concern, and taken together pressure buildup is a manageable issue (81).

With regard to induced seismicity, Zoback & Gorelick (76) argue that CO₂ injection in saline aquifers could lead to slip along preexisting faults and to associated induced seismicity. Most of the existing CO₂ storage projects have not experienced such problems (82), but more extensive investigation of the geomechanical effects of CO₂ injection is now under way (83, 84). Additionally, although induced seismicity is rare in the 50 MtCO₂/year injection taking place in existing CO₂-EOR projects, an “unusual and noteworthy instance where gas injection may have contributed to triggering earthquakes” is observed along a preexisting but undetected fault in Cogdell, Texas (85, p. 18789). In general, the topic of induced seismicity is gaining attention with, for instance, disposal of wastewater from hydraulic fracturing operations for shale gas development in the United States (86) and natural gas extraction in the Netherlands. Researchers are actively investigating whether and how much induced seismicity is a constraint to CO₂ storage and, if needed, how to manage injection operations to avoid it.

3.3.2.3. Monitoring. Monitoring has been a key element of the industrial-scale storage projects and of many small CO₂ injection pilot programs, notably at Sleipner (87), In Salah (88), Weyburn (89), Frio (90), Cranfield (91), Otway (92), Ketzin (93), Illinois (94), and Nagaoka (95). Investigators have successfully developed and tested several techniques, including seismic monitoring to track migration of a CO₂ plume (87, 90, 95, 96), electrical resistance tomography to track the CO₂ plume and dissolved CO₂ (97), InSar satellite imaging to map land surface deformation caused by pressure buildup (98), pressure monitoring to confirm the cap rock is not leaking (99), water samples to evaluate geochemical interaction with the rocks (100), flux chambers and eddy covariance towers to quantify surface leakage rates (101), and mobile high-precision isotopic analyzers

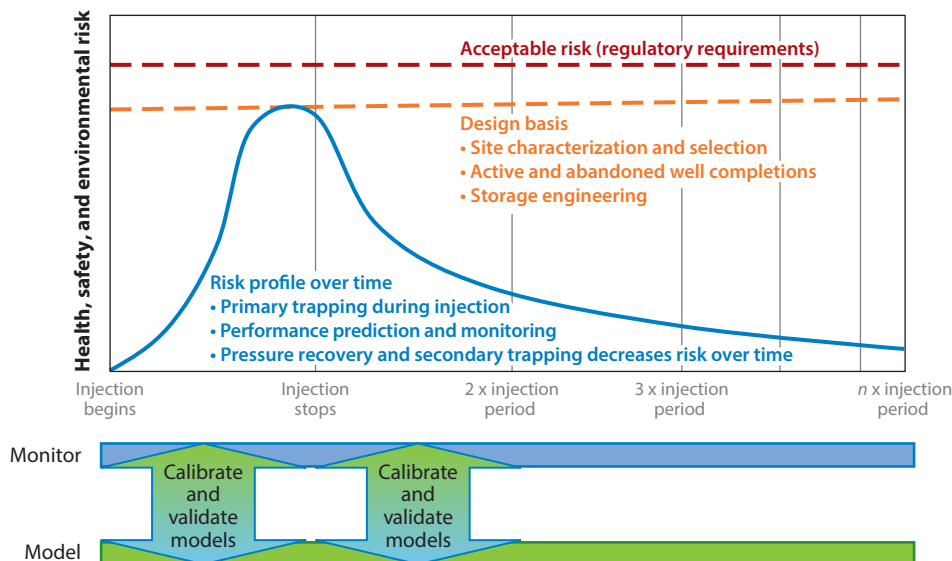


Figure 4

Conceptual schematic illustrating the anticipated magnitude of health, safety, and environmental risks over the lifetime of a typical geological storage project. Performance specifications, or acceptable risks, will be set by regulatory authorities.

to detect leakage (102). Methods to monitor CO₂ storage projects are quite mature, and although they are sufficient for purposes today, improvement is likely with more experience from large-scale projects.

3.3.2.4. Risk management. A regulatory regime will need to assure that the risks of CCS are acceptable, including CO₂ emissions and health dangers, safety and environmental impacts of leakage, groundwater pollution, and induced seismicity. Risks of storage are managed through a combination of site characterization and selection, well completion design and practices, storage engineering, stewardship of abandoned wells, and monitoring (8). Leakage up abandoned or poorly cemented wells is a recognized risk that must be managed by locating, assessing, monitoring, and remediating wells with the potential to leak (103, 104). Over time, information gained from operational experience, performance modeling, and acquisition of monitoring data needs to be used both to optimize performance of the project and to provide assurance that the project is conforming to the design specifications, or remediation measures will be taken to address unforeseen risks. After injection stops, the pressure in the storage reservoir will begin to decrease, lessening the risk of CO₂ leakage or brine migration. Risk will change over time, growing during the early stages of the project, as first CO₂ is injected into the storage reservoir and then the pressure increases inside the reservoir (see **Figure 4**).

