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Review

Carbon capture and storage at the end of a lost decade

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SUMMARY

Following the landmark 2015 United Nations Paris Agreement, a growing number of countries are committing to the transition to net-zero emissions. Carbon capture and storage (CCS) has been consistently heralded to directly address emissions from the energy and industrial sectors and forms a significant component of plans to reach net-zero. However, despite the critical importance of the technology and substantial research and development to date, CCS deployment has been slow. This review examines deployment efforts over the last decade. We reveal that facility deployment must increase dramatically from current levels, and much work remains to maximize storage of CO_2 in vast subsurface reserves. Using current rates of deployment, CO_2 storage capacity by 2050 is projected to be around 700 million tons per year, just 10% of what is required. Meeting the net-zero targets via CCS ambitions seems unlikely unless worldwide coordinated efforts and rapid changes in policy take place.

INTRODUCTION

Carbon capture and storage (CCS), the suite of technologies to directly address CO_2 emissions at source, is widely regarded as a crucial component of efforts to meet national and international climate change mitigation goals through the safe storage and sequestration of carbon emissions. The International Energy Agency (IEA) and Intergovernmental Panel on Climate Change (IPCC) analysis outlines that CCS remains integral to the reduction of global emissions and the meeting of international climate goals.[1] The importance of CCS is made clear in the sustainable development scenario (SDS) of the IEA, which outlines the rapid transition to net zero.[2] The technology alone accounts for up to 15% of cumulative emissions reductions to meet the global target by 2050, behind only renewables and energy efficiency methods (with these three sectors accounting for around 70% between them by 2050[3]). To meet these targets, it is anticipated that around 5.6 gigatonnes per annum of CO_2 will need to be captured and stored by 2050 using CCS technologies.[4] However, despite this urgency, widespread roll-out of CCS remains slower than anticipated.[5,6] It is encouraging that there has been recognition of the importance of global climate ambitions with the submission of nationally determined contributions (NDCs) and long-term greenhouse gas (GHG) emissions strategies from a number of countries, many of which highlight a growing commitment to CCS methods.[7] Despite this, climate action efforts have fallen short of the internationally agreed targets, and it remains that individual government mitigation plans must be accelerated at a more rapid pace.

Efforts to establish CCS, originating with the G8's agreement in 2008 to enhance international cooperation on CCS and to target the launch of 10 large-scale CCS demonstration projects by 2010, failed to materialize on the scale required. The significant cost of implementing such large-scale facilities means initial political and financial commitments have fluctuated and waned, particularly around the issues of sharing financial risk and providing sufficient subsidy to make CCS projects viably competitive in their wider markets. After 50 years of CCS development[8] the number of large-scale facilities numbers 65, of which under half (26) are in operation, 2 have suspended operations, 3 are under construction, and 34 are in various other stages of development. It is forecast that, to reach the SDS levels outlined, the number of industrial-scale facilities needs to increase 100-fold—to more than 2000 by 2040.[1,4] Meeting this ambition poses a clear challenge and now requires a step-change in policy and coordinated worldwide action that has so far failed at scale.

The CCS landscape since 2009 has seen a vast change. The historical reality now informs us of what ignited the initial optimism for CCS and, importantly, what factors are at play that has hindered its progress. A major headline of the last decade is the move away from coal that meant a significant number of large-scale power plants, all set to be fitted with CCS capabilities, were never built. With this, there have been significant shifts in the nature of what we should be focusing investment on, such as CCS for industries that are especially hard to decarbonize (e.g., the cement and iron and steel industries), an emerging hydrogen economy, and new negative emission technologies that have taken a more central role. However, these new initiatives mean a refocusing of investments and time that is already limited, and the success of these new projects is reliant on full deployment, which inevitably takes time. Moreover, the

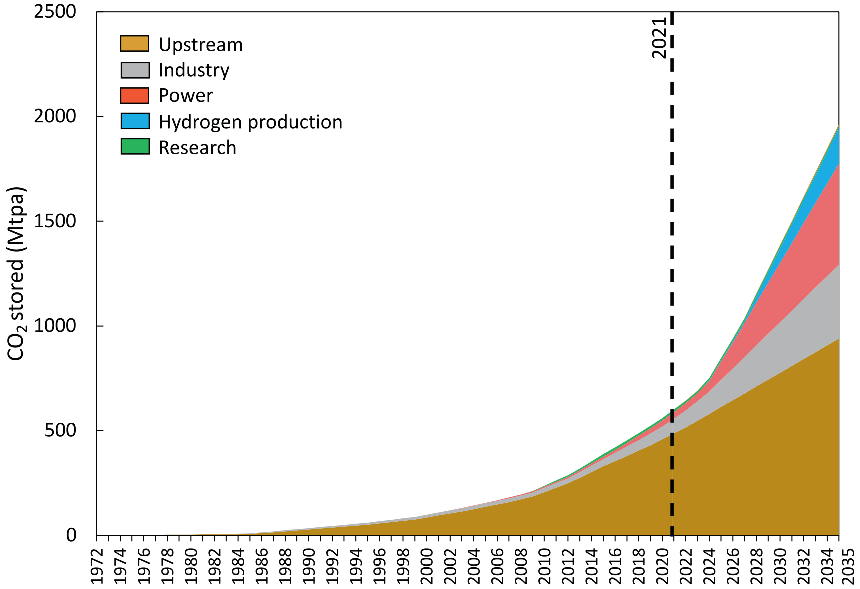

Figure 1. CCS deployment projects through time

Projects since 1972 and the projection to 2035. The black dashed line represents the current situation in 2021. Similar to the situation in 2009, the vast majority of current projects are in the upstream sector, predominantly natural gas-processing plants. This clearly shows that deployment in other sectors is urgently required if CCS is to mitigate the effects from the power and industry sectors, as is intended in the various IPCC scenarios.

fundamental role of CCS in providing an infrastructure capable of securely and permanently isolating many millions of tons of CO$_2$ away from the atmosphere, underpins the negative emission technologies of bioenergy with CCS (BECCS) and direct air capture with CCS (DACCS) that are being promoted. Therefore, CCS plays a critical role in enabling the 100% decarbonization that is required to achieve the net-zero emissions targets stipulated in the UN Paris Agreement.[9]

This review presents an overview of the status of CCS deployment efforts over the last decade and then provides a comparison with the optimistic outlook made in 2009. In understanding how facility deployment has progressed, we identify the lack of large-scale project roll-out compared with what is needed to meet net-zero targets and highlight the changing nature of CCS technology and investment. In further efforts to assess the future direction of CCS, we closely examine the global readiness for the required project deployment. We find that, with current rates of deployment, CO$_2$ storage capacity by 2050 is projected to be around 700 million tons per year, which is merely 10% of what is required. Such a result identifies the under-utilization of theoretically available storage capacity, and also indicates challenges associated with the vast subsurface reserves needed for the safe geological storage of CO$_2$. Our conclusions signal that the future effectiveness of CCS is dependent on a coordinated and direct approach ensuring initial policy design and investment facilitates and maintains the next generation of projects and beyond.

CCS STATUS OVER THE LAST 10 YEARS

The deployment of worldwide CCS projects

The IEA blue road map scenario[10] of 2009 signaled the optimism for the growth of, and deployment of, CCS facilities (Figure 1). Since that time, ambition has been relatively short lived, resulting in a considerable slowing of the rate of CCS facilities development.[11] Despite extensive research and development, many CCS initiatives have stalled and presently there appears to be no realistic sign of improvement in the near term.[5] Between 2010 and 2017, the number of facilities actively invested in CCS technology (early development, advanced development, under construction, or operating) declined from 77 to 37.[12,13] While encouragement is offered from the increase in active projects to 65 today[4] and the continued diversification and growth in the global portfolio of CCS facilities, the rate of successful deployment remains much slower than expected (Figure 1).

The optimism in 2009 was illustrated by the number of CCS projects planned to be in operation in the following decade.[14] However, this is very different to the number that have actually been deployed over this period. Ambitions for a multitude of large-scale plants to operate since 2010 have not been fulfilled[1,14] (Figures 2A and 2B). Anticipated reliance on pre- and post-combustion coal-power projects meant these dominated the planned developments from 2009 to 2021, but very few of these have subsequently been implemented. Previous predictions regarding the unlikelihood of all the planned projects materializing post-2010 have also proved realistic.[5,15] Of the 42 planned projects between 2009 and 2021, only 20 working facilities with CCS capability have been developed. Notably, not all of these facilities came from those that were planned, highlighting the changing direction in CCS policy and funding. Most demonstration projects have failed to transition into fully operating plants due to fluctuating markets, insufficient financial support, and the shift in emphasis to other fuels and technologies. Based on this, estimates of the emissions as a result of the projects that have not materialized, and a failure to directly sequester the produced CO$_2$, equates to around 475 Mt.

With the added cancelations to large-scale and demonstration projects such as the Texas Clean Energy Project (US), Longannet, Peterhead, White Rose, Kingsnorth, and Don Valley projects (all UK), and Compostilla (Spain), confidence and investment in CCS has inevitably wavered. Significant delays are also commonplace. The CCS component of the Gorgon Facility came online some 2 years behind schedule, and Lake Charles (US), Teeside Low Carbon (UK), and the Drax facility (UK) have all suffered years of setbacks adding to the slowdown of global ambitions.

