



Climate Action Network

Position: Carbon Capture, Storage and Utilisation

January 2021

Climate Action Network (CAN) is the world's largest network of civil society organizations working together to promote government action to address the climate crisis, with more than 1300 members in over 120 countries.

www.climatenetwork.org

Introduction¹

Climate change is one of the biggest challenges facing humankind in this century. The Paris Agreement seeks to respond to the climate crisis by providing a collective framework for nationally determined actions with the goal of limiting global average temperature increase to 1.5°C above pre-industrial levels. The aim is to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. In practice, achieving this goal means greenhouse gas emissions must decrease to as close to zero as possible by mid-century at the latest.

CAN's vision for a safe climate centers on rapid and deep economy-wide decarbonisation of all countries and a transition to a just, equitable, and sustainable future. A range of solutions and climate mitigation tools can help achieve this vision, including, renewable energy, energy efficiency, forest conservation, ecosystem restoration, sustainable reforestation, and reduced meat consumption as well as shifting to sustainable consumption patterns by the global rich and middle classes. CAN urges a global Just Transition to 100% renewable energy, supported by ambitious energy conservation and efficiency measures by mid-century at the latest, conducted earlier by richer countries and essential to meet the Paris Agreement goal.

Carbon Capture and Storage (CCS) is a technology promoted by some as essential to limiting global average temperature increase to 1.5°C. Many climate models produce scenarios, including CCS in the power and industrial sectors, bioenergy with CCS (BECCS), direct air capture with CCS (DACCS), and carbon capture and utilisation (CCU), to either limit warming and/or account for overshooting of the 1.5°C target through the removal of carbon dioxide emissions from the atmosphere. Other scenarios model ways to limit warming without overreliance on or any CCS.

¹ Environmental Defense Fund (EDF) does not support all aspects of this document. EDF believes we cannot afford to a priori reject the CCS potential.

The Integrated Assessment Model scenarios with low or no CCS deployment require considerable increases in energy efficiency and near-term rapid fall in energy demand to meet commitments under the Paris Agreement.² Climate models show that if the current pace in global energy demand growth and emission reductions continue, the pathway to limit warming at 1.5°C without CCS will be out of reach within some years. The path we take is a societal choice, with significant implications for intergenerational equity, social and economic justice, land use rights, access to energy, sustainable development, and our ultimate effectiveness in decarbonising our economies.

As detailed in this paper, CAN prioritizes ambitious climate mitigation to meet targets under the Paris Agreement. CAN is concerned that CCS risks distracting from the need to take concerted action across multiple sectors in the near-term to dramatically reduce emissions. Overall, to meet the 1.5°C limit, richer parts of society must consume less, and all must consume efficiently, and sustainably. This will provide space for the globally poorer parts of society to ensure their legitimate space ensuring social and economic well-being for all.

Carbon Capture and Storage (CCS) types and deployment

CCS encompasses a range of carbon capture, storage applications. This paper focuses on the following: CCS in the power and industrial sectors, BECCS, DACCS. Additionally, this section considers related issues concerning Enhanced oil and gas recovery [EOR/EGR] and carbon capture and utilization (CCU).

Fossil Fuel/Industrial CCS

Whilst in different stages of development, as further discussed in Appendix 1, many CCS applications are still largely unproven at scale. Despite billions in public support over the past decade,³ there are 51 large-scale CCS projects across the globe, of which 19 are operating and most are pilot-scale projects that demonstrate only a part of CCS (e.g., capture but not storage).⁴ These figures include operational carbon capture projects in the power and industrial sectors but do not include BECCS or DACCS facilities in operation, which are briefly discussed below.

Collectively, currently operational CCS projects (excluding EOR operations) are injecting and storing less than 5 million tonnes of CO₂ (MtCO₂) per year.⁵ The International Energy Agency (IEA), which counts only two large-scale CCS projects operating in the power sector with a combined capture capacity of 2.4 million tonnes of CO₂ per year,⁶ notes the technology remains well off track to reach the 760 MtCO₂ by 2030 and about 2.8 Gt CO₂ by 2050 storage rate outlined in IEA's own Sustainable Development Scenario.⁷

BECCS

² Grubler, A., Wilson, C., Bento, N. *et al.* A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat Energy* 3, 515–527 (2018). <https://doi.org/10.1038/s41560-018-0172-6>

³ See Appendix 2.

⁴ Global CCS Institute (2019). Facilities Database, available at: <https://co2re.co/FacilityData> (accessed 19 September 2019).

⁵ Calculation based on figures provided on by Global CCS Institute (2019). Facilities Database, available at: <https://co2re.co/FacilityData> (accessed 19 September 2019).

⁶ Boundary Dam and Patra Nova, located in Canada and the US, respectively. Both projects involve EOR.

⁷ IEA's Sustainable Development Scenario holds temperature rise to below 1.8 °C with a 66% probability without reliance on global net-negative CO₂ emissions; this is equivalent to limiting the temperature rise to 1.65 °C with a 50% probability. Global CO₂ emissions fall from 33 billion tonnes in 2018 to less than 10 billion tonnes by 2050 and are on track to net zero emissions by 2070. See International Energy Agency (2020a). CCUS in power, available at: <https://www.iea.org/reports/tracking-power-2019/ccus-in-power#abstract> (accessed 1 February 2020); see also International Energy Agency (2020b). World Energy Model, available at: <https://www.iea.org/reports/world-energy-model/sustainable-development-scenario> (accessed 1 February 2020).

BECCS still remains in the very early stages of development and has yet to be demonstrated at a commercial scale: Globally, there is one large scale BECCS facility currently capturing and storing 1MtCO₂ p.a., and four small scale plants (all combined with EOR) in operation – all ethanol plants. A single pilot project in the UK has been demonstrating capturing of about a ton of CO₂ (but not storing) per day from 100% biomass feedstock combustion, starting in 2019 at the Drax Power Station.⁸

DACCS

Very few DACCS projects are operating globally at any scale although several companies are working to commercialise the technology.⁹

CCU

CCU covers a range of technologies at differing levels of maturity, cost, and market size, with many applications still in the research and development (R&D) phase.¹⁰

Technological maturity aside, CCS applications face myriad deployment barriers and raise a number of environmental, economic, and social concerns. As summarised in Appendix 1, the CCS applications discussed in this paper are currently expensive to deploy, may not result in substantially lower or negative emissions, and/or raise significant sustainability and environmental justice concerns in light of their potential energy, water, land use, and other resource demands. CAN therefore remains unconvinced of the many aspects and value of CCS applications and their value as climate mitigation tools.

Conclusions on CCS

Based on current global trends and an analysis of existing literature and reports, as discussed in Appendix 1, CAN concludes about CCS and its potential to serve as a climate mitigation tool as follow:

- 1. CCS at scale remains largely unproven and its potential to deliver significant emission reductions by mid-century is currently limited.** Current evidence supporting CCS as an effective and scalable climate mitigation tool is largely theoretical, and still under debate. Furthermore, for CCS to play a significant role in achieving the Paris Agreement goal, gigatonnes (Gt) of CO₂ would need to be captured and permanently stored. This would require the financing and construction of CO₂ transport infrastructure roughly equivalent in scale to today's oil and gas pipeline and marine transport networks. The political, social, economic, and technical barriers to achieving this cannot be understated. Equity, cost-effectiveness, and abatement potential are all important factors in determining whether CCS should be considered a technology solution.
- 2. Safe, permanent, and verifiable storage of CO₂ is difficult to guarantee.**¹¹ Well-selected, fully characterised, properly designed, and appropriately managed CO₂ storage sites are likely to have

⁸ Drax Group plc (2019). Carbon dioxide now being captured in first of its kind BECCS pilot. Press Release issued 7 February 2019. Available at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/.

⁹ Fasihi, M., et al (2019). Techno-economic assessment of CO₂ direct air capture plants. *Journal of Cleaner Production*, Vol. 224: 957-980. 1 July 2019. Available at: <https://doi.org/10.1016/j.jclepro.2019.03.086>

¹⁰ IOGP (2019). The potential for CCS and CCU in Europe. Report to the 32nd meeting of the European Gas Regulatory Forum 5-6 June 2019. Available at: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.