4. LEGAL, POLICY, AND PUBLIC PERCEPTION DEVELOPMENTS

The legal, regulatory, and public perception developments around CCS are diverse across countries and regions around the world. This section discusses the main generic developments around legislation (whether CCS can be done legally), policy (what incentives or enablers governments put in place both for full-scale implementation and for research, development, and demonstration),

and public perception (the attitudes of the lay public, the inhabitants of storage areas, and environmental organizations) regarding each issue, illustrated by examples from around the world.

4.1. Legal Developments Regulating CO₂ Storage

The legal arrangements around geological storage of CO₂ depend first and foremost on the legal ownership of the subsurface. In most of the world, the deep underground is owned by the state, which can permit and make rules about usage. In the United States, the subsurface is owned by the surface owner, and the state manages only the environmental and safety elements.

Furthermore, legislation for other subsurface industrial activities, such as natural gas storage, acid gas storage, or EOR, provides a framework for regulating CO₂ storage (105). Legal areas where CCS is different relate mainly to the challenges of predicting behavior and regulating CO₂ storage over millennia (106). The question of when or under which conditions liability of the storage site is transferred to the state is key here, as storage operators are unlikely to invest if the conditions for liability transfer are unclear or unfavorable and if climate liability may be imposed on them (107). However, the general public and the state are unlikely to accept transfer of liability unless safety can be warranted. The issue of transfer of liability is treated differently among countries and even among US states (108).

Developed countries or regions have all started legislation on CCS. In the European Union, a Directive on the Geological Storage of CO₂ was agreed to in 2009, and it contains detailed guidance on how to handle the contentious issues around CO₂ storage, including liability transfer. The EU Directive attracted criticism for not resolving all barriers and for not being fully consistent with other EU legislation (109).

In the United States, federal oversight of CO₂ storage involves regulations from the US Environmental Protection Agency (EPA) and congressional legislation surrounding safe drinking water and well safety (110). Pore-space ownership is regulated at the state level, leading to different approaches in different states (108).

Existing environmental legislation in China could accommodate licensing for CO₂ storage, although this would require an interplay between local, regional, and national councils and institutions (111). In Australia, offshore CCS beyond the state waters is regulated on the federal level, whereas onshore storage is a provincial matter. Several provinces, including Victoria and Western Australia, have a comprehensive legal framework for both onshore and offshore CCS (110).

To allow CO₂ injection in the ocean underground, under international maritime law, changes have been made in the Oslo-Paris Convention (covering the North-Eastern Atlantic), but the amendment to the London Protocol (which is part of the Oslo-Paris Convention and would allow cross-border transportation of CO₂ with the aim of offshore geological storage in a broader geographical realm) must still enter into force. Despite proposals for how to resolve the lack of agreement on the London Protocol Amendment (112), it is unlikely to happen soon for various political and practical reasons (107, 110).

4.2. Policy Developments

Figure 5 provides a timeline since the 1990s of milestones in the policy developments of CCS worldwide and in the most active countries. At the global level, the founding of the IEA GHG R&D Program (IEA GHG, one of the IEA Implementing Agreements) in 1991 signified the start of several activities: It held the first international CCS conference (Greenhouse Gas Control Technologies) in Amsterdam in 1992 and played a significant role in the SRCCS, published in 2005 (113).