It is reasonable to envisage meeting short-term climate targets by 2030–2035 through the closure of coal-powered facilities, the implementation and expansion of renewables and promoting energy efficiency without the need to rapidly develop CCS

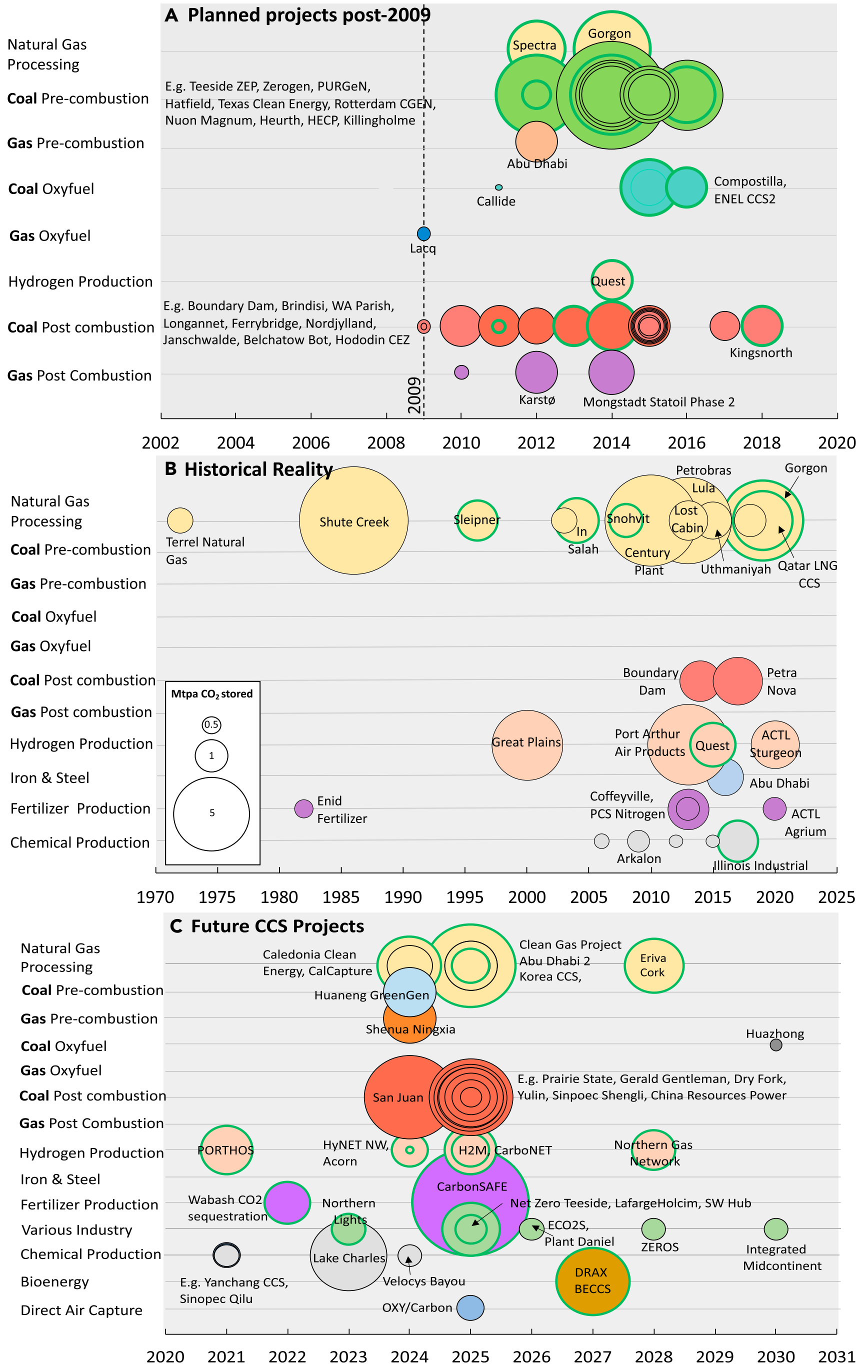

Figure 2. Nature of planned and future CCS projects

(A) Chart of large-scale CCS projects planned post-2009 worldwide, plotting year of planned operation against capture type and fuel. Coal and post-combustion power plants dominated (redrawn from Haszeldine et al.[14]).

(B) Chart displaying active large-scale CCS projects pre- and post 2009 showing what projects were actually fully deployed compared with the 2009 outlook.

(C) The future status and planning of large-scale CCS projects, which highlights the introduction of new capture techniques, e.g., Bioenergy and DAC. Black rimmed bubbles are EOR projects, green rimmed bubbles are dedicated storage projects.

technology. This may be a factor in the slow progress and re-direction of funding, but it is fast becoming a widely held view that, to remain on course to meet 2050 net-zero targets, CO_2 storage is still essential.[6,16,17,18] However, with the slow progress of facility development outlined here, maintaining its current pace means that it is increasingly unlikely that targets will be met. The failure at scale of CCS facility deployment may have significant implications for global temperatures in both the near and longer term. An overshoot in temperatures beyond 1.5°C would be expected unless accelerated growth of renewables such as solar and wind power facilities is forthcoming, along with significant changes in energy use behavior. The optimism that this can be achieved is not without caveats. Without CCS, vast additional investment would be required in renewables just to achieve the same level of reductions in emissions brought by CCS deployment and the onset of hydrogen production. For example, to meet net-zero emissions by 2050, the increases needed from solar and wind power, alongside CCS, are forecast to be 20 and 11 times that of today, respectively.[3]

Coal

The past decade has seen a significant shift in the nature of active and proposed CCS facilities. The move away from a reliance on coal, especially in Europe and the US, is the main driver leading to the reduction in the number of projects associated with the power sector. Since 2009, only two of the proposed coal-fired CCS power plants successfully passed into the operational phase (Boundary Dam in Canada and Petra Nova in the US).

Despite the growing expectation for a slowing of coal-power growth, mainly due to the increase in gas power plants and the emergence of cheaper and more efficient renewable energy, coal continues to be backed by some economies. Australia, China, and the US continue to promote its use with CCS through tax breaks and incentives. However, with the significant costs associated with fitting CCS technology to existing coal-power plants and plants operating well below predicted efficiency and capture rate targets, this approach may be short lived.[19,20] Examples of the financial burden applied to some coal plants comes from the failure of the Kemper County carbon capture facility and the recent mothballing of the CCS retrofit unit at the Petra Nova plant in Texas.[20] With oil price volatility impacting enhanced oil recovery (EOR) operations (and thus CO_2 price), the financial decision to power-down the Petra Nova CCS unit (responsible for the delivery of its captured CO_2 to the West Ranch oil field) means that only one coal-fired power plant with CCS remains working worldwide (that of Boundary Dam, Canada). Questions remain on the efficiency of coal-powered retrofit technology in light of the Petra Nova cancelation, suggesting that facilities of this nature may not be as financially viable as predicted.[20] Despite this, in countries where power generation is heavily reliant on coal (e.g., China and Australia), and options such as low-cost natural gas and renewables are so far limited, the retrofit of CCS technology to power plants must be stepped up if coal is to remain a player in future mitigation options. Although the logistical, financial, and policy decisions that it rests on will remain a significant barrier, the urgency to meet global emissions reductions targets means that CCS still needs to play a leading role in accelerating deployment to enable future change.

Natural gas processing

The injection of CO_2 from natural gas production has long been proven through the continued success of the Sleipner (injecting ~1 million tons per annum [Mtpa] since 1996) and Snøhvit (injecting ~700,000 tpa since 2008) facilities in Norway. However, since 2009, of the two proposed natural gas-processing projects (considered "upstream" in Figure 1), only Gorgon in Australia, although much delayed, has been successfully implemented. Despite recent criticism of the failure to meet their 5-year CO_2 sequestration target,[21] the project has stored 5 Mt since 2019, and while operations are now increasing, it is a reminder of how challenging large-scale mitigation efforts are. Spectra's Fort Nelson plant failed to materialize, but a number of other large CCS facilities have since been added, e.g., Century Plant, Jilin, Uthmaniyah, Qatar LNG CCS, and Petrobras Lula are all injecting in the region of 1 Mtpa or more[1,3] (Figure 2C). New projects in the pipeline, such as ADNOC's Abu Dhabi phase 2, set for operation in 2025 and aiming to capture ~5 Mtpa before 2030,[22] is further good news for expanding CCS using gas production plants. While it is encouraging that CCS is continuing to expand in this area and it is deemed critical to meet the net-zero targets of major oil and gas companies, it does not come without some caveats. Many of these projects are simply reinjecting CO_2, which is removed and captured from the subsurface during natural gas extraction. So, while enthusiasm for CCS exists in gas-processing plants, this only mitigates emissions associated with extraction of fossil fuels and does not address emissions produced by using the fossil fuels themselves.

Hydrogen

The promotion of hydrogen into the global energy mix is very much at the forefront of future policy design at present. While green hydrogen (production of H_2 by electrolysis using renewable energy) is favored by many, the present costs associated with it are around 2–3 times more than blue hydrogen[23] (H_2 production from fossil fuels coupled with CCS; previously referred to as "pre-combustion" CCS), providing incentives for blue hydrogen to play a significant role in decarbonization efforts. Projects are in the pipeline, for example, Equinor's plan to deliver the first government-backed blue hydrogen plant in the UK with CCS capabilities (H2H Saltend) is due by 2026. This may offer a timely catalyst for CCS to be embraced through the promotion of hydrogen projects such as this. While waiting for cost reductions and economies of scale in the wind and solar industries to make green hydrogen a more viable long-term option, there also seems to be a growing acceptance that the production of hydrogen from well-managed fossil fuels provides a faster track toward a greener hydrogen economy. With a clear view to maintaining the flow of hydrocarbons, Canada and the US have placed an emphasis on hydrogen production for the bitumen refining process (e.g., Quest, Port Arthur Air Products, and the newly introduced ACTL Sturgeon refinery). The captured CO_2 from these facilities is around 8.5 Mtpa, some of which is utilized for nearby EOR initiatives, although the Quest project undertakes dedicated geological storage of the produced CO_2 at ~1 Mtpa.