¹¹ See Appendix 1.

a low risk of leakage.¹² Such storage sites, however, are expected to be a limited resource and will not be evenly distributed across the globe.¹³ It is therefore likely that some CO₂ storage will occur in lower quality sites, and it is reasonable to assume not all sites will be properly managed, thereby increasing leakage risk.¹⁴ At the same time, it is very difficult to detect CO₂ leaks, which can occur in different timescales.¹⁵ The implications for climate mitigation as well as other environmental and public health risks makes governance and the risk of leakage, even at very low rates, a serious concern.

- 3. The climate impact of CCS should consider all emissions and costs from concomitant processes.** The costs and emission of greenhouse gases and some pollutants from processes associated with CCS need to be carefully factored in. Power plants and industries intended to sequester CO₂ will use additional energy to compress, transport to suitable reservoir and pump into the ground the captured CO₂. Studies calculate that 15-25% more energy would be required, depending on particular CCS technology used.¹⁶
- 4. CCS is not needed in the power sector.** Faster, cleaner, safer, more efficient, and cheaper means exist to reduce CO₂ emissions, such as phasing out fossil fuels and replacing them with renewable energy, energy efficiency, and energy conservation.
- 5. EOR/EGR is dangerously at odds with any climate action,¹⁷** and will not lower emissions in comparison to renewable energy and energy efficiency. To meet the Paris Agreement target, the majority of fossil fuel reserves must be left in the ground.
- 6. A suite of strategies and technologies already exist to cut emissions in the industrial sector, without CCS .¹⁸** Emissions in the industrial sector can be significantly reduced by increasing process efficiency, but there is a need also to increase the speed of development and/or deployment of low or zero carbon processes and materials, replacing fossil fuels with renewable energy, increasing recycling rates, and designing alternative materials with lower emission footprints than steel, conventional cements, plastics and aluminum. CAN strongly supports further and internationally coordinated research, development and deployment into CO₂-free processes and alternative materials with the objective that these can ensure that energy-intensive industries eliminate all emissions by mid-century at the latest.

¹² Anderson, S. (2017). Risk, Liability, and Economic Issues with Long-Term CO₂ Storage—A Review. *Natural Resources Research* 26, 2017, pp. 89-112. <https://doi.org/10.1007/s11053-016-9303-6>; In such reservoirs, the IPCC noted in 2005 that the fraction of CO₂ retained in such geological reservoirs is “very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years.” IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

¹³ Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: <https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/>.

¹⁴ See Appendix 2, which discusses how mismanagement of the In Salah CO₂ storage project in Algeria led to fracturing of a storage formation’s caprock.

¹⁵ Hvidevold, H.K., Alendal, G., Johannessen, T., Ali, A., Mannseth, T., Avlesen, H. (2015). Layout of CCS monitoring infrastructure with highest probability of detecting a footprint of a CO₂ leak in varying marine environment. *International Journal of Greenhouse Gas Control* Vol. 3, June 2015, pp. 274-279. <https://doi.org/10.1016/j.ijggc.2015.03.013>.

¹⁶ European Environment Agency, “Carbon capture and storage could also impact air pollution”, last modified 10 December 2019, see: <https://www.eea.europa.eu/highlights/carbon-capture-and-storage-could>

¹⁷ See Appendix 1.

¹⁸ See Appendix 1.

- 7. Large-scale deployment of BECCS would result in unacceptable negative impacts on food security, land use rights, and biodiversity given its land use, water, and resource requirements.**¹⁹ CAN also concludes there is no definitive evidence that large scale BECCS will deliver on its negative emissions promise. It should also be emphasized that CAN has already agreed to focus the need for negative emissions primarily, and as much as possible, on increased carbon sequestration in the biosphere, including primarily the protection and restoration of forests and other carbon- and biodiverse rich natural ecosystems, and sustainable agricultural practices. Whilst bioenergy is already playing a role in the energy transition in some countries, its use must be strictly limited and regulated to avoid social and environmental harm. Displacement of communities due to land grabs for massive cultivation of bioenergy crops is a key concern for many developing countries. There are also serious concerns on permanence and food security around afforestation in many countries, as well as on the overall net benefits of carbon sequestration when converting unutilized grasslands/savannahs and other lands for energy crops.
- 8. DACCS is in its infancy and is very costly and energy intensive, with serious doubts about its effectiveness.** DACCS poses significant challenges for energy use and there is currently insufficient evidence that it provides a feasible climate mitigation solution. Recent research revealed that for DAC removal in the US of about 850 Mt CO₂, (2% of global energy-related CO₂ emissions annually), the equivalent of almost all global present wind power would be needed,²⁰ or about 1000 TWh electricity representing *4% of all global electricity produced*. That approximates about 550 Mt CO₂ in the global electricity mix.²¹ Using present global power mix, DACCS would require about two third of a ton of CO₂ emissions to sequester one ton of CO₂. Or if using only renewables, it would significantly undermine renewable-based power sector decarbonization. Therefore, the potential larger expansion of DACCS in the near term runs counter to CAN's climate vision and would significantly delay efforts to achieve and maintain a 100% renewable energy system. DACCS is also not immune to the same CO₂ storage problems and concerns as other CCS applications. Any future consideration of DACCS as a potential means to reduce CO₂ emissions must address energy requirement concerns and alignment with the UN's Sustainable Development Goals.
- 9. Long-term CO₂ storage creates financial, liability, and climate risks that are highly likely to be transferred from the private sector to the public sector.** Liability questions for CO₂ storage have yet to be answered in many places, and most countries lack a governance structure to maintain and ensure the long-term fiscal integrity of CO₂ storage sites. Some proponents of CCS have sought to relieve private sector parties engaged in CCS of financial and legal liability by transferring risk to governments and/or incorporating liability limits into law. Even with strong financial security mechanisms in place, there is a risk that governments will ultimately be responsible for the long-term monitoring, management, and remediation of CO₂ storage sites.
- 10. Continued pursuit of CCS, for example in the power sector, risks diverting attention and resources from proven, cost effective solutions.**²² CCS is expensive, resources are limited, and

¹⁹ See Appendix 1.

²⁰ Larsen, J et al., Rhodium Group (2019). "Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology", p. 45. Available at: <https://rhg.com/research/capturing-leadership-policies-for-the-us-to-advance-direct-air-capture-technology/>

²¹ International Energy Agency (2019). *World Energy Outlook 2019*, p. 680.

²² See, e.g., Center for International Environmental Law (2019). *Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis*. February 2019. Available at: <https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/>; see also Ash, K. (2015). *Carbon*

time is of the essence. There is a risk that public and private monies spent supporting CCS may decrease funding available for solutions that can deliver safe and permanent emission reductions. This means the fossil fuel industry may adopt CCS as a strategy to maintain business as usual or expand operations, and potentially access climate subsidies.

- 11. CCS raises significant intergenerational equity concerns as well as environmental and social justice concerns.** CCS deployment would result in resource allocation decisions likely to undermine efforts to secure a just, equitable, and sustainable future. CCS also passes the responsibility for today's climate pollution onto future generations by requiring them to maintain and ensure the long-term integrity of CO₂ storage sites.

Climate Action Network position statement

CAN fully endorses a transition to 100% renewable energy for all energy use by mid-century at the latest²³ and adopts the following positions:

- 1. CAN strongly supports the Paris Agreement's goal to limit global average temperature rise to 1.5°C above pre-industrial levels, and believes that all sustainable solutions and strategies need to be implemented to achieve this goal. CAN does not consider currently envisioned CCS applications as proven sustainable climate solutions.** It is therefore imperative that actions to reduce emissions are maximised.
- 2. CAN calls upon all governments to phase out all fossil fuel production and use, and phase in 100% renewable energy, as quickly as possible but no later than mid-century.** Achieving the 1.5°C goal requires transformational change based on a managed phase-out of fossil fuel production, increased deployment of renewable energy, dramatic reductions in energy consumption, and greater efficiency along with substantial changes in production and consumption patterns at a much faster rate than what particularly governments of richer countries have pursued or committed to thus far.
- 3. All government subsidies, loans, grants, tax credit, incentives, and financial support for fossil fuels and technologies that use or otherwise support the continued use of fossil fuels, including CCS, should be phased out as soon as possible.** CAN opposes government support to the fossil fuel industry. CAN affirms that renewable energy, energy efficiency, smart grid technologies, and electricity storage provide the best value route to reducing emissions from electricity generation. Governments should rule out new fossil fuel investments, in line with a just transition and consistent with carbon budgets identified by the IPCC, to not exceed 1.5°C average global warming by the end of this century.
- 4. CAN believes and reiterates that radical action needs to be taken to reduce greenhouse gas emissions as quickly as possible.** In terms of negative emissions approaches, absolute priority should be given to increasing the capacity of natural carbon sequestration through the protection and restoration of forests and other natural ecosystems that maximise the co-benefits to people

Capture Scam: How a False Climate Solution Bolsters Big Oil. Greenpeace USA. July 2015. Available at: <https://www.greenpeace.org/usa/research/carbon-capture-scam/>.