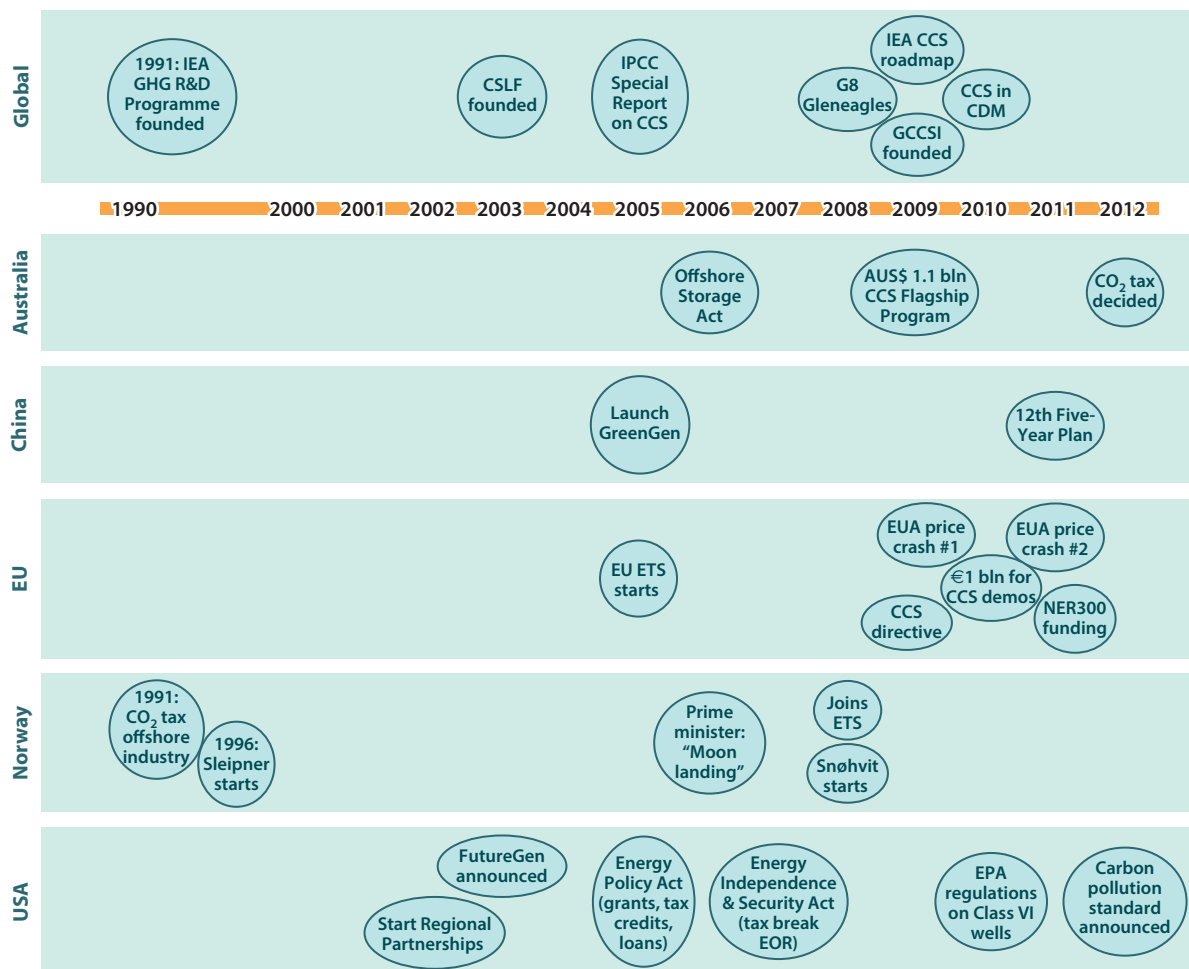


Figure 5

Overview of select CCS policy and legislation milestones. (Acronyms/abbreviations are for various organizations or projects, most of which are discussed in the text, e.g., CDM, Clean Development Mechanism; CSLF, Carbon Sequestration Leadership Forum; EPA, Environmental Protection Agency; ETS, Emissions Trading Scheme; EUA, emission allowance unit; GCCSI, Global CCS Institute.)

Almost simultaneously, in 1991, the Norwegian government passed a tax on CO₂ emissions from offshore operations that incentivized the first purposeful CCS demonstration, the Sleipner project, in 1996. Van Alphen et al. (114) characterize the early developments of Sleipner as mostly done and funded by Statoil, the Norwegian state-owned oil company, in cooperation with Norwegian research institutions and technology vendors, in particular Kvaerner. However, an exchange of knowledge facilitated by the IEA GHG and R&D projects financed by the European Commission also contributed to the ability of Statoil to implement this lighthouse project, which is still operational today. Through consistent investment in innovation capacity in Norway, market formation by the government, and participation of both the private sector and public research institutions in international consortia, Norway built a functioning innovation system (114).

Countries have taken different routes on enabling CCS. The United States has opted for funding and tax credits for research, development, and demonstration, starting with smaller demonstrations and including EOR (political reasons made more generic climate mitigation policies difficult to realize), and the European Union started, in the spirit of the Kyoto Protocol to which it is an enthusiastic signatory, with an ETS in 2005, a demonstration program with subsidies (often complemented by funding on the member state level). Both the European Union and the United States funded research programs.