Industry

Capture from fertilizer manufacturing, iron and steel production, and chemical production plants have also replaced the focus on coal, capturing ~4 Mtpa since 2009. Future projects are still being planned post-2020 and there appears to be momentum building in investment, especially when an emphasis is placed on the development of industrial hubs and clusters. Among those in advanced development are the Norwegian Longship CCS project (Northern Lights), CarboNet in Australia, Porthos in the Netherlands, and the recently operational ACTL facilities in Canada. Industry clusters are now seen as critical to decarbonization as they offer integrated transport and storage networks to cut emissions from a multitude of industrial point sources that include hard-to-abate sectors, such as cement, iron, and steel plants.[24] The UK government is currently applying seed investment to set up a number of regional clusters with the emphasis of decarbonizing heavy hard-to-abate industries,[25] including clusters in Teeside, South Wales, North West England, and Scotland. Confirmation from the UK government of £1 billion to establish four CCS clusters by 2030 (and aiming to capture 10 Mtpa) also signals the heightened ambition to support the development of net-zero hubs.[26] With financial support and the right incentives in place, collaborations from major energy companies in delivering projects seems more likely. For example, the Northern Lights transport and storage component of Longship CCS is being run by Equinor, with Shell and Total investing as equal partners in a project that has the potential to store up to 5 Mtpa once in full operation.[27]

BECCS and DACCS

Further reduction of CO_2 emissions is possible through the use of BECCS and DACCS, which are starting to gain popularity and traction in CCS schemes (Figure 2C). These are seen by many as necessary to achieve net-zero targets and to allow large-scale industry clusters to switch from major emissions sources to becoming negative emission technology hubs. The Oxy Low Carbon DAC plant in Texas will be the world's largest and the first of its kind to directly remove 1 Mt of CO_2 per year[28] from the atmosphere for use in EOR operations as soon as 2025. Other DAC pilot plants at a much smaller scale are also in operation e.g., at the CarbFix site in Iceland (50 tpa) with plans to scale-up to ~4 ktpa. Currently, large-scale bioenergy technology is being utilized in the US at the Illinois Industrial project, capturing up

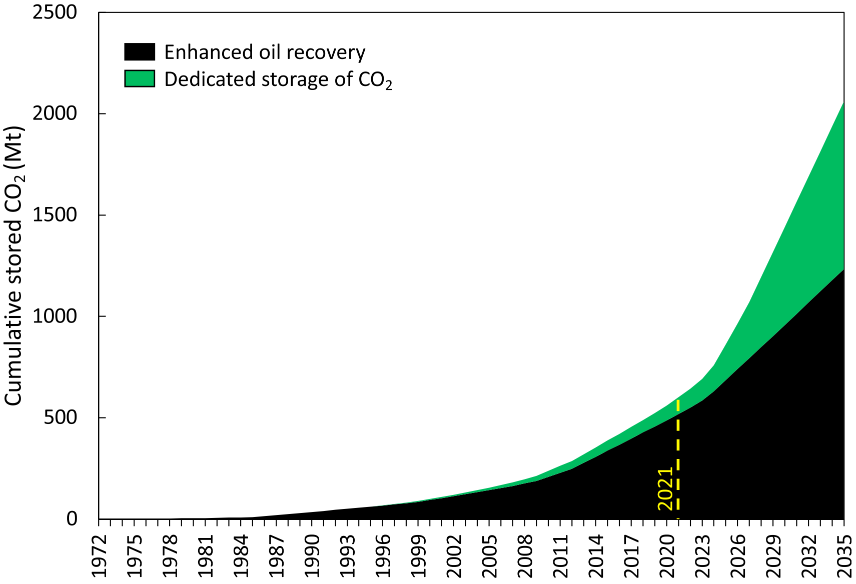

Figure 3. Historic and planned future (to 2035) partitioning of CCS

Visual representation between EOR operations and dedicated CO_2 storage. Yellow dashed line shows the status of projects in 2021.

to 1 Mtpa as part of fermentation processes,[12] while the Drax power station in the UK is also piloting BECCS technology on wood pellet-fired power generation in the push toward negative emissions delivery.

CCS and EOR

Given the period of time and financial backing that it takes to fully develop dedicated storage sites, it is unsurprising that captured CO_2 is at present predominantly used for EOR (Figure 3). In the near term, of the 26 currently operating projects, only 6 do not use the captured CO_2 for EOR methods (the Gorgon natural gas plant in Australia, the Quest facility in Canada, Qatar's LNG plant, Equinor's Sleipner and Snøhvit projects, and the Illinois industrial BECCS plant). Partitioning between EOR and dedicated storage shows that, cumulatively (in 2020), ~73 million tons has been stored in dedicated reservoirs, while ~487 million tons (which includes both captured CO_2 and CO_2 extracted from natural reservoirs) has been used in EOR operations globally, mostly in the US. If the planned projects beyond 2021 go ahead (Figure 2), the predicted dedicated storage amount by 2035 would grow to just over 700 million tons, supporting only 10%–12% of the 6,000–7,000 Mtpa expected by 2050.[29] EOR has become a useful incentive for CCS projects and, once injected, it has a high storage retention factor.[30] However, much of the CO_2 used in the EOR process is still derived from natural underground sources, either specifically for EOR, or as a by-product of natural gas extraction, and therefore does little to mitigate the emissions associated with using fossil fuels. According to the IEA global database of EOR projects,[31] ~500,000 barrels of oil are produced daily using CO_2-EOR methods. This is forecast to grow by 2040 to more than 4.5 million barrels per day. Although seen as counter-productive to climate change mitigation, the economic attractiveness of continuing to produce oil through EOR can be considered as helping to promote decarbonization efforts, bridging the gap to CCS deployment over time.[32] However, this must be with the caveat that the CO_2 used is captured and transported anthropogenic CO_2 from existing emitting facilities e.g., from hard-to-decarbonize industrial sources such as the cement and iron and steel industries.[1,33,34] The proximity of CO_2 capture plants and the existence of pipelines and transport mechanisms to oil fields requiring EOR can be a ready-made opportunity to utilize emissions produced anthropogenically (e.g., the Boundary Dam power plant and the Petra Nova plant). The success of storage through EOR is also a potential opportunity to keep oil production through tertiary methods "clean" by encouraging CO_2 injection with stacked storage (which combines EOR with dedicated storage) even after all the oil has been removed.[15,35]

GLOBAL CCS PROGRESS

Most large-scale CCS projects are located in the US where growth has been faster than for other countries. The US is an innovative leader and carbon sequestration is by no means a new concept.[36] Since the early 1970s, the US has led in the deployment of EOR-CCS technology with the implementation of the Terrell Natural Gas facility (formally known as Val Verde). The importance of CO_2 for the extraction and sale of oil through EOR is perhaps the biggest driver and catalyst for CCS capacity in the US. With the cost of CO_2 indexed to the current oil price, it is no wonder that at times of high oil prices (e.g., ~US$70/barrel) the profitability of CCS projects becomes more appealing. The infrastructure and expertise, helped by private-sector involvement, has therefore been in place for decades transporting millions of tons of CO_2 to both productive and depleted oilfields. Now, the US is host to 9 of the 21 large-scale operational facilities worldwide capturing more than 25 million tons annually.[1]

While project financing remains one of the greatest challenges to CCS deployment, other global nations may look to the US for inspiration. Government-led support is key to the development of CCS in the US, which has provided not only direct funding for infrastructure, but also created an environment that demonstrates a specific value on carbon beyond that of EOR.[36] Incentives such as carbon sequestration tax credits (e.g., the 45Q tax credit, since 2008 and reformed in 2018) are seen as a progressive step in promoting projects that capture CO_2. Enhancements to this legislation in 2018 mean that companies are now able to claim up to US$35 for each ton of CO_2 that is used commercially (e.g., for EOR or other industrial uses), rising to US$50 per ton on permanent storage of the CO_2.[12,13] In addition, beyond national programs, individual state run incentivization is promoted (e.g., the Low Carbon Fuel Standard [LCFS] in California) offering credits to fuels that have lower carbon intensities with the aim of diversifying the fuel mix.[37] In placing an investible value on carbon through this approach, it encourages emitting industries to accelerate building programs, especially when credits from both the LCFS and 45Q schemes can be stacked together (as in the Oxy Low Carbon DAC plant). These incentives, as well as a collection of policies and financial support from the US Department of Energy since 1997 (more than US$5 billion) have helped to alleviate the risks associated with setting up CCS-related projects.[38] With the initial support of the government to get projects off the ground and to up-scale and de-risk, further collective private and financial institution investment is then more forthcoming. Other global nations and economic regions (e.g., the EU) might learn from the incentives and regulatory policies put in place by the US to speed up their own pace of deployment. With blends of policies in place, the reliance on one funding stream may be reduced, especially if that funding stream ends as has been the case in some UK projects. For example, the Longannet and Peterhead projects had government investment pulled completely, effectively terminating their development.

While successes in the US are celebrated, comparisons can be made with other nations in terms of meeting climate targets with their commitment to CCS initiatives. In Europe, Norway has recently submitted enhanced and more progressive climate targets under the Paris agreement, which aim to reduce emissions by at least 50% and toward 55% by 2030.[39] In spite of this, exploration activity and investment is set to continue on the Norwegian Continental Shelf showing little sign of abating in the coming decade[40] outlining the continuing value of oil and gas revenue to the nation. However, Norway's green ambition and its efforts to meet climate targets have made significant early progress, not least in CCS. Norway is host to both Sleipner (the world's first dedicated storage facility since 1996) and Snøhvit facilities (since 2008) that have collectively now stored more than 22 million tons of CO_2.[1,4] The initial success of these is in part due to financial incentives introduced by the Norwegian government, which included an offshore carbon tax enacted in 1991, an approach that encouraged Statoil (now Equinor) to engage in CCS projects.[41] The global oil and gas exporting position of Norway and the opportunity to integrate CCS into facility development is another key reason for the short implementation times for both facilities, taking 4 and 6 years to start injection, respectively.[42]

Since the early efforts resulting in Sleipner and Snøhvit facilities, the continued government support for CCS in Norway has been considerable. Since 2001, a change in policy meant that all new fossil fuel-based power plants must be built with CCS capabilities,[43] and in 2005 an Emissions Trading Scheme (ETS) that overlaps with the EU-ETS scheme was launched, which applied to the largest GHG emitters.[44,45] Coupled with a significant carbon tax of 410NOK/tCO_2 (US$48/$tCO_2$) for petroleum activities,[41] the steps taken toward diversifying Norway's energy mix and 2050 net-zero targets are encouraging. However, making CCS deployment to other sectors a reality has been tougher than expected. The Mongstad full chain demonstration project is one example of this challenge, originally expected to be in operation by 2020 but canceled by the Norwegian government in 2013 based on financial risk and difficulties faced by the refining industry.[46] With investment partnerships from Equinor, Shell, and Total, Norway's full chain CCS goal has finally been realized with the approval of the Longship and Northern Lights projects. Final investment decisions have been made for the capture, transport, and storage of CO_2 from Norcem's Heidelberg cement plant (the first cement plant with capture facilities of its kind) and the Fortum waste-to-energy plant.