²³ http://climatenetwork.org/sites/default/files/can_position_energy_ambition_in_ndcs_june2019.pdf

and biodiversity. **CAN cannot and will not support any effort to promote negative emissions or offsets as an alternative to stringent emission reductions.**

5. **CAN does not recognise BECCS as a proven large-scale mitigation option that delivers negative emissions, and does not support its deployment at any scale if it results in food insecurity, resource and land use conflicts, and detrimental biodiversity impacts.** Respect of human rights, which underpins the Paris Agreement, must not be compromised through the use of BECCS or any other climate mitigation tool.
6. **CAN supports proven sustainable strategies to address carbon emissions in the industrial sector.**²⁴ CAN sees no definitive evidence that CCS is the fastest, cheapest, cleanest and most durable way to decarbonise the industrial sectors, including the cement, iron ore-based steel and other metals, and chemical industries. For some of these industries, alternative technologies and solutions already exist and should be rapidly deployed. The promise of CCS must not delay necessary action in the present. Governments should start and expand R&D programs for these industries to have the solutions needed to adapt.
7. EOR/EGR combined with CCS utilises captured CO₂ to improve and enhance the exploitation of oil and gas fields. Such activities do not lower overall CO₂ emissions and contradict the need to keep the majority of remaining fossil fuel reserves in the ground. **CAN opposes such a practice.**
8. **CAN does not believe DACCS will be able to contribute to significant emission reductions in the coming years,** thus it has no place in decarbonisation scenarios focusing on early and steep CO₂ emissions reductions.
9. While certain CCU applications theoretically have the potential to mitigate climate emissions at scale (e.g., carbon fibers as substitute for steel), there are concerns regarding cost-effectiveness and environmental impacts. **At present, without additional mitigation incentives, further R&D, and a comprehensive review of potential environmental impacts, CCU is a mere detour for decarbonisation and unlikely to deliver mitigation in the order of gigatons of CO₂ needed to address climate change.**

²⁴ See Appendix 1.

Appendix 1- Carbon Capture, Storage, and Use Applications

This appendix provides a summary overview of the carbon capture, storage, and use applications discussed in this paper based on CAN's review of existing literature and reports. It provides detail on various potential applications for CCS technology, including limitations likely to prevent their safe, efficient and cost-effective deployment as a carbon mitigation or carbon removal technology. Whilst not exhaustive, this overview summarises the main issues associated with CCS and its deployment.

The following CCS applications are the subject of this paper:

- CCS in the power sector
- CCS in industry to capture process and smokestack emissions (also known as “industrial CCS”)
- Bioenergy with carbon capture and storage (BECCS)
- Direct air carbon capture and storage (DACCS)
- Carbon capture and utilisation (CCU), which is distinct to CCS due to the different end-of-life use for the captured CO₂: rather than sequestered in geological formations, captured CO₂ is converted into a new product.
- While not a type of CCS, EOR/EOG can be applied alongside CCS, having significant implications on its potential as a climate technology and is also discussed below.

CCS is an integrated process comprised of three distinct parts: carbon capture, transport, and storage (including measuring, monitoring, and verification).

- Capture technology collects CO₂ from a point source (e.g., power station smokestack) that can be compressed, transported, and stored.
- Transport of captured CO₂ is mostly likely to take place via pipelines, but could also be moved via ships, rail, and road.
- CO₂ storage is most likely to occur underground in geological sites on land or below the seabed of at least 800 meters (up to more than three kilometers) under a caprock. Whilst CO₂ disposal at the seafloor (ocean carbon sequestration) has previously been proposed by certain governments, this method has been largely discounted by UN-fora or even banned by many nations due to the significant impacts it would have on the ocean ecosystem and legal constraints that effectively prohibit it.²⁵

CCS Applications

A. CCS in the Power Sector

Fossil fuel power stations, particularly those that burn coal provide a large point sources of CO₂. Some power stations emit as much as 10 MtCO₂ or more per year, creating an economy of scale for capture, transport, and storage. CCS has a limited commercial track record in the power sector

²⁵ For example, the United Nations Convention on the Law of the Sea (UNCLOS), the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention), the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol, which will eventually replace the London Convention), and regional agreements such as the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention).

and associated costs for different capture technologies (e.g., amine-based post-combustion capture and oxyfuel combustion) remain high.²⁶

Power sector applications of CCS have several drawbacks, including increasing overall energy demand (which means burning more fossil fuels to produce the same amount of energy) and reducing power plant efficiency. For example, the energy penalty for pulverized coal power stations fitted with carbon capture can be 25% or more, whilst the efficiency penalty can be as high as 15%.²⁷ Such penalties mean more fuel has to be burned to produce the same amount of power, which has a host of implications related to energy costs, non-CO₂ air pollutants, and power station resource demands. In short, using capture technology on power stations increases costs, emissions of non-CO₂ air pollutants, power station water demand, and impacts associated with the mining, extraction, and transport of fossil fuels.²⁸

Even more importantly, from a climate perspective, carbon capture does not eliminate CO₂ emissions from fossil fueled power stations. Theoretically, CCS has the potential to reduce power station CO₂ emissions by as much as 90%. In practice, however, capture rates on most of the power stations fitted with capture technology have been much lower.²⁹ CCS also results in additional upstream or downstream emissions, including those generated upstream through the mining and transport of fossil fuels and the transport and storage of CO₂. When such emissions are accounted for, CCS results in even lower net capture rates over the life of a project.³⁰

Large-scale fossil fuel CCS power stations also risk running counter to and could hinder the transition to a 100% renewable energy system. Some argue that CCS can provide a climate solution while renewable energy is deployed worldwide, while others note the risk this strategy will incentivize or justify prolonged fossil fuel use. In general, coal-fired power plants have a limited technical ability to balance variable renewable energy resources like wind and solar. Coal CCS would therefore not improve this ability and could even constrain other fossil fuel power plants' capacity to serve as a flexible resource for technical and/or economic reasons.³¹

One of the crucial environmental impacts is enhanced water consumption by carbon capture applications in power plants. Freshwater is a scarce resource, a precondition for all life on Earth, and needs to be protected much more particularly in times of enhanced global warming and

²⁶ See, e.g., Lazard Ltd (2018). Lazard's Levelized Cost of Energy Analysis—Version 12.0. Lazard Ltd. November 2018. Available at: <https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf>, which shows the cost of CCS power stations relative to other energy technologies. Note that the Lazard LCOE analysis does not include costs for CO₂ transport, storage, and monitoring.

²⁷ Budinis, S., Krevor, S., MacDowell, N., Brandon, N., Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. *Energy Strategy Reviews*, Vol. 22, November 2018, pp. 61-81. <https://doi.org/10.1016/j.esr.2018.08.003>.

²⁸ See, e.g., Newcastle University, Institute for Sustainability, Impact of carbon capture & storage on water, available at: <https://www.ncl.ac.uk/sustainability/ourresearch/excellence/water/ccs/> (accessed 1 February 2020).

²⁹ See, e.g., Schlissel, D. (2019). IEEFA op-ed: Reality of carbon capture not even close to proponents' wishful thinking. Guest editorial in *Denver Post*. 8 August 2019. Available at: <https://ieefa.org/reality-of-carbon-capture-not-even-close-to-proponents-wishful-thinking/>.

³⁰ Jacobson, M. (2019). The health and climate impacts of carbon capture and direct air capture. *Energy & Environmental Science*, 12, 2019, pp.3567-3574. <https://doi.org/10.1039/C9EE02709B>.