A comparison shows that both pathways are vulnerable to political risks and external developments. In the European Union, the drop in carbon prices (caused by a combination of economic crisis and overallocation of carbon credits) frustrated large-scale demonstrations. In the United States, the large-scale FutureGen demonstration project was reinvented numerous times after its first announcement in 2003, and, although not yet under construction, it is slated to proceed after a funding decision by the US government (115).

In the United States, the combination of smaller-scale demonstration of geological storage of CO₂, the prospect of large-scale implementation, and potential for EOR seems to have sustained progress in CCS. Moreover, the EPA has proposed a new carbon pollution standard that would require capture and storage of 50% of CO₂ emissions from new coal plants. The European Union, by contrast, has almost exclusively focused on large-scale implementation through demonstrations and carbon-market incentives, in part because the SRCCS (1) suggested that technological barriers were surmountable by large-scale integrated projects. At the moment, it seems that the more careful and flexible strategy of the United States has better supported CCS.

All eyes are now on China. With its already high and rising emissions from both manufacturing and energy industries (116) and its plans to implement large-scale demonstrations, EOR projects, and longer-run carbon policies (13), China's strategy seems set on adopting parts from both the US and EU strategies on CCS.

4.3. Public Perception of CCS

In 2005, when the IPCC SRCCS was published, the literature on the public's perception of CCS was so limited that a paragraph in the summary for policy makers of that report was found to have insufficient basis. However, a considerable literature has emerged since then (e.g., 117). Two perspectives can be distinguished regarding public engagement around CCS: Some consider engagement a success when people can make more informed decisions on CCS, whereas others consider it a success only when resistance to CCS projects is prevented or reduced (2).

A synthesis provided by Benson et al. (8) highlights lessons from projects and studies that indicate that communicating early, honestly, transparently, responsively, inclusively, and clearly around a potential CCS project and framing it in the context of climate change action are essential elements of effectively engaging the public and reducing the likelihood of resistance. A key issue is the lack of knowledge of CCS (118), but another is the difference in risk perception between the lay public and experts (119). Concerns of the public around CCS seem to include safety, environmental impacts, and (in the locality) loss of property value, but resistance is also fueled by a decision-making process perceived as unfair and by a lack of trust in the actors; in short, it is propelled by a sense of procedural injustice (120).

An evaluation of events shows that public acceptance can make or break a CCS project. The most visible example of a project cancelled because of public resistance is the Barendrecht project in the Netherlands (120, 121). In Germany, the general view that CCS diverts efforts away from renewable energy contributed to the parliamentary rejection of CCS legislation and the cancellation of one of the EU's demonstration projects in Jämschwalde (2011). In the United States and

Australia, the general attitude seems more favorably disposed toward CCS, perhaps because of a more positive view of the fossil-fuel industry, but even in those countries, resistance has emerged around several CCS projects, focused on safety, public benefits, and environmental justice issues (8, 117).

Regulation can also play a role in public engagement around CO₂ storage projects. IEA (110) proposes that generic regulation is important (e.g., the degree to which locally relevant decisions are made at the national level, disempowering local forces) but also that stakeholder engagement regulations in environmental impact assessments and other licensing may facilitate consultation and ownership of CCS projects by local communities and politicians. Several publications point out, however, that the public is unclear whether governments have actually taken note of the recommendations and shifted from a stance of “decide, announce, defend” to one of “investigate, adapt, engage.” For instance, Canada reports that its CCS demonstration projects are not subject to a comprehensive environmental assessment and therefore are not required to engage the public or even establish a review panel (110).

5. CCS INDUSTRIAL-SCALE PROJECTS

The initiation of four projects from 1996 to 2008 provided a great deal of momentum in the early days of CCS (**Figure 6**). Following this period, a hiatus in new projects contributed to the view that progress in CCS was slowing. However, in the coming years, eight new projects will start operations, more than doubling the existing CCS capacity. An additional group of about 70 projects is in various stages of development. Nevertheless, experience over the past decade suggests that only a fraction of the 70 projects in the pipeline are likely to come to fruition (13).