While many countries have indicated that CCS is at the forefront of their climate mitigation policies, the implementation of decarbonizing efforts, in reality, are much slower in comparison with those leading the innovation. Currently, China is host to just three operating CCS plants. Despite the country accounting for more than half of global coal use,[47] the development and uptake of technologies has been slow. However, China has shown a commitment to carbon sequestration, including CCS, in its national carbon mitigation strategies since 2007.[47,48] This support has resulted in the implementation of a number of carbon capture plants, mainly for EOR or coal-bed methane recovery purposes. There is some evidence that the technology and potential CO_2 storage resources exist onshore and offshore on viable scales to enable CO_2 sequestration,[49,50] although China's main focus on the utilization of CO_2 to enhance oil recovery is currently more attractive to its growing economy and is a major reason for the lack of traditional CCS activity. Similarly, and perhaps more urgently, a significant barrier to implementing CCS in China is the lack of specific legislation and regulatory frameworks to make it an ongoing reality.[51,52]

Japan's initial pledge in 2016 to cut emissions by 80% by 2050 has only recently been followed by government ambitions to cut carbon emissions to net-zero by 2050. Japan's earlier rather non-committal plan to become carbon neutral "at the earliest possible time in the latter half of this century" was seen as not going far enough to tackle their dependency on coal, especially as this industry is responsible for around a third of the country's electricity supply.[53] Previous financial backing from some of Japan's major banks and financial institutions for new coal-powered plants across Asia, itself suggested a significant role for fossil fuels in Japan's future energy mix. However, this approach is now being revised in favor of a shift toward renewable energy and a new commitment to halt government backing for unabated coal power in line with G7 pledges.[54] Although significant progress has been made in both pilot and large-scale CCS demonstration projects, such as Tomakomai (300,000 tCO_2 successfully stored to date), concerns continue to surround the long-term vision and commitment to Japan's carbon capture policies. The obvious importance of fossil fuels to the economy, without having an ambitious, clear, and developing CCS program tied to the continuing investment in coal is understandably worrying.

The reliance and importance of fossil fuels also remains evident in the wealthiest oil-producing nations. For example, CCS was started in 2015 at the Uthmanijah project in Saudi Arabia, injecting around 800,000 tCO_2/year for EOR, and remains the region's only operational facility despite the vast storage potential of the kingdom. The future plans for CCS in the UAE, are also predominantly driven by fossil fuel extraction and utilization for EOR. Owing to fluctuating oil prices and demand, many new energy diversification projects are put on hold because of inconsistent carbon reduction regulations and policies. More recently, efforts have been taken more seriously with the announcement of a future carbon trading scheme and proposed moves toward renewable energy. The Saudi national government has also committed to providing $150 million to fund clean energy technology that includes CCS.[55] Yet, the current focus on oil and gas production without a sustained and prolonged push to develop more active CCS facilities in the region remains significant.

The future role and significance of CCS in less-developed nations or those with transitioning economies are more difficult to predict. India, for example faces massive future transformation and demand for energy. The rapid growth in population and industrialization is the main driver of the country's reliance on its fossil fuel base and the World Coal Association predicts that around 60% of India's power generation is satisfied by coal, which will remain a key part of the economy for the foreseeable future.[56] Coupled with the economic downturn as a result of COVID-19 and its reliance on expensive (and declining) imports, the announcement of 41 coal mining blocks to be auctioned perhaps comes as little surprise.[57] However, growing concern within the private sector regarding environmental and net-zero targets has led to little appetite for this investment,[57] signaling a move toward renewables and the lowering of emissions intensity by 33%–35% by 2030.[58] The need and interest for CCS in India is recognized but does not form a major part of future mitigation efforts. As with many developing nations, progress is slowed predominantly by the cost of introducing the technology but also by a lack of research and development, limited financial investment, environmental concerns, the lack of a comprehensive study on the geological storage solutions, and strong public and political opinion.[59] Faced with this multitude of barriers to deployment, this places the geological sequestration of CO_2 much further down the list of priorities in many of the world's developing nations.

GLOBAL STORAGE CAPACITY AND CCS READINESS

Of the 21 operational CO_2 capture projects worldwide, only 6 are dedicated to geologic storage (Sleipner, Snøhvit, Quest, Illinois Basin, Qatar LNG, and Gorgon). These are cumulatively currently storing around 7 Mtpa of the 40 Mtpa that is captured. Although CO_2 storage tonnage has been increasing year on year since 1972[15] (Figure 4A), the slow rate of growth remains a challenge to reaching net-zero targets. The projected storage rate in 2050, based on historic and planned projects (both dedicated storage and EOR) up to 2025, is ~718 Mtpa[15], far from the 6,000–7,000 Mtpa rate called for by the IEA.[29] An examination of the rate of past storage growth, just accounting for dedicated storage projects alone, is considerably less optimistic. Based on an annual dedicated storage rate of ~7 Mtpa in 2020, it is projected that, in 2050, if the growth rate remains the same, the storage rate will be ~75 Mtpa. However, if the projects envisaged to come on stream between 2020 and 2030 do so, based on this growth rate it would be ~306 Mtpa (Figure 4B). This is still nowhere near enough to meet IPCC and IEA scenario targets, and would only account for between 4% and 5% of the storage rate required.

In the construction of storage estimate curves used in Haszeldine et al.,[15] and developed further here (Figures 4A and 4B), the calculation and estimation of storage data present several challenges. Distinguishing between types of project (capture versus storage) is not always clear and it is apparent that tonnages of CO_2 injection are often overestimated. For example, actual masses of CO_2 injected into the subsurface are unlikely to be available for every project. In many cases, large databases list the capture capacity of the relevant capture plant, but this does not always translate into the amount stored. Published total storage values often simply multiply the quoted yearly storage capacity by the number of years in operation, while in reality many injection rates are lower or facilities have stopped injecting sooner than is reported. An example of the variability encountered is the Century plant in the US, where 5 Mtpa was stored up until 2012, 8.4 Mtpa between 2013 and 2015, and 5 Mtpa thereafter.[61] Unless this level of change is recorded in all facilities globally, actual storage estimates will always be difficult to constrain.

Recent efforts to investigate whether potential CCS capacity is sufficient to meet IPCC targets identifies the amount we might need given certain emission pathways.[60] Hence, the global potential for CO_2 storage capacity is becoming better understood and theoretical resource estimates (encompassing both potential undiscovered and discovered storage sites) are immense (up to around 17,000 Gt). When compared with the estimated cumulative storage needed by 2100 for both 1.5°C and 2°C scenarios, there is more than enough, as less than 10% of total theoretical storage capacity is estimated to be used by 2050 (Figure 5A). However, translating storage estimates to storage site development for CCS is typically complicated, not least by growth rates of CCS projects but also in quantifying how much of a storage resource is a bankable reserve, i.e., of a known size and pore space to exploit. In addition, projections of development rates based mainly on EOR activities are misleading unless future incentives and policies are introduced and maintained to ensure anthropogenic CO_2 is permanently stored.[15]

Furthermore, the amount of storage space that is actually accessible is still to be determined on a global scale. Likewise, the storage site needs to be close to or within a transportable distance from the emitting point sources to make it viable. Levels of regional identification of storage capacity are variable and at different stages globally, ranging from limited assessments to full-scale estimates.[65,66]

Recently, the use of historic well-development scenarios from offshore and mature hydrocarbon basins has been seen as important in helping understand bankable resources.[67] Successful and volumetrically significant offshore basins extensively used by oil and gas companies for decades can match and exceed the Gt-scale resources that are required. Furthermore, the deployment of only a fraction of the historical well rates from petroleum exploration can provide sufficient injection rates. To be effective, multiple and simultaneous developments globally (e.g., a single Gulf of Mexico model or five Norway well-development models) would be required to satisfy the CCS targets by 2050.[67]

The implementation of multiple injection developments is dependent on several factors. The availability and readiness of depleted oil and gas reservoirs used by the industry with a multitude of available data, such as its potential storage space and the security to trap fluid is certainly encouraging and attractive. However, in the absence of CO_2 injection infrastructure equivalent to that which has served the oil and gas industry effectively,