³¹ Domenichini, R., Mancuso, L., Ferrari, N., Davison, J. (2013). Operating Flexibility of Power Plants with Carbon Capture and Storage (CCS). *Energy Procedia* vol. 37, pp.2727-2737. <https://doi.org/10.1016/j.egypro.2013.06.157>.

biodiversity decline. Carbon capture in coal and gas power plants can result in increased water consumption by 20% to 60% in the absence of water recovery options.³²

Economics is one of the primary reasons why CCS hasn't been more extensively deployed in the power sector. Outfitting new or existing fossil fuel power stations with CCS is very expensive, requires considerable space near the power plant for the capture device, and costs significantly more than zero emission renewable energy technologies per tonne of CO₂ avoided.³³ To-date, only few coal power plants capturing CO₂ emissions exist worldwide and a handful of gas power plant CCS projects are under development. Significantly, there is not a single commercial-scale power plant capturing and sequestering emissions for the purpose of climate mitigation at-scale anywhere in the world.³⁴

Considering the costs, especially without CO₂ restrictions or without a considerable CO₂-price well above €50-70 per ton of CO₂ which is two to three times the present carbon price in the European Emissions Trading System, no power producer would consider building a new fossil fuel power plant with CCS or retrofit an existing power plant for CCS. The economic case for CCS in the power sector, in the absence of public support and revenue from captured carbon sales to EOR/EGR operations, therefore rests on carbon pricing or government support. Studies have suggested that even a very high carbon price (e.g., greater than US\$50 MWh) would not guarantee that CCS is able to overcome current cost barriers.³⁵

Based on operational experience in the past decade, it is likely that CCS will not advance substantially in the power sector in the coming decade.³⁶ This leaves only niche applications for the technology, which would have to carry the full R&D, deployment, and infrastructure development costs.

I. Enhanced Oil and Gas Recovery

In its application with CCS, EOR describes the process of captured CO₂ being injected underground extract otherwise unreachable of oil and gas. EOR/EGR is not a new process,

³² Magneshi et al. (2017). Available at:

<https://reader.elsevier.com/reader/sd/pii/S1876610217319720?token=C460FDDC1C312BAFF5F2A4D447B5C7B7FE2981C45134C3B7DC842DBFC272B610EADC2405A8E9414C2EDE03E9D266406B>

³³ Jacobson, M. (2019). The health and climate impacts of carbon capture and direct air capture. *Energy & Environmental Science*, 12, 2019, pp.3567-3574. <https://doi.org/10.1039/C9EE02709B>.

³⁴ The Boundary Dam project in Saskatchewan, Canada is often touted as the world's first coal-fired CCS project. The project is a post-combustion retrofit of a single coal-fired unit that cost more than US\$1 billion; a large part of the project's cost was paid for with government funding. Boundary Dam has been plagued by operating difficulties and has had difficulty maintaining a high capture rate. What's more, captured CO₂ is sold to a nearby EOR operation rather than stored in a standalone geological formation. Schlissel, D. (2018). Holy Grail of Carbon Capture Continues to Elude Coal Industry. Institute for Energy Economics and Financial Analysis. November 2018. Available at: https://ieefa.org/wp-content/uploads/2018/11/Holy-Grail-of-Carbon-Capture-Continues-to-Elude-Coal-Industry_November-2018.pdf.

³⁵ Cost estimates for CCS often focus on the level of carbon price needed to make a power station fitted with carbon capture technology economic whilst discounting or ignoring the cost of transport, injection, storage, and storage site monitoring. See, e.g., Lazard Ltd (2018). Lazard's Levelized Cost of Energy Analysis—Version 12.0. Lazard Ltd. November 2018. Available at: <https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf>, which shows the cost of CCS power stations relatives to other energy technologies. Note that the Lazard LCOE analysis does not includes costs for CO₂ transport, storage, and monitoring.

³⁶ "...as far as the power sector is concerned the overall message seems to be that for the moment it is 'game over' for CCS, in the EU especially, with renewables offering a cheaper option." Elliott, D. (2018). Whatever happened to carbon capture? *PhysicsWorld*. 5 September 2018. Available at: <https://physicsworld.com/a/whatever-happened-to-carbon-capture/>.

and has been in commercial use since the 1970s. At present, EOR/EGR is one key aspect to the economic viability for CCS projects – most notably in the United States.³⁷

Estimates of the amount of CO₂ remaining underground when used in EOR/EGR operations vary widely. Nevertheless, the risk of leakage in such underground storage sites can also be significantly higher due to the existence of multiple wells that may or may not have been properly sealed.³⁸ Sound independent and scientific monitoring and verification activities at such sites, if they occur at all, are usually not transparent and information is rarely shared with the public. However, more than three quarters of the reportedly stored all CO₂ from CCS is based on EOR.

Lifecycle analyses of the CO₂ mitigation potential of CCS linked with EOR/EGR vary in their results primarily due to differing boundary definitions, which makes comparisons between studies difficult. Cradle-to-grave analyses that assess the net lifecycle emissions of CO₂-EOR projects from coal mining to product combustion conclude that CO₂-EOR projects have historically emitted more CO₂ than they have removed through geologic storage³⁹. In this way, EOR/EGR could perhaps be described as a CO₂ capture and release strategy whereby CO₂ captured from power station smokestacks is used to recover fossil fuel resources that may have otherwise remained underground that, when burned, release CO₂ back into the atmosphere. While EOR/EGR makes business sense for the fossil fuel industry, it is not a winning strategy for the climate.

B. Industrial CCS

Energy-intensive Industries and some with CO₂ process emissions are a large source of CO₂ emissions in some countries and are part of global supply chains. For example, the iron and steel industries use pure carbon-rich coking coal for reduction of iron ore (oxide) to metal and emits about 2 Gt CO₂ worldwide. Graphite electrodes for the electrolysis used in the production of aluminum are transforming to CO₂. The cement industry has to heat limestone, which then as process emissions emits vast amounts of CO₂. The entire cement making emits about 2.5 Gt CO₂ worldwide. Chemical and fertilizer industries produce polyethylene and Ammonia, respectively, two very energy-intensive processes from fossil fuels. - Other high-emitting industries include paper and pulp production and oil refineries.

While industrial CCS is promoted by some as a key feasible strategy to decarbonize industry, a wide range of solutions for net zero industry are emerging including increased material efficiency, material recirculation and new production processes. Different approaches, alternative materials, and R&D, particularly into new processes have the potential to eliminate the need for CCS in this

³⁷ Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: <https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/>.

³⁸ See Appendix 1.

³⁹ See, e.g., Jaramillo, P., Griffin, W. M., McCoy, S. T. (2009). Life cycle inventory of CO₂ in an enhanced oil recovery system. *Environmental Science & Technology*, vol. 43, pp.8027–8032. <https://doi.org/10.1021/es902006h>. Other lifecycles analyses have indicated that CO₂-EOR may reduce carbon emissions, or result in net negative emissions, for all or some portion of a CO₂-EOR project's life but the boundaries for these analyses are usually not cradle-to-grave. For a gate-to-grave lifecycle analysis along these lines, see Núñez-López, V., Gil-Egui, R., Hosseini, S. A. (2019). Environmental and operational performance of CO₂-EOR as a CCUS technology: a Cranfield example with dynamic LCA considerations. *Energies*, vol.12(3), p 448. <https://doi.org/10.3390/en12030448>.

sector. Iron ore, for example, can be mined less with better recycling and recovery methods. Alternative production processes are also being trialed, which could eliminate the need for coal, such as the iron ore reduction using renewably-produced hydrogen obtained through the electrolysis of water.

Aluminum can also be produced either with renewably-produced hydrogen or with inert electrodes instead of graphite electrodes. For the cement industry, alternative binders such as geopolymers (clays), pozzolanic (volcanic ash, ash from coal combustion), slag and magnesium-based cements can be used instead of CO₂-emitting Portland cement to make concrete. A greater focus on waste prevention, alternative sustainable bio-based materials, along with reuse and recycling, can reduce or eliminate the need to incinerate household and other wastes that contain a large fraction of plastics.

Further, district heating plants, steel mills, paper mills, and industrial heating plants are far from ideal for CCS. Such facilities tend to be much smaller in size than power stations and can be widely dispersed. Capture and transport costs will therefore be proportionally higher. A typical district combined heat and power or industrial heating plant is between 1 and 100 MW; and each plant would require a separate engineering design, environmental impact assessment, permitting, and financing process.