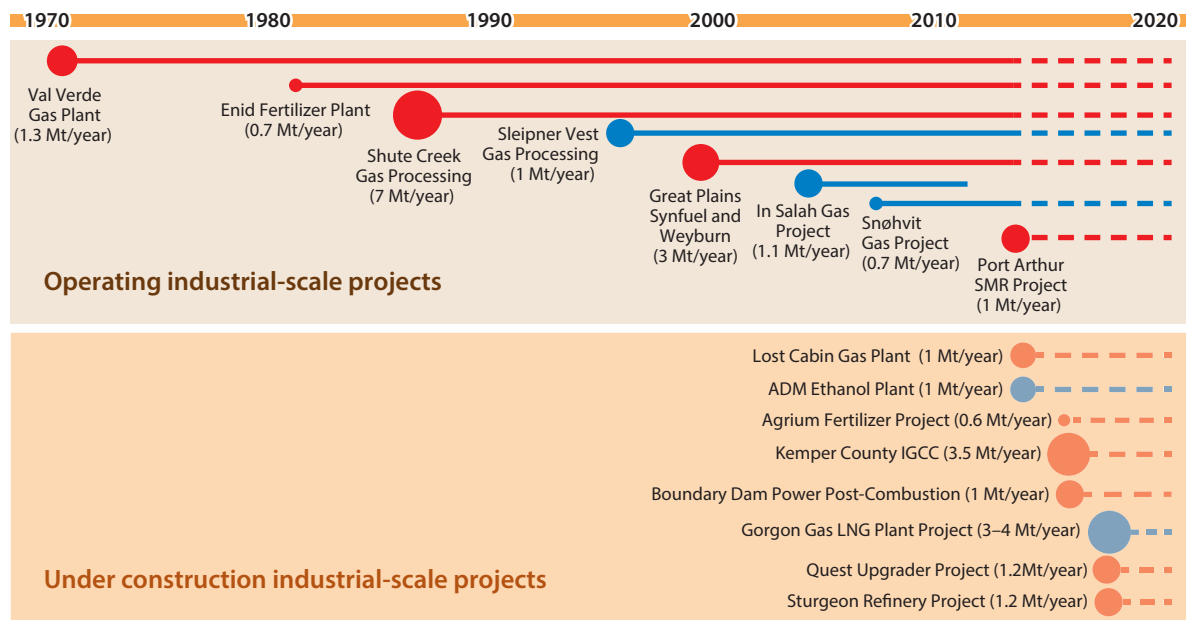


Figure 6

Timeline of starting dates of CCS demonstration projects (operational and under construction). Circle size indicates the annual mass of CO₂ stored. Red circles involve hydrocarbon recovery and blue circles indicate CO₂ storage without hydrocarbon recovery. The line that discontinues for In Salah denotes that the project has stopped operation.

5.1. History of CCS Industrial Projects

Much debate surrounds the question of whether CCS is a mature technology or merely experimental. The SRCCS (1) allocated different capture, transport, and storage technologies into categories of maturity, with CO₂-EOR and industrial separation of CO₂ being mature and mineralization considered to be in the R&D phase. Key technologies, such as geological storage in saline formations and postcombustion capture systems, were classified as needing industrial-scale demonstration. De Coninck et al. (122) note that five years later the status of these approaches to CCS has not changed significantly. Stigson et al. (123) note that some EU demonstration projects have aimed to solve problems other than those that local stakeholders have indicated are important. Evar & Shackley (124) build on this notion by indicating that rather than supporting large CCS demonstrations, the European Union should have pursued smaller-scale projects to enable learning.

Figure 6 illustrates all full-scale industrial CCS projects that use anthropogenic CO₂ and therefore reduce GHG emissions. The early projects from the 1970s through the 1990s mostly did not use CCS for climate change-mitigation purposes but provided a considerable net reduction of CO₂ anyway. The first project done for mitigation was the Sleipner project, offshore Norway. The only project that ceased operations was the In Salah gas project in Algeria. As **Figure 6** illustrates, seven CCS industrial projects are currently operational, injecting almost 15 MtCO₂/year. Five out of those seven projects recover hydrocarbons, all oil, which provides an economic basis for sustaining them. In the other two operational projects, Sleipner and Snøhvit, the incentive for CCS was the aforementioned CO₂ emission tax for offshore operations in Norway. All operational projects use CO₂ from high-purity CO₂ sources, such as fertilizer plants, natural gas sweetening operations, steam-methane reforming, ethanol production, and coal gasification. From the projects under construction, we can also clearly see that CO₂-EOR continues to play an important role in demonstrating CCS at scale. None of the operating projects takes CO₂ from a power plant, and only two of the eight CCS projects under construction (Boundary Dam and Kemper County) do, one from an IGCC (Kemper).