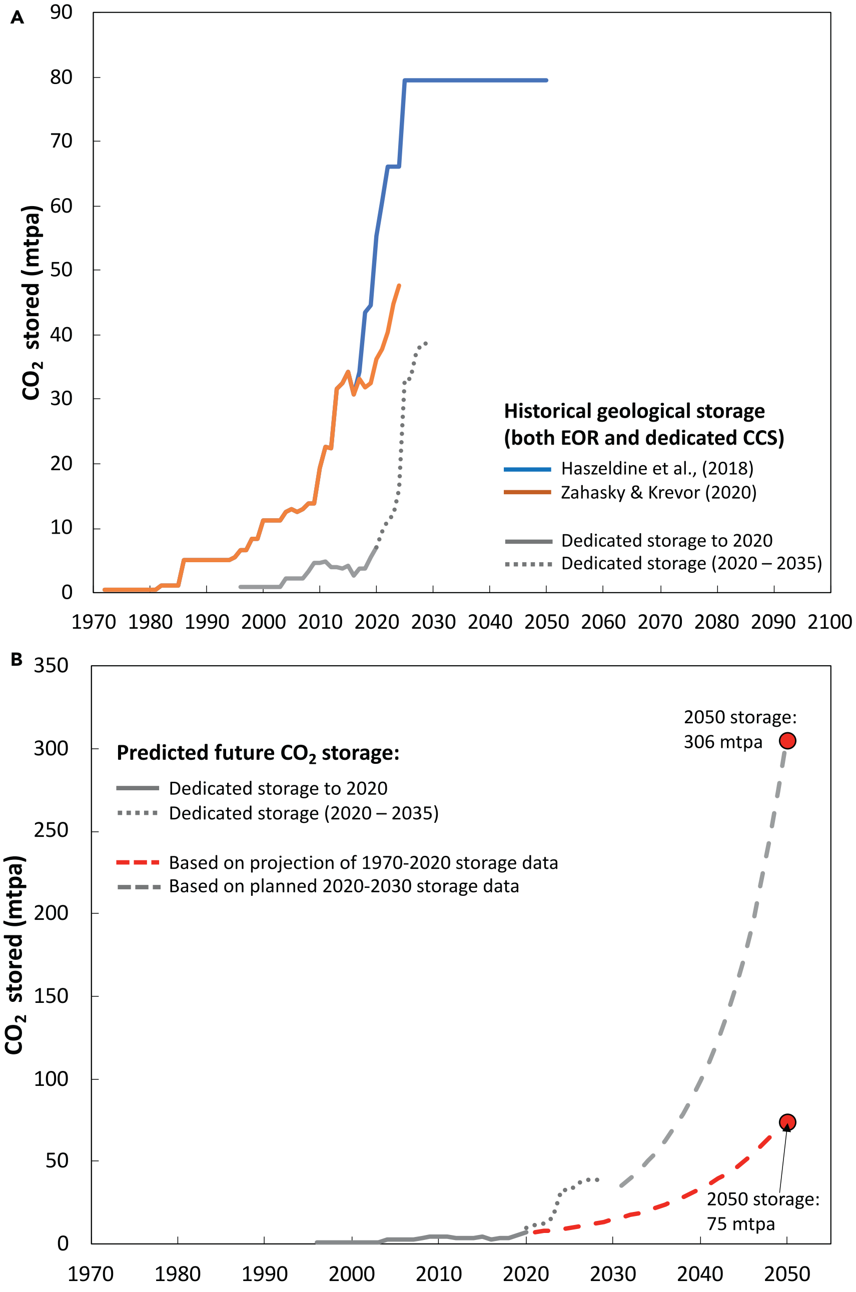

Figure 4. CO_2 storage rates from large-scale CCS projects

(A) There has been a continuous increase in storage rates to 2025 (blue line). The leveling off of this line post 2025 reflects a lack of confirmed new storage projects.[15] The orange line is comparison data from a previous study from Zahasky and Krevor.[60] It is apparent that dedicated storage of CO_2 projects up to 2020 (solid gray line) shows a much slower rate of development and tonnage stored, but predictions of the rate of dedicated storage up to 2035 (gray dotted line) are more promising should future planned projects materialize.

(B) The predicted storage by 2050 (red long dashed line) is based on the CO_2 storage volumes per year of CCS projects using current and historical rates of storage (data collated from GCCSI CO_2RE database, 2019,[12] SCCS database, 2020[61]). If storage rates are based on the number of planned future projects and tonnages predicted to be stored (gray long dashed line), by 2050 greater storage amounts will be achieved.

CO_2 transport facilities, and the time lag associated with bringing CCS facilities into operation, implementation of such an approach seems unlikely in the near term. These analyses confirm that the vast storage resources available are not yet being exploited at pace, and this means that verification of the banakable storage resource is also slow.

The ability to deploy projects from initial planning stages to start-up is a measure of the success of CCS in specific countries. CCS readiness assessments[63] of specific countries detail a country's position on the deployment spectrum, e.g., those making no progress or with little CCS potential, to those who are well prepared and actively pursuing innovation (Figure 5B). It is perhaps inevitable that the earliest opportunities for development stem from depleted oil fields nearing completion or existing CO_2-EOR projects, as is commonplace in North America. As well as in-place infrastructure and transport links, the revenue streams from pursuing additional oil may be used to provide the upfront costs of setting up new CCS facilities and significantly de-risks projects from the outset.

The International Energy Agency's Greenhouse Gas (IEAGHG) R&D Program used industry analogs to assess whether the required build-out rates for CCS implementation in the 2DS scenario were feasible.[64,68]In the estimation that 75–150 new capture facilities per year (worldwide) were needed, they considered the logistics of five aspects of CCS that required accelerated implementation: (1) commissioning of new capture facilities; (2) availability of CO_2 compressors; (3) creation of CO_2 transport networks (pipeline and CO_2 tanker ships); (4) development of CO_2 geological storage sites; and (5) the deployment of drilling rigs, and the installation of platforms and wellpads (Table 1).

The evaluation of potential storage sites selected for CCS deployment places new constraints on the timing of planned CCS development. The IEAGHG assessment found that storage site discovery was likely to be adequate, based on the amount of natural gas reservoir discoveries, and the ability to create transport and supply networks to the selected storage sites. However, there remains significant geographical limitations on CCS sites, such as the proximity to CO_2 point sources. Hence, while it is encouraging that all the technological roll-out should be achievable based on the analogous industries, maintaining that growth might be more difficult. It is estimated that up to 10 years is needed for the development of a geological storage site,[15] including the de-risking of sites and data gathering and analysis

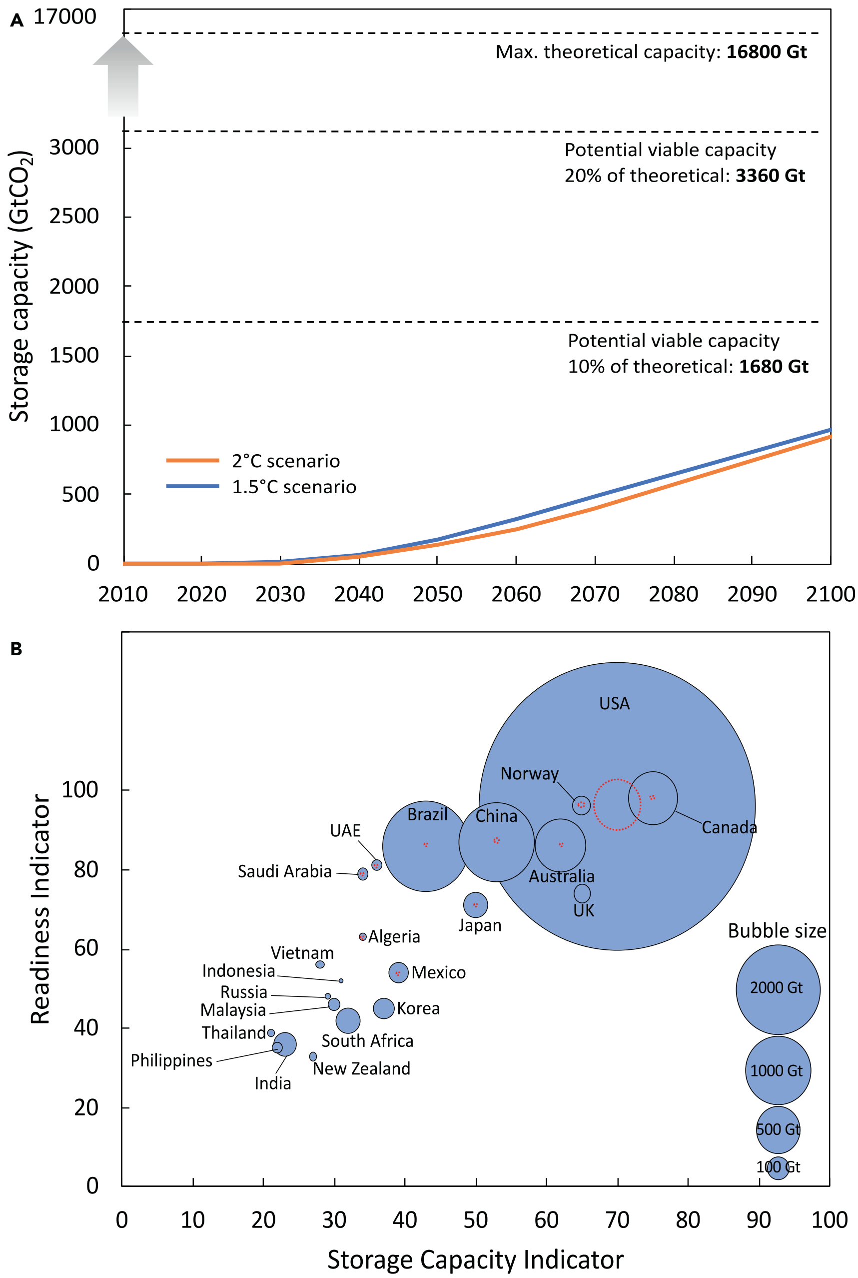

Figure 5. Storage capacity and readiness to meet IPCC scenarios by 2100

(A) Median model data from Zahasky and Krevor,[60] plotted against theoretical global storage capacity levels. Theoretical storage capacity levels figure redrawn from IEA, 2009.[62]

(B) The readiness indicator monitors a country's CCS deployment progress through assessment of its policy, law, and regulation and storage resource development.[63] The readiness level is based on a nation's capability to enable an environment for the commercial deployment of CCS. The storage capacity indicator is a measure of a nations potential storage resources. The blue bubble size is representative of maximum theoretical or effective storage capacity for each assessed country (GCCSI[64]). The red dotted circles represent the amount of CO_2 stored so far by each nation. While it has been shown that less than 10% of available storage might be needed, e.g. (A), much of this is still not identified as a bankable resource.

to prove its security. Owing to this, and the delays associated with sites being long distances from CO_2 capture plants, site discovery, and the development of CCS is likely to be slower for regions without a mature oil and gas industry already in place.