Given that current CCS costs make the economics for a single 2 GW coal power plant producing 10 MtCO₂ per year challenging, CCS is even less likely to be economically feasible for 100 smaller plants located anywhere from 10 to 100 (or more) kilometers apart. Proponents of CCS clustering in Europe have asked for grants, subsidies, and loan guarantees for projects that would share infrastructure and costs to make them economically viable and financeable.⁴⁰

C. Bioenergy with Carbon Capture and Storage

BECCS envisions the use of plants, such as trees or agricultural crops, to naturally remove CO₂ from the atmosphere; the subsequent burning of such plants to produce electricity (or heat); and the capture and storage of any emissions produced in connection with energy transformation activities. It has gained attention in recent years as a potential negative emissions strategy, and features prominently in a number of decarbonisation pathways.⁴¹ Some studies question the carbon neutrality claim of biomass⁴² as well as the negative emissions claims of BECCS.⁴³

⁴⁰ See Duruset, E. (2017). Deployment of an Industrial CCS Cluster in Europe: A Funding Pathway. i24c. 7 August 2017. Available at: http://i2-4c.eu/wp-content/uploads/2017/10/Deployment-of-an-industrial-CCS-cluster-in-Europe_v2.2_final_web.pdf.

⁴¹ As noted by Carbon Brief, “[i]n little more than a decade, BECCS had gone from being a highly theoretical proposal for Sweden’s paper mills to earn carbon credits to being a key negative emissions technology underpinning the modelling, promoted by the IPCC, showing how the world could avoid dangerous climate change this century.” CarbonBrief (2016). Timeline: How BECCS became climate change’s ‘saviour’ technology. Carbon Brief. 13 April 2016. Available at: <https://www.carbonbrief.org/beccs-the-story-of-climate-changes-saviour-technology>.

⁴² See, e.g., Southern Environmental Law Center (2019). Fact Sheet: New Report Shows Wood Pellets from Drax’s U.S. Mills Increase Carbon Emissions During the Timeframe Necessary to Address Climate Change. Southern Environmental Law Center. 8 August 2019. Available at: https://www.southernenvironment.org/uploads/publications/2019-08-08_FINAL_Biomass_Factsheet_Drax_SIG_Report_Updated1.PDF.

⁴³ Harper, A.B., Powell, T., Cox, P.M. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nature Communications 9, 2938 (2018). <https://doi.org/10.1038/s41467-018-05340-z>.

Furthermore, many experts and scientists have highlighted ecological, water and resource constraints and competition with food production which would limit its deployment.⁴⁴

A single BECCS pilot project which is burning 100% biomass feedstock exists globally and has been capturing about a tonne of CO₂ (but not storing) per day since 2019 at the Drax Power Station in the UK.⁴⁵ The Drax Power Station is a coal- and biomass-fired power station, and the UK's largest source of CO₂ emissions. The power station is also the world's single biggest burner of biomass (burning more wood than the UK produces annually).⁴⁶ The company that owns the Drax Power Station receives more than >£2.1 million in public subsidies per day to support its wood burning activities.⁴⁷ Whilst the company has signaled its intent to expand its use of BECCS at the power station, such plans are contingent on the continuation of public subsidies as well as "an effective negative emissions policy and investment framework."⁴⁸

Whilst biomass is an abundant resource, its use in the energy section should be limited given concerns about potential climate benefits as well as competing demands on land and water, especially for food production and the protection of forests and natural ecosystems. In many parts of the world, biomass production often involves land use conflict between many different interests from food to biodiversity, transport fuels, industry, as building material, power, and heat.⁴⁹ Combining biomass with CCS at a large scale is likely to exacerbate existing issues.⁵⁰ Studies on deploying BECCS at scale envisioned raises significant concerns related to land use, food security, water use, and biodiversity impacts:

- **Land use.** Estimates vary, but models have estimated millions to a billion (or more) hectares would be needed to produce sufficient biomass to achieve BECCS's share of emission reductions in many climate pathways.⁵¹

⁴⁴ See, e.g., Smith, P., Davis, S., Creutzig, F. et al. Biophysical and economic limits to negative CO₂ emissions. *Nature Clim Change* 6, pp.42–50 (2016). <https://doi.org/10.1038/nclimate2870>; see also Smith, L.J., Torn, M.S. Ecological limits to terrestrial biological carbon dioxide removal. *Climatic Change* 118, pp.89–103 (2013). <https://doi.org/10.1007/s10584-012-0682-3>.

⁴⁵ Drax Group plc (2019). Carbon dioxide now being captured in first of its kind BECCS pilot. Press Release issued 7 February 2019. Available at: https://www.drax.com/press_release/world-first-co2-beccs-ccus/.

⁴⁶ Biofuelwatch (2019a). Drax Plc: Harming Forests, Climate and Communities. April 2019. Available at: <https://reclaimthepower.org.uk/uncategorized/drax-power-station-burning-all-the-things/>.

⁴⁷ Biofuelwatch (2019b). Campaigners Call on Government to Stop Drax from Fuelling Environmental Injustice, Forest Destruction and Climate Breakdown. Press Release issued 9 October 2019. Available at: <https://www.biofuelwatch.org.uk/2019/drax-protest-pr-2/>.

⁴⁸ Fawthrop, A. (2019). Drax to deploy BECCS technology to become carbon-negative by 2030. NS Energy. 10 December 2019. Available at: <https://www.nsenergybusiness.com/news/company-news/drax-carbon-negative/>.

⁴⁹ See, e.g., European Environment Agency (2016). Land use conflicts necessitate integrated policy, available at: <https://www.eea.europa.eu/highlights/land-use-conflicts-necessitate-integrated-policy> (accessed 1 February 2020).

⁵⁰ The Illinois Industrial Carbon Capture and Storage Project in Decatur, Illinois which involves capture of CO₂ from ethanol production and storage in Mount Simon Sandstone Reservoir, for example, involves massive industrial monocropping that could compete with food production and add pressure on land and water resources when adopted at scale globally as a mitigation approach. See Greenberg, S. (2018). Illinois Basin Decatur Project - Sharing practical lessons learned about moving from pilot to large-scale demonstration. Presentation, available at: <http://conference2018.co2geonet.com/media/28835/10-greenberg.pdf>.

⁵¹ For example, "[i]n the Integrated Assessment Model scenarios consistent with a 2 °C target, a median of 3.3 GtC yr⁻¹ was removed from the atmosphere through BECCS by 2100, equivalent to one-third of present-day emissions from fossil fuel and industry. This median amount of BECCS would result in cumulative negative emissions of 166 GtC by 2100 and would supply ~170 EJ yr⁻¹ of primary energy. The bioenergy crops to deliver such a scale of CO₂ removal could occupy an estimated 380–700 Mha of land, equivalent to up to ~50% of the present-day cropland area." Harper, A.B., Powell, T., Cox, P.M. et al. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. *Nature Communications* 9, 2938 (2018). <https://doi.org/10.1038/s41467-018-05340-z>.

- **Food security.** The demand for land area for BECCS deployment at scale corresponds to globally converting approximately 50% of arable land and permanent crops for biomass.⁵² Some studies have shown that as a result of decreasing land availability, BECCS could increase food prices and increase conflict for land, biomass, and water by putting pressure on limited natural resources.⁵³
- **Water use.** If implemented at scale, BECCS could more than double the amount of water currently used for irrigation in food production to support the growth of biomass for combustion.⁵⁴
- **Biodiversity.** If implemented at scale, BECCS has the potential to reduce biodiversity, especially if land areas are converted to monoculture plantations and/or use non-native plant species.⁵⁵

Like CCS as applied to fossil fuel power stations, BECCS also has to grapple with the same energy demand associated with CO₂ capture technology, transport issues, and identifying appropriate and permanent storage sites within reasonable proximity to the bioenergy facility.

D. Direct Air Carbon Capture and Storage

DACCS involves filtering CO₂ from ambient air which represents 0.04% of air by volume. This approach, whilst technically feasible, is in its infancy. As with BECCS, DAC is promoted by some for its potential to deliver negative emissions. Several companies are currently working to advance the technology, including Climeworks, Carbon Engineering, Skytree, and Antecy. Climeworks has advanced the farthest with a small-scale demonstration including in Switzerland, where captured CO₂ is used for various applications rather than stored.⁵⁶ In 2019, Carbon Engineering and Occidental Petroleum announced plans to build the world's first large-scale direct air capture plant, where captured CO₂ would be used for EOR.⁵⁷

Two key barriers to DACCS commercialisation are cost and energy demand. DACCS is currently very energy intensive and expensive because massive volumes of air must be filtered to capture any reasonable amount of CO₂. One study examining the potential of DACCS to help meet the Paris Agreement goal found that widescale deployment of DACCS would account for a full one-quarter of global energy demand for heat and power by the end of this century.⁵⁸ Cost estimates

⁵² *Ibid.*

⁵³ Stokstad, E. (2019). Bioenergy plantations could fight climate change—but threaten food crops, U.N. Panel warns. *Science*. 8 August 2019. Available at: <https://www.sciencemag.org/news/2019/08/bioenergy-plantations-could-fight-climate-change-threaten-food-crops-un-panel-warns>.