All CCS industrial-scale projects in operation and under construction are in the United States, Norway, Canada, and Australia, with an emphasis in North America. None is currently under construction in the European Union, despite the considerable subsidies promised by the European Commission in its economic recovery package and in the NER300 policy for full-scale demonstrations in the power sector. Several factors explain this difference: First, the potential for and experience with CO₂-EOR is much lower in Europe than in North America (**Figure 6** illustrates that EOR is critical in incentivizing industrial-size projects). Second, Europe targeted the (more difficult) power sector for CCS demonstration, rather than the low-hanging fruit in industry. This choice was a consequence of the EU ETS, which in principle would have paid a carbon price for the low-cost CCS projects in industry rather than power, and so additional policy was not considered necessary in the industry sector. However, with the economic crisis in the late 2000s and the concomitant drop in carbon prices, the ETS-induced carbon price incentive did not materialize, causing both the demonstrations in the power sector and potential projects in industrial, high-purity sectors to cancel their plans. Third, the US choice of at first investing in smaller demonstration projects and then scaling up appears to have been more successful than investing in complex, industrial-scale demonstrations immediately, although the evidence is not conclusive.

5.2. Business Models of New CCS Demonstrations

The most commonly assumed business driver for non-EOR CCS is a price on carbon emissions, either a cap-and-trade system or a carbon tax. Other approaches include CCS for certain sectors

or even all large immobile sources of CO₂ (1, 125), tax credits, a feed-in tariff on the electricity or carbon price, and grants (126). Some authors have noted other realities in the business of CCS, including bridging the differences between storage companies and CO₂ sources, finding a value proposition, and value-sharing arrangements (127).

The business model for CCS (i.e., how a CO₂-emitting plant equipped with CCS remains economically viable) depends on whether and what type of carbon policy exists. An emission standard or CCS mandate means that costs need to be transferred to the consumer in a level playing field (other producers face the same mandate). A carbon price or tax adds to the production costs, meaning that cost avoidance is the CCS business model (this is the model for the Statoil's Sleipner and Snøhvit projects listed above). A subsidy (feed-in, investment grant, or otherwise) covers the additional costs of CCS.

Absent these incentives, and particularly in times of budget constraints and the lagging public and political urgency over climate change, business models that work without government intervention are important. Researchers have often pointed out that early business cases (or negative-cost options) for CCS exist in the combination of high-purity CO₂ sources and enhanced hydrocarbon recovery (1, 128–130), or even in power plants with EOR (131). Most demonstrations listed in Section 5.1 are indeed in this category.

Esposito et al. (131) also highlight three ways to contractually organize CCS: within a single company (self-build), between different companies (joint venture), and based on a CCS service company (pay at the gate). Furthermore, even with incentives that are insufficient to cover CCS costs, agglomerations of CO₂ sources could make use of combined transport and geological storage infrastructure and save costs (15). A company could also value a first-mover advantage on an element of the CCS chain or find it worth hedging for future carbon regulation. An example of such a case is a combined biomass/CCS/efficiency scenario with flexible CCS (132).

6. A REVIEW OF CRITICAL CONDITIONS FOR CCS

The development of CCS in recent years is falling short of what is needed for it to play the climate change-mitigation role that the IPCC and IEA expect it to play (133, 134). There is broad agreement that stronger climate policies are needed to change this (1, 110), but as the discussion above shows, more than price incentive is needed to bring CCS to fruition. This section attempts a comprehensive, actor-based overview of the critical conditions needed for CCS to play such a role, taking into account the complexities of both the technology and the constellation of drivers, actors, and impediments that shape its development. In doing so, we consider the perspective of three groups: (a) communities around a storage location, (b) political leaders, and (c) investors. These groups are crucially needed to feel motivated to act on or allow for CCS deployment.

Of course, more actors, such as policy makers, nongovernmental organizations (NGOs), storage operators, scientists, think tanks, local decision makers, and the companies operating CO₂-emitting plants, are relevant to CCS. However, these actors are all dependent on the former three groups. A utility needs an investor to have confidence in the financial viability of a CO₂ capture plant. A policy maker cannot act unless there is political support for action. NGOs need their constituency in communities to back their views and policies. A storage operator needs to be paid for its work, which again involves the investor. All other relevant actor groups are to a large degree followers of the leading three, although interactions exist.