Countries with an advanced and well-developed oil and gas industry fair better than those that are either just starting to invest or show an interest in CCS. For example, the vast mature systems in the US means readiness indicators are highest and roll-out times for new storage projects can be relatively fast. Similarly, other nations that score highly in assessments of proven offshore or onshore resources, e.g., UK, Norway, Canada, Australia, etc., should follow suit, especially if they show an inherent and historical interest in developing CCS. Despite some countries displaying favorable storage resource estimates, e.g., Saudi Arabia, the readiness to deploy projects is often hampered by a greater interest in developing hydrocarbon production for economic gain rather than climate mitigation. In these scenarios, roll-out of CCS would be delayed somewhat (around 5–10 years) so that the appraisal of sites suitable for projects can be undertaken. For countries that have no mature hydrocarbon industry and no evidence of any CO_2 injection projects, it is anticipated that the roll-out of facilities will be much longer (e.g., India). In this scenario, work and preparation must be accelerated from the early reconnaissance and data-gathering phase before any form of construction and injection can take place.

THE ROLE AND PREPAREDNESS OF THE OIL AND GAS SECTOR

Faced with pressure from governments, stakeholders, and environmental policy, the realization for the need to rapidly decarbonize is becoming more apparent to the biggest global oil and gas companies. As one of the main emitters of global greenhouse gases, the oil and gas industry is seen as a major player in mitigation efforts. The unique economic and technological position of the industry also lends itself to the development of CCS. A number of European oil and gas majors have recently adopted and set long-term net-zero targets (NZT). The targets broadly feature commitments to reducing their scope 1 and 2 emissions (operational emissions) to net-zero by 2050, and to reduce by some proportion (in the range of 50%–80% by 2050) the intensity of scope 3 emissions (the direct emissions from energy products sold to customers). The ambition and details of these reductions is not as transparent or equal for all

Table 1. IEAGHG R&D assessment of required build-out rates for CCS deployment

Resource being assessed	Amount of resource needed	Industry comparison	Feasibility
Commissioning of new capture facilities	75–100 new capture plants/year (worldwide) would be required	historic commissioning rates of combined cycle gas turbines (CCGT) (global CCGT build out peaked in early 2000s, commissioning more than 70 new plants/year between 2000 and 2005, with a maximum of 119 plants/year in 2003)	the required build-out rates thus seem to be possible, but it remains to be seen whether the high rate can be maintained over the decades necessary to bring carbon capture up to speed
Availability of CO_2 compressors	1 compressor per new capture plant would be required	current size of CO_2 compressor industry used as comparison	while production capacity may initially be limited, the industry would be able to adapt and expand to meet CCS requirements
Creation of CO_2 transport networks	assumed 10% of CO_2 would be transported by ship, the remainder by pipeline. An estimated 4,500–12,000 km of new CO_2 pipeline/year would be required. CO_2 transport by ship estimated to be required to increase by 15–30 Mtpa	development of natural gas transportation pipelines used as a proxy for CO_2 pipeline build-out rates. For shipping estimates, shipping rates of liquefied natural gas (LNG) was used	natural gas pipeline construction has maintained a build-out rate of 5,000–9,000 km/year since the 1990s, comparable with estimated requirements for CO_2 transport. Shipping of LNG has an average yearly increase of ~20 Mtpa CO_2 equivalent. Transport of captured CO_2 is not anticipated to block to CCS deployment
Development of CO_2 geological storage sites	up to 60 storage sites required to be discovered and developed/year (injecting 5–10 Mtpa for 20 years, with final cumulative storage of 100–200 Mt). This equates to discovering 3.0–5.5 Gt storage resource/year, rising to 6.5 Gt by 2050	comparison with natural gas discovery rates	historically, gas fields discovered at an average rate of ~6 Gt CO_2 storage/year, suggesting that early-stage storage site discovery rates are feasible, but that exploration efficiency will be required to increase in the future to allow continued CCS development
Deployment of drilling rigs/platforms/ wellpads	1–4 wells required per 1 Mtpa of CO_2 injection (to account for failed wells, poor injectivity, monitoring, and production wells). A requirement of between 300 and 1,200 new wells per/year after 25 years of growth, ~40–100 drilling rigs, and installation of 60–120 wellheads or platforms/year	comparison with historic global drilling rig counts	historic global drilling rig counts increase and decrease on the order of 300 rigs/year. New rigs can be constructed quickly in response to increased demand, suggesting that the required increase in rigs for storage site development is feasible

major players, although alignment toward a common goal is becoming clearer.

Recent transition pathway initiative (TPI) evaluations state that leading players, such as Shell and ENI, have some of the most ambitious plans that aim to meet with or be close to the IPCC 2°C scenario by 2050.[69] Shell outline an ambition to be net zero on all emissions from the manufacture of their products by 2050,[69] and also aim to significantly reduce the net carbon footprint of the energy projects it sells by around 35% by 2035 and to 65% (increased from an initial 50%) by 2050. The broad commitments made by ENI include reducing its overall carbon intensity by 55%, while BP aim for a 50% cut by 2050 or sooner. Repsol have gone further in stating that it aims to reach zero emissions (including scopes 1, 2, and 3) by 2050. Figure 6 shows the alignment of major oil and gas companies in terms of their commitment to carbon neutrality and their positioning on the commitment to CO_2 sequestration spectrum. There is a disparity between companies that disclose full, detailed emissions targets and demonstrate successful dedicated CO_2 storage operations (e.g., Shell, Equinor, etc.) with those that lack visible net-zero target pledges in line with the Paris Agreement and who show little interest in carbon storage activity. This offset is also seen in companies that only look to lower operational emissions (rather than the end-use consumer products as well) and in those that utilize CO_2 for EOR and financial gains. Furthermore, given a large proportion of oil and gas companys' product sales occur within national and supranational actors with existing or proposed 2050 NZTs, global emissions intensity targets might represent pathways to compliance rather than furthering ambition.

Most non-European oil and gas companies (especially in North America) and National Oil Companies (e.g., Saudi Aramco) lag behind their European counterparts in their net-zero target setting. The TPI assessment (2020)[69] showed that only Petrobras had considered emissions targets that include coverage of scope 3 and no assessed companies headquartered outside of Europe assessed were in alignment with the Paris Agreement.

The alignment of major global oil and gas companies to the storage of CO_2 and the development of CCS projects remains

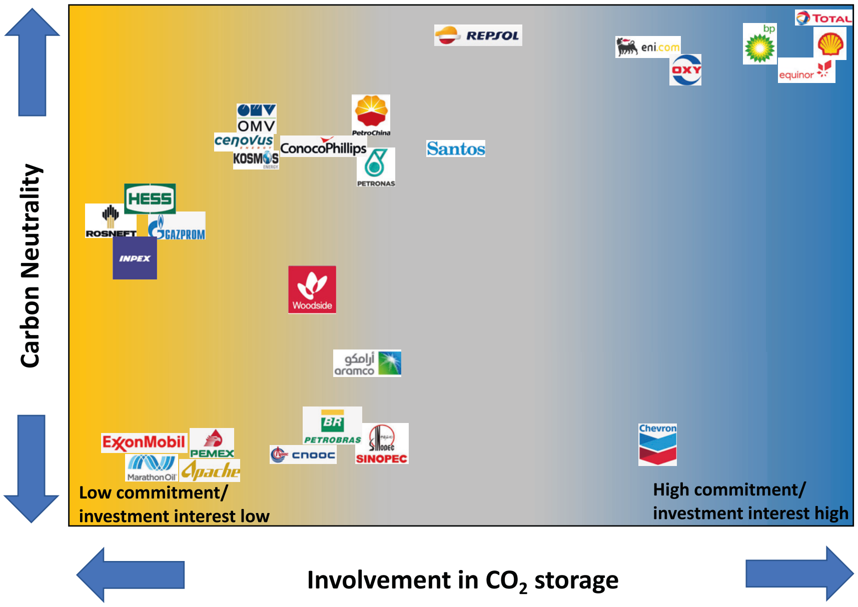

Figure 6. Major oil and gas company commitments to carbon neutrality

The color gradient reflects yellow, lower commitment to CO_2 storage; gray, some commitment/predominantly EOR activity; and blue, higher commitment/already injecting in operational facilities. Higher levels of carbon neutrality is reserved for those companies that commit to reducing scope 1, 2, and 3 emissions. The companies used in this analysis are based on the CDP research and league table for oil and gas companies (Beyond the Cycle report[70]) and updated for this study with recent company disclosures.

uncertain. Economic feasibility, policy, and public perception have all played a part in this and there is growing skepticism of what the major companies are doing to invest in the permanent storage of CO_2. Despite the slow progress, there is evidence of investment from oil and gas companies. Well-known large-scale projects currently storing CO_2 include Sleipner and Snøhvit (led by Equinor with ExxonMobil and Total involvement), which, together, store around 1.7 million tons per year. Gorgon, a Chevron project, is aiming to store around 4 million tons annually, while Shell's Quest project in Canada stores around 1 million tons. The development of the Northern Lights project in Norway, the Greensands project in Denmark, and the Net Zero Teeside project in the UK also highlights the future commitment from some major oil and gas players to CO_2 storage.