⁵⁴ Yamagata, Y., Hanasaki, N., Ito, A. et al. Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). *Sustainability Science* 13, pp.301–313 (2018). <https://doi.org/10.1007/s11625-017-0522-5>.

⁵⁵ Smith, P., Price, J., Molotoks, A., Warren, R., and Malhi, Y. (2018). Impacts on terrestrial biodiversity of moving from a 2°C to a 1.5°C target. 376. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. <https://doi.org/10.1098/rsta.2016.0456>.

⁵⁶ National Academies of Sciences, Engineering, and Medicine (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, Chapter 5 Direct Air Capture. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25259>.

⁵⁷ Rathi, A. (2019). Carbon Engineering is doubling its CO₂-capturing machine even before it's built. *Quartz*. 21 September 2019, available at: <https://qz.com/1713529/carbon-engineering-and-occidental-will-capture-1-million-tonnes-of-carbon-dioxide/>.

⁵⁸ Realmonde, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications* 10, 3277 (2019). <https://doi.org/10.1038/s41467-019-10842-5>.

vary widely and span an order of magnitude, from US\$100 to US\$1,000 per ton of CO₂, not including associated transport and storage costs.⁵⁹ Critically, these estimates represent the cost of CO₂ captured rather than the cost of net CO₂ removed from the atmosphere. Factoring in this cost tends to make DACCS the most expensive atmospheric CO₂ removal approach.⁶⁰

Overall, there are serious doubts about the effectiveness of DACCS given the tension between the need for high capture rates and the very low concentration of CO₂ in the atmosphere. Another potential barrier to widescale DACCS deployment is pollution concerns associated with the chemical sorbent manufacture at “vast scales” to capture CO₂ from the atmosphere.⁶¹ Also a point of concern is the fact that DACCS has attracted attention and investment from the oil and gas sector, which views the technology as a potential source of CO₂ for EOR/EGR operations.⁶²

E. Carbon Capture and Utilisation

CCU covers a variety of processes which involve the absorption or conversion of CO₂ during the manufacture of usable product. For example, CO₂ can be utilised as a chemical feedstock or input to produce products, like synthetic fuels. CO₂ could be also used to fertilise algae or increase CO₂ levels in greenhouses to boost plant growth. It is also possible to use CO₂ to produce carbon fibers as a substitute for many materials and applications containing other mineral fiber components⁶³.

Theoretically, CCU is a promising technology which, depending on its application, may support achieving the 1.5°C target. However, many CCU applications are in the early research phase and very far from commercialisation. Costs and market size are also difficult to assess at this stage.⁶⁴ However, it is clear that the volume of CO₂ that would need to be captured far outpaces potential uses in industrial and other applications, including EOR/EGR operations.⁶⁵

Because CCU typically results in the re-release of captured GHG emissions, its potential is limited to a carbon neutral technology. Further, some processes that use CO₂ as a chemical intermediary, such as the production of synthetic fuels have limited or no value from a climate mitigation perspective. Only CCU processes that integrate and permanently store CO₂ would have the

⁵⁹ Ishimoto, Y., M. Sugiyama, E. Kato, R. Moriyama, K. Kazuhiro Tsuzuki, and A. Kurosawa (2017). Putting costs of direct air capture in context. Forum for Climate Engineering Assessment Working Paper Series: 002. Washington, DC: American University School of International Service.

⁶⁰ National Academies of Sciences, Engineering, and Medicine (2019). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, Chapter 5 Direct Air Capture. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25259>.

⁶¹ Realmonte, G., Drouet, L., Gambhir, A. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications* 10, 3277 (2019). <https://doi.org/10.1038/s41467-019-10842-5>.

⁶² Center for International Environmental Law (2019). Fuel to the Fire: How geoengineering threatens to entrench fossil fuels and accelerate the climate crisis. February 2019. Available at: <https://www.ciel.org/reports/fuel-to-the-fire-how-geoengineering-threatens-to-entrench-fossil-fuels-and-accelerate-the-climate-crisis-feb-2019/>.

⁶³ The problem with light weight carbon fibers is their very high energy need when produced from virgin materials but they presently have very low re-cyclability. Since they hardly decompose because of their physio-chemical inertness, products with carbon fibers end mostly in landfills. The opportunity for carbon fibers lies in the reusability of the product in case the physical shape does not change, like plane and car envelopes.

⁶⁴ IOGP (2019). The potential for CCS and CCU in Europe at 3. Report to the 32nd meeting of the European Gas Regulatory Forum 5-6 June 2019. Available at: https://ec.europa.eu/info/sites/info/files/iogp_-_report_-_ccs_ccu.pdf.

⁶⁵ Group of Chief Scientific Advisors (2018). Novel carbon capture and utilization technologies. European Commission Directorate-General for Research and Innovation. May 2018. Available at: https://ec.europa.eu/research/sam/pdf/sam_ccu_report.pdf.

potential to mitigate and or remove CO₂ emissions albeit with varying concerns associated in specific applications.⁶⁶

Carbon Dioxide Storage

Globally, experience with the long-term underground/sub-seabed storage of CO₂ through CCS applications is limited. The longest running CO₂ storage project in the world, the marine Sleipner oil field in Norway, has only been operational since 1996 and is still actively injecting CO₂.⁶⁷ The IPCC noted in 2005 that the fraction of CO₂ retained in such geological reservoirs is “very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years.”⁶⁸ Whilst the existence of naturally occurring carbon dioxide deposits provides an indication on the permeance of storage through CCS, issues concerning CO₂ leakage risks, governance and storage capacity inform on the challenges of CCS technologies. While a 2005 special report from the IPCC⁶⁹ assessed the CO₂ storage as safe, some scientists⁷⁰ and some NGOs (footnote) seeing large risk with storage facilities like Sleipner and in the North Atlantic in general.

A. CO₂ Leakage

For CCS to serve as a safe, effective mitigation tool, captured carbon must be injected and stay underground permanently.⁷¹ The IPCC had shown in its Fifth Assessment Report in 2013 that up to 40% of atmospheric CO₂ stays there for at least 1000 years. Therefore, even very low leakage rates over long periods of time could negate the climate benefits of CCS. For example, a leakage rate of 0.1% per year would release 73% of stored CO₂ from a storage site over 1,000 years.

As long as CO₂ is present in geological formations, there is a risk of leakage. In contact with water, CO₂ becomes a weak but permanent acid and therefore corrosive and can compromise the integrity of caprocks, well casings, and cement plugs. Undetected fractures and abandoned, improperly, or unsealed wells (in the case of depleted oil and gas fields) can also provide an avenue for CO₂ to escape. Remediation for CO₂ leaks may be possible but there is no track record or cost estimate for such measures.

Whilst leakage rates in appropriately selected and maintained storage sites particularly in the sub-seabed⁷² are likely to be limited, such sites are a limited resource and will not be distributed evenly

⁶⁶ For example, CO₂ can be used to “cure” cement, or in the manufacture of aggregates. Doing so stores some CO₂ for the long term and could displace emissions-intensive conventional cement but does not offset all emissions from the cement production process.

⁶⁷ See Appendix 2 for a discussion of potential leakage risk in the Sleipner formation.

⁶⁸ IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

⁶⁹ The IPCC noted in 2005 that the fraction of CO₂ retained in such geological reservoirs is “very likely [above 90% certainty] to exceed 99% over 100 years and is likely [above 60% certainty] to exceed 99% over 1000 years; IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

⁷⁰ <https://www.airclim.org/acidnews/myths-about-carbon-storage-%E2%80%93-sleipner-case>

⁷¹ Therefore, national CCS laws (e.g., Germany) assume zero leakage. If leakage occurs - in contrary to this assumption - the operator of the storage site has to start measures to stop this.