Figure 7 indicates what each of the three crucial groups needs to play positive roles in enabling CCS:

- Investors need certainty that their investment in CCS will pay off. This means robust, long-term, and continuous political support and a low risk of political and public resistance, a

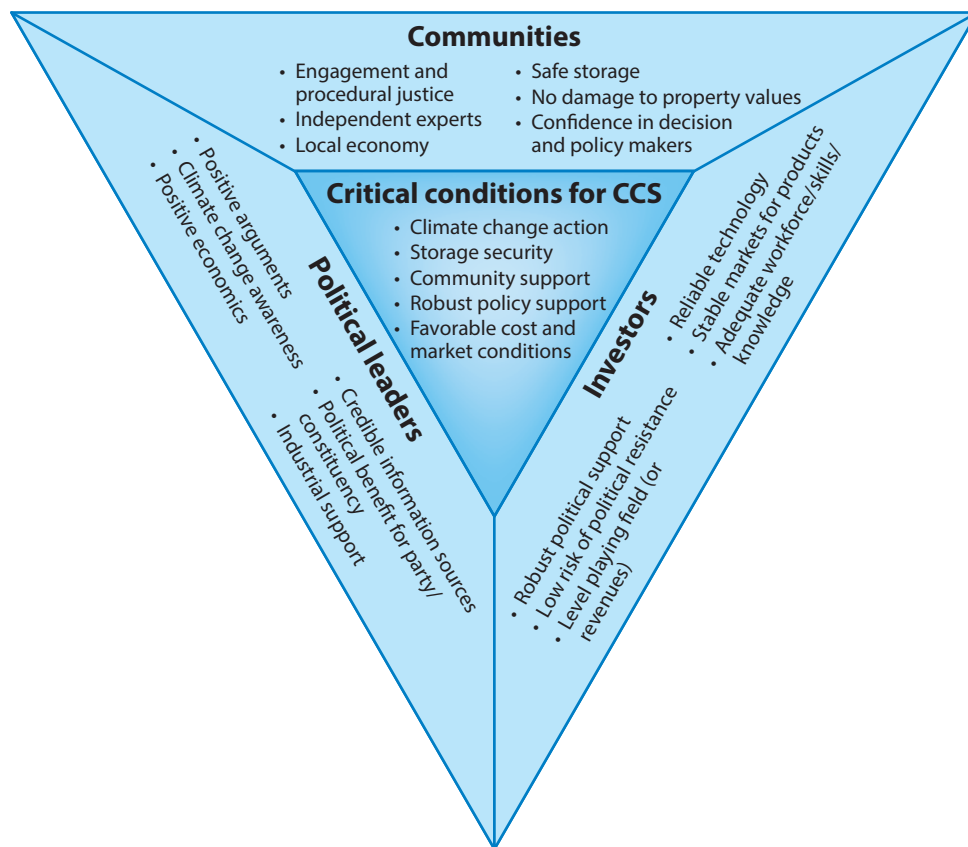


Figure 7

Schematic representation of critical conditions for a future for CCS. Political leaders, communities, and investors are critical actors; other actors follow these three. Lists within each field indicate what the actor needs to fulfill its role in CCS deployment. The central triangle lists overall critical conditions for CCS derived from the three critical actors. Importantly, the conditions are interdependent: They affect and interact with each other.

level playing field so that revenues can be generated, low technological risk, a stable market for the products from the CO₂ source, and the presence of an adequately trained workforce to guarantee reliable operations. Hence, investors need progress in CCS R&D, a supportive society, and action so that CCS delivers revenues.

- For a community to support CCS, the literature indicates that it needs procedural justice, stakeholder engagement, trust in independent experts and decision makers (which is partly related to procedural justice), safety of storage, secure property values, and benefits for the local economy. Many of these elements can be provided by government and the research community.
- Political leaders, rather than policy makers, are crucial, too. They can provide the clarion call for CCS, frame the technology as a necessity in public debates, and change the broader public view on CCS. However, for political leaders to act likewise, they need to be aware of the problem of climate change and the scope of action. They need positive political arguments (including a positive economic outcome or a political benefit for the constituency) for CCS,

credible information sources that can help them shape their views on CCS, and industry support for such a way forward. A policy with low industry support is unlikely to make it through the political process.

There are many interdependencies between and among the critical actors and conditions. For example, political leaders can provide robust policy and political support that investors (industry or financiers or both) need, but politicians also need community support to reduce risk of political and public resistance. For this, climate change awareness and engagement and procedural justice are needed, as are experts who are perceived as independent, in order to have a source of information to turn to (121).

For the three actor groups—political leaders, communities, and investors—to jointly create the policy window necessary to make CCS happen, the first condition that needs to be met is climate change action. If climate change action is not taken, CCS will remain constrained to a limited number of affordable EOR projects. Also crucially important for the three actor groups are four more conditions: demonstrated security of CO₂ storage; support from local communities; robust, long-term policy support for CCS (climate action is unlikely to be enough on its own); and favorable costs and market conditions, such as innovation that reduces costs. To fulfill these conditions, much needs to happen in many countries all over the world.