Although CCS is a keystone included in companies' individual energy transition models, oil and gas majors need to prioritize climate change mitigation over maintaining market dominance. Some investment is occurring in low-carbon alternatives (less than 4% of capital expenditure),[71] but a small proportion of this is dedicated to CCS compared with other carbon reducing methods, such as wind, solar, and biofuels. A recent surge has also shifted the emphasis of CO_2 burial on to nature-based solutions. This has drawn heavy investment with, for example, Shell planning to invest $200 million in natural ecosystems between 2020 and 2021 as part of its net zero by 2050 initiative.[72] However, this approach draws criticism especially in the way carbon credits may be claimed by multinational companies that invest in government-led initiatives. Additional criticism may also be drawn if there is an over-reliance on nature-based solutions in published net-zero plans, especially if this does not encourage a reduction in fossil fuel promotion.

CCS DRIVERS AND OBSTACLES

To realize the potential for the implementation of CCS requires a number of drivers for mobilization ranging from financial to technical.[73] The use of CO_2 to prolong depleted oil and gas reservoirs helps drive the development of CCS where the right incentives are in place to encourage permanent storage. Similarly, the presence of oil and gas infrastructure and CO_2-EOR transport facilities can also accelerate deployment. Despite this, encouraging CCS projects through the promotion of EOR activities is somewhat contradictory. However, owing to the unique position that the oil and gas industry has acquired, this trade-off might be beneficial if regulation is put in place requiring companies to set up agreements ensuring the longer-term secure storage of CO_2 post-oil or -gas extraction.[74] In addition, ensuring the promotion of carbon pricing and financial regulatory environments that legislate against the largest emitters of greenhouse gases, provides added incentives for major companies to help develop CCS projects. Although there are 64 initiatives either implemented or scheduled to be implemented that would cover 12 Gt of CO_2 equivalent, the roll-out and progressiveness of policies varies nationally.[75] In the US alone, cap and trade policies are active in just 11 states making up the Regional Greenhouse Gas Initiative (RGGI), but only one of these (California) bases their emission taxes on multiple industry sources. It should be noted that CCS does not yet factor in the main emissions offset categories of the RGGI. This perhaps provides scope and opportunities for the future design of this policy. In contrast, the China ETS has taken time to implement,[76] but has now been recently adopted, while other large emitting countries where schemes such as this would be beneficial, such as India, have no such scheme formally in the pipeline. Even with these initiatives, the increasing variation of carbon prices across close neighboring states or regions (e.g., the US or EU) might have implications for the long-term development of CCS. The urgency for deployment may be hindered by differing approaches to emissions reductions causing economic ''leakage'' whereby reduced output by one jurisdiction is offset by an increase in another—to the overall detriment of NZTs. It remains to be seen if measures suggested to address emissions offshoring, such as the EU's proposed Carbon Border Adjustment Mechanism might improve the CCS investment case.[77] Due to the nature of some CCS schemes that are reliant of multiple point sources and transport networks that span different countries or states, the importance of cross-border cooperation to legislate a single value on carbon high enough to make CCS viable becomes vital.

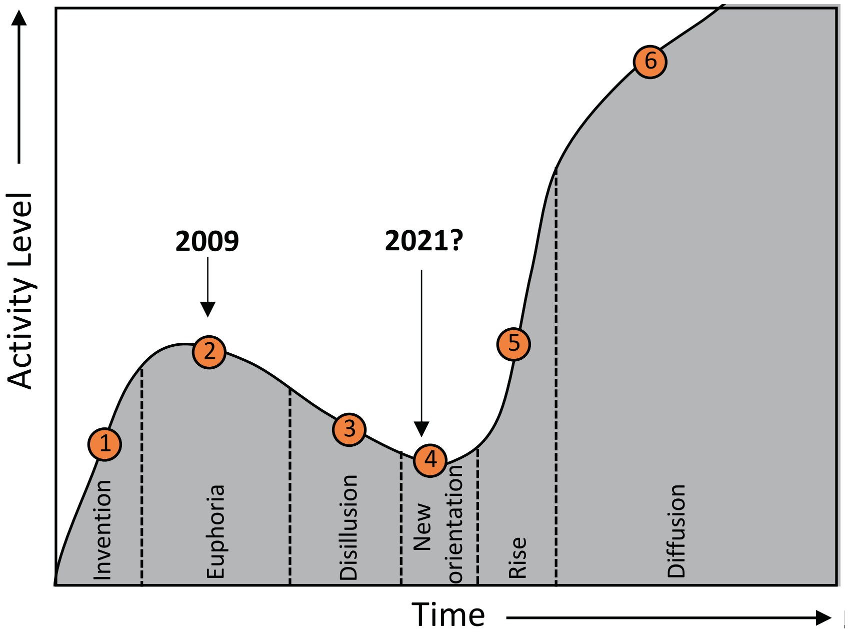

Figure 7. The life cycle of CCS
Figure redrawn from Ragden et al.[93] with the predicted placement of 2009 and 2021 outlooks on CCS. The initial optimism of the IEA Blue-Map scenario in 2009 (stage 2) was closely followed by a period of disillusionment (between 2009 and 2021) where CCS project and facility deployment was not as forthcoming as predicted. Today, in 2021, we are in a period of new orientation (stage 4) where investment and momentum seem to be building toward the deployment of multi-industry hubs and clusters utilizing shared facilities and CO_2 transport networks, and new technology deployment such as hydrogen production, DAC, and BECCS.

Generally, although CCS deployment is a desirable outcome for many, the associated risks often outweigh investment. Well-documented failures of government-backed schemes to get CCS up and running with the involvement of major companies are a concern (e.g., the Longannet and Peterhead projects in the UK) and questions remain regarding the commitment required to make it a reality. Additional challenges occur in the form of the cost and the associated legislations and liabilities of CCS.[78–81] Studies have made efforts to calculate the potential costs of the technology[81–84] and, while this is no easy task based on variability across different industries, it shows that the capture phase is generally the most costly when compared with transport and storage.[81] Similarly, start-up costs for initial projects are usually extremely high as these bear the brunt of supplying the transport and storage mechanisms, of which subsequent projects can then take advantage.

The level of legislation applied to CCS deployment varies globally. In the US, for example, this is devolved to the state level, where those doing the most CCS (e.g., Texas) are those that have clear regulations in place covering injection and monitoring methods, such as groundwater protection. For other nations there are still major uncertainties about short and long-term liability, an example of this being the EU, where the legal and financial framework outlined in the CCS directive is seen by many member states as a substantial barrier.[85,86]

Perhaps one of the most obvious obstacles to deployment is the slow pace of assessing, verifying, and exploiting the vast storage resources that are available. This no-doubt heightens the perceived risk for geological storage of CO_2, especially in terms of confidence in the capacities and the risk of CO_2 leakage at a chosen storage site.[87–89] This feeds directly into the general public's acceptance and perception of the role of CCS and adds obstacles to the smooth transition toward decarbonization efforts. Recent investigations reveal that there is little public awareness regarding CCS technologies, leading to a lack of understanding about the problem CCS is meant to address.[90] Results also show that public attitudes to CCS vary widely.[91] Negative perceptions stem from the lack of understanding or a "not in my backyard" attitude, while positive viewpoints emerge when CCS is positioned with the utilization of CO_2 (or when a value is placed on carbon) where there seems to be a higher level of support. Despite this, the utilization of carbon and recycling back into usable materials and fuels is limited, being dominated by the fertilizer and food industries. Predominantly, the utilization is particularly relevant in the oil and gas sector for EOR. In addition, the long-term sequestration of CO_2 into concretes, plastics, and fuels is still in various stages of development limiting its immediate potential, and thus carbon capture and utilization, not including for EOR, are currently only responsible for the abatement of less than ~0.5 Mt CO_2 per year,[92] compared with the 40 Mt per year from CCS.

THE OUTLOOK FOR CCS

CCS is continually mooted as necessary if the effects of climate change are to be dealt with and NZTs are to be met. The life cycle that CCS has been through and the path that it continues on is subject to a number of peaks and troughs[93] (Figure 7). The speed of facility deployment and then the slowdown since the initial excitement and growth phases, such as observed in 2009, signals that the industry is encountering challenges and disillusionment about its costs, timescales, and future direction. The expectations that CCS was initially built upon and the optimism that came with it, have wavered because of these barriers. Now, more than ever, this offers the opportunity to learn lessons from the past decades in forging new pathways for the technology to avoid CCS being deemed as an overhyped technology. While it remains widely agreed that CCS is needed to deliver the targets for net zero in the near and longer term, it is also a good time to reassess what is needed to accelerate the large-scale deployment required to achieve these targets. This assessment is perhaps never more timely owing to the recent unforeseen global COVID-19 pandemic which saw CO_2 emissions decline steeply in 2020. However, despite the emissions savings made early on, the subsequent economic recovery combined with a lack of established clean energy pathways has meant that energy-related CO_2 levels are already back to, and rising above, pre-pandemic levels.[94]

CCS is currently only cited in 11 government agreed NDCs,[4,7] although with updates ongoing in readiness for the UN Climate Change Conference, 2021 (COP26), this is likely to increase. However, despite plans being discussed, implementation of these must be delivered at a far greater pace than currently observed if we are to reap the benefits from this technology. The same questions regarding the potential of CCS as a key part of the global climate response are continually posed. Although a fluctuating picture, in terms of support and the deployment of facilities, the momentum of CCS looks to be improving due to the change in direction toward new technology options such as hydrogen production, DACCS, BECCS, and the targeting of large industrial emitters.[95] More broadly, with the addition of new technology to the CCS portfolio and the increase in the installed capacity of renewables,[3] it perhaps shows how these technologies can work hand-in-hand rather than deeming one more critical than the other in reaching net zero. Although a renewables-based approach to mitigation is widely supported, its success is reliant on aspects, such as shifts in behavioral change and developing greater efficiencies in the use of energy, which can fluctuate and take time. Through encouraging the continued financial commitment from governments and private-sector stakeholders in CCS deployment, and technological advances to abate further emissions, this may also act as a catalyst toward a green energy transition and avoid slipping into long periods of disillusionment.