⁷² Vielstädte, L. et al, “Footprint and detectability of a well leaking CO₂ in Central North Sea: Implications from a field experiment and numerical modeling”, International Journal of Greenhouse Gas Control, Vol 84, May 29, pp. 190-203 <https://doi.org/10.1016/j.ijggc.2019.03.012>, available in: <https://www.sciencedirect.com/science/article/pii/S1750583618304857>

across the globe.⁷³ Moreover, significant uncertainty remains in estimates of potential leakage risk.⁷⁴ Depleted oil and gas fields, including those used in EOR/EGR operations, are one type of storage site used by CCS applications. These storage sites tend to be very well characterised but the multiple bore holes and wells drilled in them to find and extract oil and gas increase the risk of leakage.

The increased risk is due, in part, to what may be labeled as a lack of diligence on the part of the oil and gas industry to clean up after itself. Many wells in oil and gas fields are improperly sealed or not sealed at all. For example, an investigation conducted by the Associated Press (AP) in the wake of the British Petroleum Deepwater Horizon disaster found that oil companies “routinely circumvented” regulations for temporarily abandoned wells. More than 1,000 temporarily abandoned wells in Gulf of Mexico “lingered in an unfinished condition for more than a decade.”⁷⁵ In that same AP investigation, whilst an oil company representative insisted that it was in everyone’s interest to seal wells and to do so properly, state officials estimated that “tens of thousands [were] badly sealed, either because they predate[d] strict regulation or because the operating companies violated the rules.”⁷⁶

Aside from compromising climate mitigation efforts, depending on volume and concentration, CO₂ leakage also has the potential to contaminate ground and surface waters, impact soil ecology and the marine environment, and harm human health. A natural example of the danger of CO₂ leakage occurred in a volcanically active area at Lake Nyos in Cameroon in 1986. Large quantities of CO₂ that had accumulated at the bottom of the lake were suddenly released, killing 1,700 people and thousands of cattle over a range of 25 kilometres.⁷⁷

B. Liability for CO₂ Storage

Another barrier to CCS deployment is the question of who is liable for CO₂ once it is stored underground. The answer to this question determines who is likely responsible for monitoring a CO₂ storage site, remediating CO₂ leaks to the extent possible, providing financial security, and paying for any “harm” to the climate, private property, environment, human health, etc. in the event something goes wrong. It is for these reasons that public opposition to onshore CO₂ storage further limits opportunities to deploy CCS. Due to concerns regarding leakage and seismic events,⁷⁸ communities have mobilised to stop CO₂ storage projects from going forward. Public acceptance for onshore CO₂ storage, in particular, is limited in Europe, with storage projects

⁷³ IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

⁷⁴ Anderson, S.T. (2017). Risk, Liability, and Economic Issues with Long-Term CO₂ Storage—A Review. *Natural Resources Research* 26, pp.89–112 (2017). <https://doi.org/10.1007/s11053-016-9303-6>.

⁷⁵ Donn, J. and Weiss, M. (2010). Gulf awash in 27,000 abandoned wells. Associated Press. 7 July 2010. Available at: <https://www.cbsnews.com/news/27000-abandoned-gulf-oil-wells-may-be-leaking/>.

⁷⁶ *ibid*. The article also mentions a 2006 report from the US Environmental Protection Agency regarding wells on land. The report notes that, “[h]istorically, well abandonment and plugging have generally not been properly planned, designed and executed.”

⁷⁷ Diesendorf, M. (2006). Can geosequestration save the coal industry?, in J Byrne, L Glvoer & N Toly (eds), *Transforming power: Energy as a social project*, Energy and Environmental Policy Series vol. 9, 2006, pp. 223-248.

⁷⁸ Under pressure, CO₂ is an extremely efficient lubricant and may create earthquakes. According to the US National Academy of Sciences, “[l]arge-scale CCS may have the potential for causing significant induced seismicity.” National Research Council (2013). *Induced Seismicity Potential in Energy Technologies* at 12. Washington, DC: The National Academies Press. <https://doi.org/10.17226/13355>.

scrapped in the Netherlands and Denmark as companies have failed to persuade residents that the benefits outweigh the risks.⁷⁹

Industry actors are often unwilling to invest in CCS unless they are protected from the risks associated with long-term CO₂ storage. Concerns over liability are so great that utilities are often unwilling to make CO₂ available for storage unless they are relieved of ownership upon transfer of CO₂ from the power station. Others have urged that their legal liability for stored CO₂ be limited to defined periods of time, e.g. 10 years. In some countries, efforts to limit the liability of those engaged in CCS have included liability caps, federal indemnity programs, and a complete transfer of liability from the private to public sector.⁸⁰

Long-term CO₂ storage over hundreds or even thousands of years hands over our climate responsibility to a plethora of future generations - it also raises questions about whether regulatory frameworks can appropriately manage and allocate risk throughout every phase of a CO₂ storage project. These questions remain unanswered as the world has limited experience with CO₂ storage (particularly sub-seabed) and CCS regulatory frameworks that exist are largely untested. In 2009, the European Union (EU) established “a legal framework for the environmentally safe geological storage” of CO₂.⁸¹

This framework creates a risk-based approach for CO₂ storage to prevent and eliminate environmental and public health risks as much as possible. This is a laudable goal but will be difficult to achieve in practice. To-date, the permitting framework for CO₂ storage has been infrequently used with a handful of permit applications submitted for review and only two storage permits issued.⁸² The effectiveness of the framework’s financial security mechanism, which includes provisions to ensure storage operations provide funding to maintain storage sites through their operation and post-closure phases, remains to be seen. How much funding will be needed, for example, to support long-term monitoring and mitigation is unknown. The risk of inadequate funding is significant with industry lobbying for lower funding requirements.

C. CO₂ Storage Capacity

Many CCS reports and studies assume abundant global or regional capacity to store captured CO₂. In Europe, for example, some have previously claimed the North Sea can store 1,000 years of CO₂ emissions.⁸³ Taking such claims at face value, is risky, as these types of top-down estimates of

⁷⁹ The Barendrecht onshore CO₂ storage project was cancelled by the Dutch government in 2010 due, in large part, to local opposition to the project. Carbon Capture & Sequestration Technologies @MIT (2016). Barendrecht Fact Sheet: Carbon Dioxide Capture and Storage Project. Available at: <https://sequestration.mit.edu/tools/projects/barendrecht.html> (accessed 1 February 2020); see also Acid News (2016), CCS sidelined by public oppositions, No.1, April 2016. Available at: <https://www.airclim.org/acidnews/ccs-sidelined-public-opposition>.

⁸⁰ Havercroft, I. and Macrory, R. (2014). Legal Liability and Carbon Capture and Storage: A Comparative Perspective. October 2014. Available at: https://sequestration.mit.edu/pdf/GHGT8_deFigueiredo.pdf.

⁸¹ Directive 2009/31/EC.

⁸² European Commission (n.d.). Implementation of the CCS Directive. European Commission. Available at: https://ec.europa.eu/clima/policies/innovation-fund/ccs/implementation_en (accessed 5 September 2019).

⁸³ Equinor (2019). Here’s how your CO₂ emissions can be stored under the ocean, available at: <https://www.equinor.com/en/magazine/carbon-capture-and-storage.html> (accessed 1 February 2020).

CO₂ storage capacity (e.g. the 2,000 Gt CO₂ in IPCC SR CCS, 2005) are largely estimates of theoretical rather than effective or practical capacity.⁸⁴

Theoretical storage capacity estimates are of limited use as they do not account for a variety of site-specific factors, including pore space availability and injectivity, which are a critical in evaluating the suitability of a geological formation for CO₂ storage. Injectivity refers to the rate at CO₂ can be injected through a well into a formation and is based on how much pressure can be increased within a formation without compromising site (e.g., caprock) integrity. Injectivity is poorly understood in most geological formations and has significant cost implications for CO₂ storage.⁸⁵ Such estimates also fail to account for the fact that potential CO₂ storage locations are not evenly distributed. Co-location of captured CO₂ and potential storage locations has economic implications for the cost of CO₂ transport and storage.

When such factors are evaluated, top-down capacity estimates are frequently revised drastically downwards. For example, the Utsira formation where the Sleipner CO₂ storage project operates had “practically unlimited” storage potential and could handle CO₂ emissions from “all power stations in Europe for the next 600 years.”⁸⁶ However, after an in-depth study, the Norwegian Petroleum Directorate downgraded the storage capacity estimate for the Utsira formation from “able to store all European emissions for hundreds of years” to “not very suitable.”⁸⁷

⁸⁴ Bjureby, E., Rochon, E., Gulowsen, T. (2009). Reality Check on Carbon Storage. Greenpeace International. May 2019. Available at: http://www.globalislands.net/greenislands/docs/norway_reality-check-on-carbon-storage.pdf.