7. CONCLUSION

Significant technological advances in the CCS field have occurred recently. Government- and private sector-funded R&D and small-scale demonstration projects have provided insights into the feasibility of CCS technologies. In geological storage of CO₂, researchers have gained experience in dedicated, large-scale, commercial projects that have been running safely for years, such as Sleipner. Decades of CO₂-EOR in North America have added to the knowledge base. Contributions to geological storage research have come from smaller-scale experiments, development of improved monitoring and performance prediction tools, and lab-scale experiments. Nevertheless, costs have not come down significantly because of other price factors.

Advances have also been made in the field of CCS legislation, and we now know much better that communities living near CO₂ storage sites need to become participants in CCS projects rather than be treated as passive bystanders without a stake in what is going on. Ignoring those lessons may lead to resistance that can be strong enough to block projects locally and give CCS a bad name nationally. At the same time, progress in monitoring of geological storage and risk management has been significant.

Yet despite these advances, the future of CCS is highly uncertain. The past decade has shown how dependent the technology is on its social and political context. The failed Copenhagen climate conference of 2009, the 2008 financial crisis and subsequent prolonged economic crisis, the fast rise of shale gas in the United States and lower cost of renewable energy, a public that is skeptical partly because of poorly handled consultation efforts around demonstration projects, and rising resource costs have all contributed to waning attention to CCS, cancelled demonstration projects, and a disinvestment of even the most fossil-invested industries. EOR projects can temporarily fill a gap, but for CCS to play a significant role in mitigating climate change, EOR is not sufficient.

This assessment suggests that climate change action is the most important condition for CCS prospects to improve. Action on climate change—whether national or international and whether through pricing carbon, mandating technology on a sectoral basis, or imposing emission standards—requires political leaders to make clear choices against a high-carbon future. They will not make such choices without a public mandate for carbon reductions and industry views that are

at least somewhat supportive of climate change mitigation. But only political leaders, and policy makers in their slipstream, can provide the favorable market conditions and robust policy and research support necessary to reassure investors that the many billions of dollars of investments needed for capture installations, transport infrastructure, and storage and monitoring operations will be worthwhile.

Apart from the broader public viewpoints on climate change and CCS, community support on the local level is crucial. For this, it needs to be beyond doubt that geological storage of CO₂ is a safe and effective means to stabilize and in the long run even reduce atmospheric CO₂ concentrations. But secure storage is not enough. Credible, accessible, and scientifically sound information sources, appropriate engagement activities, and an eye for local benefits are other crucial elements of community support for CCS.

One country has, at least for a while, shown the positive feedbacks among political leaders speaking out for CCS, a strong research base, industry support, and a public mandate, also voiced through a relatively pro-CCS environmental movement: Norway. However, even in Norway, the strong knowledge base has not yet fully translated into entrepreneurial activity (114), and as other issues emerge on the political agenda, CCS risks losing momentum.

Many other countries are still missing several of the critical components for CCS deployment that were present in Norway—in particular, outspoken political leaders and a favorable attitude of the general public. If R&D continues to reduce capture cost, and smaller demonstrations and EOR are increasing confidence in storage integrity, a policy window such as the one that briefly opened before 2009 could be put to quicker and better use and may still lead to more hopeful prospects for CCS. However, if the current context of CCS prevails, it is unlikely that the world can rely on CCS to do its share in climate change mitigation.

SUMMARY POINTS

1. Significant scientific and technological advances have been made over the past decade that provide options for reducing the cost of CO₂ capture and increasing confidence in the security of CO₂ storage. Nevertheless, additional progress is needed in both areas. In particular, progress with CO₂ capture requires additional reductions in the energy penalty and further reduction in costs overall. For CO₂ storage in saline aquifers, we need approaches for managing the effects of pressure buildup, improving site characterization methods, and increasing confidence in long-term trapping beneath seals and with secondary trapping mechanisms.
2. By 2020, the number of operating projects is expected to double. Several of these will combine power generation with CCS, a critical step in the scale-up of this technology.
3. Despite considerable R&D investments and progress in CCS in the past ten years, fewer large-scale demonstrations have materialized than anticipated for various economic, technical, and social reasons. These reasons need to be better understood in order to be effectively addressed.
4. In the coming years, most technological insights are likely to come from demonstrations incentivized by enhanced oil recovery rather than by climate policy. More demonstrations are planned in China in the longer term.
5. If the current context of weak climate change-mitigation policy prevails, it is unlikely that the world can rely on CCS to do its share in climate change mitigation.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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