⁸⁵ Whiriskey, K. (2014). Scaling the CO₂ storage industry: A study and a tool. Bellona Europa. November 2014. https://bellona.org/assets/sites/4/Scaling-the-CO2-storage-industry_Bellona-Europa.pdf.

⁸⁶ Bjureby, E., Rochon, E., Gulowsen, T. (2009). Reality Check on Carbon Storage. Greenpeace International. May 2019. Available at: http://www.globalislands.net/greenislands/docs/norway_reality-check-on-carbon-storage.pdf.

⁸⁷ *Ibid.*

Appendix 2- Brief History of CCS (2001-2017): Expectations and Results

High hopes were pinned on CCS in the first decade of the 2000s after, among other things, promising results from the Sleipner storage site in Norway where roughly 1 MtCO₂ have been injected per year since 1996.⁸⁸ CCS garnered strong support from the US under the Bush administration, the EU, and governments in the UK, Canada, Australia, and Germany. The UN General Secretary (and Angela Merkel) appointed the Vattenfall CEO Lars G. Josefsson, a leading coal apologist and CCS champion, as climate advisor. The EU enacted legislation aimed at supporting 10-12 operating CCS demonstration projects (mostly power plants, but also for industrial process emissions) by 2015 and Norway's Prime Minister Stoltenberg claimed 2007 that CCS was that country's "moon landing" project.

Support for CCS only grew following the release of the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC Report) in 2005.⁸⁹ The IPCC Report claimed that "in /most scenarios/ in a least-cost portfolio of mitigation options, the economic potential of CCS would amount to 220–2,200 Gt CO₂ ... cumulatively, which would mean that CCS could contribute 15–55% to the cumulative mitigation effort worldwide until 2100".⁹⁰ The IPCC Report also stated that it was "likely" that at least about 2,000 Gt CO₂ geological storage capacity existed. Almost every major power company believed coal was an inevitable part of the future, and the only way to make the continued use of coal consistent with efforts to lower global greenhouse gas emissions was through CCS.

The European Commission summed up the global mood on CCS in May 2008: "[i]ntroducing CCS may delay the need to reduce levels of fossil fuel use by at least half a century."⁹¹ At the time, the conventional wisdom was that:

- Renewables were too expensive and CCS would be a bridge technology whilst alternatives to fossil fuels are further developed and deployed."
- There was a strong link between economic growth and energy growth, especially electricity consumption, so energy efficiency was a limited option.
- There was no realistic option and no major political power to stop coal growth, so the fuel shift option (from coal to gas) was limited.
- 550 ppm CO₂ and higher was considered as mitigation. The ultimate objective of UNFCCC in Art. 2 was only operationalised and adopted at COP 16 in 2010 ("2-degree limit"). At the G8-Summit in Heiligendamm (2007) there were intense discussions on the 2-degree limit but no consensus could be found as US-President Bush objected to that.

Since the early 2000s, however, a lot has changed in the energy landscape. World CO₂ emissions have decelerated to <0.5% growth per year between 2013 and 2017, compared to 2.5% the previous 10 years. Electricity consumption has more or less stabilized in major economies such as the US, EU, and Japan. Coal use in the power sector declined in the OECD from >4000 TWh to <3000 TWh between 2007 and 2017.

⁸⁸ The Sleipner project in Norway strips CO₂ that is co-produced with a natural gas stream from a field in the North Sea. The CO₂ is then re-injected below the seafloor in a saline aquifer in order to avoid payment of a CO₂ tax.

⁸⁹ IPCC (2005). IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

⁹⁰ *Ibid.*

⁹¹ See, e.g., European Commission DG ENV (2008). News alert, Issue 105, May 2008. Available at: https://ec.europa.eu/environment/integration/research/newsalert/pdf/105na3_en.pdf.

New coal power has become a no-go in an increasing number of countries whilst a great deal of existing coal capacity has been phased out. CCS was presented as a “bridge technology” but as renewables have surged ahead, CCS has barely advanced. Renewable energy deployment is now booming across the globe thanks to significant cost declines. Wind power production, for example, has grown by a factor of more than 10 since the IPCC report was released in 2005- from 104 TWh 2005 to about 1,400 TWh in 2019⁹². Yet, wind and solar energy combined are presently responsible for only nearly 9% of global electricity and about 1.5% of global final energy demand, still far too low and much too slow than what could bring the world to an alternative path.

Meanwhile, CCS has failed to advance despite billions in public support. In the US, for example, nearly half of the US\$2.6 billion spent by the US Department of Energy since 2010 to advance fossil fuel technologies was spent on CCS;⁹³ Australia has spent AUS\$1.3 billion on CCS since 2003;⁹⁴ the provincial government in Alberta is in the process of spending CA\$1.24 billion on two projects;⁹⁵ the UK spent £168 million on two failed CCS competitions and continues to allocate millions in public funds to CCS on an annual basis;⁹⁶ and despite passing the CCS Directive (2009/31/EC) and spending €424 million over 10 years, Europe has zero CCS demonstration plants to date.⁹⁷

Notable project failures and technical flaws include:

- In Salah—Poor management at the CO₂ storage site in Algeria resulted in the cessation of injection activities in 2011 after over-pressurisation of the formation fractured the caprock;⁹⁸
- FutureGen and Kemper—These high-profile US projects were cancelled after major cost overruns, delays, and technical issues;⁹⁹ and
- Mongstad—Norway’s “moon landing” CCS project was scrapped after cost overruns and delays.¹⁰⁰
- Sleipner—Discovery of fractures near the CO₂ storage site, discovered in 2012, have led to concerns that CO₂ could eventually leak;¹⁰¹

⁹² World Energy Outlook, IEA 2020

⁹³ Patel, S. (2018). DOE Sank Billions of Fossil Energy R&D Dollars in CCS Projects. Most Failed. Power. 9 October 2019. Available at: <https://www.powermag.com/doe-sank-billions-of-fossil-energy-rd-dollars-in-ccs-projects-most-failed/>.

⁹⁴ Brown, B., Swann, T. (2017). Money for Nothing. The Australia Institute. 30 May 2017. Available at: <https://www.tai.org.au/content/money-nothing>.

⁹⁵ Alberta (2020). Carbon capture and storage, available at: <https://www.alberta.ca/carbon-capture-and-storage.aspx>.

⁹⁶ Rathi, A. (2017). The UK could have changed the way the world fights global warming. Instead it blew \$200 million. Quartz. 2 May 2017. Available at: <https://qz.com/972939/the-uk-could-have-changed-the-way-the-world-fights-global-warming-instead-it-blew-200-million/>.

⁹⁷ Rathi, A. (2018). The EU has spent nearly \$500 million on technology to fight climate change—with little to show for it. Quartz. 23 October 2018. Available at: <https://qz.com/1431655/the-eu-spent-e424-million-on-carbon-capture-with-little-to-show-for-it/>.

⁹⁸ Spotts, P. (2014). Can we hide carbon dioxide underground? Algeria site offers note of caution. Christian Science Monitor. 27 May 2014. Available at: <https://www.csmonitor.com/Environment/2014/0527/Can-we-hide-carbon-dioxide-underground-Algeria-site-offers-note-of-caution>.

⁹⁹ Mississippi ratepayers are responsible for US\$1 billion of the cost of the failed Kemper project. Wilson, S. (2019). Two Years Since Kemper Clean Coal Project Ended. Mississippi Center For Public Policy. 17 July 2019. Available at: <https://www.msppolicy.org/two-years-since-kemper-clean-coal-project-ended/>.

¹⁰⁰ Holter, M. (2013). Norway Drops ‘Moon Landing’ as Mongstad Carbon Capture Scrapped. Bloomberg. 20 September 2013. Available at: <https://www.bloomberg.com/news/articles/2013-09-20/norway-drops-moon-landing-as-mongstad-carbon-capture-scrapped>.

¹⁰¹ Acid News (2018). Myths about carbon storage—the Sleipner case, No.2, June 2018. Available at: <https://airclim.org/acidnews/myths-about-carbon-storage-%E2%80%93-sleipner-case>. However, leaks have not yet been detected. Cavanagh, A. (2015). Statoil CO₂ storage experience: 20 years and 20 million tonnes; <http://conference.co2geonet.com/>. Presentation in Session 5 from the second day (12 May 2015).