A greater push for economies of scale, such as CCS technology focused on industrial hubs and clusters, is efficient especially when governments and private companies all apply investment to those activities and there is no actual limit on how many point sources link up to these. The Norwegian Longship project is one example of how this is now becoming a reality and similar approaches in the UK are finally showing encouraging signs with the awarding of £171 million to nine projects promoting decarbonization.[96] The development of frameworks, such as those that aim to use CCS for the decarbonization of hard-to-abate heavy industries while promoting cleaner energy generation, such as hydrogen production and renewables, should be accelerated to help shape future discussions regarding the energy transition paradigm.

The last few decades have proven that the technical expertise and knowledge exists to implement CCS technology at scale. To convert this potential into reality a significant push in government policy and regulation is required. This will help forge a pathway for the rise of facility deployment and the diffusion of this innovation for continued success (stages 5 and 6, Figure 7). Consideration for early movers into CCS deployment should be widely encouraged, especially in start-up phases, which are often where many barriers exist in terms of upfront costs and the financial pressures of maintaining CCS infrastructure and capture technologies. It is also important not to lose sight of efforts ongoing today to permanently store CO_2 (either by EOR or into dedicated storage reservoirs) and to encourage ongoing efforts to identify viable and safe underground storage resources.[60] This is especially important now, while new pilot and demonstration projects are getting off the ground and as new innovative technologies start to be proven to maintain the pace and commitment needed to ensure CCS stays on track.

CONCLUSIONS

The considerable efforts from research and CCS development indicate that the technology is both ready and essential for reducing the ever-growing impact of climate change. Now, more than ever, pressure and an urgency exist from the public and industry to deliver on promises made to undertake climate change mitigation. However, it is concerning that the lessons from the last decade are that CCS projects have been slow in their delivery and that considerable challenges remain in linking the potential of CCS to the investment and deployment of facilities.

The gap between what is expected from CCS deployment and what is being delivered is still all too visible. It is clear that there now exists a diversity of capture and utilization technologies but that the pace of development means that these options are not being exploited. Facility deployment must increase urgently compared with what is currently operating to fulfill its role in climate change mitigation. For the full potential to be realized, work still remains on maximizing the direct storage of CO_2 emissions into our vast and available subsurface reserves. At the current rate, CO_2 storage by 2050 is projected to be just above 700 Mtpa, just one-tenth of what is required. Meeting these storage ambitions seems unlikely by 2050 unless worldwide coordinated efforts and a more rapid change in policy takes place.

Encouraging the engagement of both governments and multinational companies with the expertise and resources to help facilitate CCS technology is key. While those nations and regions with established and commercial hydrocarbon industries are best placed to enable the transition toward the growth in CCS activity and a renewables-based future, maintaining a government-led approach to the effort remains pivotal. A rapid step-change in policies is required that ensures that decarbonization is not pushed down the agenda. A direct approach might include regulating company strategies that outline plans for hydrocarbon extraction where a requirement for CO_2 storage to offset emissions must be integrated post-extraction. In addition, ensuring more direct targeting and funding for new (or retrofit) deployment projects toward the hard-to-abate sectors, where CCS is by far the best short-term mitigation option and where the technology already exists, may be an ‘‘oven-ready’’ solution in need of acceleration.

It is clear that development of CCS still has much to offer in the short term, as well as being essential in reaching the longer-term ambition of a sustainable level of net-zero emissions. Despite this, the promises of significant government support and ambitious building programs over the last decade have fallen short of expectations, resulting in a failure to capitalize from early developments and diversification to maintain a continuous ‘‘learning-by-doing’’ CCS culture.

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AUTHOR CONTRIBUTIONS

Conceptualization, V.S., S.G., R.S.H., and E.M.-R; writing – original draft, E.M.-R.; writing – review & editing, E.M.-R., V.S., S.F., G.J., and S.G.; funding acquisition, V.S. and S.G.; supervision, V.S. and S.G.; data gathering and analysis, S.F., E.M.-R., R.S.H., and V.S.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Global CCS Institute (2019), Global Status of CCS Report 2019, Melbourne, Australia.
2. IEA (2020a). Energy Technology Perspectives 2020. Special Report on Carbon Capture Utilisation and Storage. CCUS in Clean Energy Transitions (IEA). https://webstore.iea.org/download/direct/4191.
3. IEA (2021). Net Zero by 2050, A Roadmap for the Global Energy Sector (IEA). https://www.iea.org/reports/net-zero-by-2050.
4. Global CCS Institute (2020), Global Status of CCS Report 2020. Melbourne, Australia.
5. Scott, V., Gilfillan, S., Markusson, N., Chalmers, H., and Haszeldine, R.S. (2012). Last chance for carbon capture and storage. Nat. Clim. Chang. https://doi.org/10.1038/NCLIMATE1695.
6. IEA (2016a). 20 Years of Carbon Capture and Storage: Accelerating Future Deployment (Organisation for Economic Co-operation and Development (OECD) and International Energy Agency (IEA)).
7. UNFCCC (2021). Communication of Long-Term Strategies. https://unfccc.int/process/the-paris-agreement/long-term-strategies.
8. Loria, P., and Bright, M.B.H. (2021). Lessons captured from 50 years of CCS projects. Electricity J. *34*, 106998.
9. UNFCC (2016). Report of the Conference of the Parties on its Twenty-First Session, Held in Paris from 30 November to 13 December 2015 (United Nations Framework Convention on Climate Change (UNFCC)).
10. Energy Technology Perspectives (2010). Scenarios and Strategies to 2050 (IEA). https://webstore.iea.org/download/direct/727?fileName=etp2010.pdf.
11. IEA (2019a). Exploring Clean Energy Pathways. The Role of CO2 Storage (IEA). https://webstore.iea.org/exploring-clean-energy-pathways.
12. GCCS Institute CO_2RE Facilities Database, (2020). Available online: https://co2re.co.
13. IEA (2019b). World Energy Outlook 2019 (IEA). https://www.iea.org/reports/world-energy-outlook-2019.
14. Haszeldine, R.S. (2009). Carbon capture and storage: how green can black be? Science *325*, 1647.
15. Haszeldine, R.S., Flude, S., Johnson, G., and Scott, V. (2018). Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. Phil. Trans. R. Soc. *A376*, 20160447.
16. IEA (2020b). CCUS in Power, Tracking Report (IEA). https://www.iea.org/reports/ccus-in-power.
17. IPCC (2018). Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways. In The Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty, V. Masson-Delmotte, P. Zhai, H.O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, and R. Pidcock, et al., eds. (IPCC).
18. IPCC, (2021). Climate Change 2021, the Physical Science Basis. Working Group 1 Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.
19. Hammond, G.P., and Spargo, J. (2014). The prospects for coal-fired power plants with carbon capture and storage: a UK perspective. Energy Convers. Management *86*, 476–489.
20. IEEFA (2020a). Petra Nova Mothballing Post-Mortem: Closure of Texas Carbon Capture Plant Is a Warning Sign. https://ieefa.org/wp-content/uploads/2020/08/Petra-Nova-Mothballing-Post-Mortem_August-2020.pdf.
21. Morton, A. (2021). 'A Shocking Failure': Chevron Criticised for Missing Carbon Capture Target at WA Gas Project (The Guardian). https://www.theguardian.com/environment/2021/jul/20/a-shocking-failure-chevron-criticised-for-missing-carbon-capture-target-at-wa-gas-project. (Accessed 2 August 2021).
22. ADNOC. (2018). ADNOC Moving Ahead with Plans to Expand its CO2 Capture to Boost Oil Recovery. https://www.adnoc.ae/en/news-and-media/press-releases/2018/adnoc-moving-ahead-with-plans-to-expand-its-co2-capture. (Accessed 2 August 2021).
23. IRENA (2020). Making Green Hydrogen a Cost-Competitive Climate Solution. https://www.irena.org/newsroom/pressreleases/2020/Dec/Making-Green-Hydrogen-a-Cost-Competitive-Climate-Solution.
24. Sun, X., Alcade, J., Bakhtbidar, M., Elío, J., Vilarrasa, V., Canal, J., Ballesteros, J., Heinemann, N., Haszeldine, S., Cavanagh, A., et al. (2021). Hubs and clusters approach to unlock the development of carbon capture and storage—case study in Spain. Appl. Energy *300*. https://doi.org/10.1016/j.apenergy.2021.117418.
25. ECOFYS (2017). In ICCUS Readiness of UK Industrial Clusters: An Assessment, M. Stork and M. Schenkel, eds. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/759424/iccus-readiness-of-uk-industrial-clusters.pdf.
26. BEIS (2021). The Carbon Capture and Storage Infrastructure Fund. An Update on the Design of the CCS Infrastructure Fund (Department of Business, Energy and Industrial Strategy).
27. Equinor (2020). Historic Investment Decision for Transport and Storage of CO_2. https://www.equinor.com/en/news/2020-05-northern-lights.html.
28. Carbon Engineering (2019). Engineering of World's Largest Direct Air Capture Plant Begins. https://carbonengineering.com/news-updates/worlds-largest-direct-air-capture-and-sequestration-plant/.
29. IEA (2015). Carbon Capture and Storage: The Solution for Deep Emissions Reductions (International Energy Agency Publications).
30. Melzer, S. (2012). Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. Report for the National Enhanced Oil Recovery Initiative (Center for Climate and Energy Solutions).
31. IEA. Global Database of EOR Projects. Can CO_2-EOR Really Provide Carbon-Negative Oil?. https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil.
32. Núñez-López, V., and Moskal, E. (2019). Potential of CO_2-EOR for near-term decarbonization. Front. Clim. *1*, 5. https://doi.org/10.3389/fclim.2019.00005.
33. IEA (2018). World Energy Outlook 2018 (IEA). https://www.iea.org/reports/world-energy-outlook-2018.
34. IEA (2019c). Can CO_2-EOR Really Provide Carbon-Negative Oil?. https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil.
35. Stewart, R.J., Johnson, G., Heinemann, N., Wilkinson, M., and Haszeldine, R.S. (2018). Low carbon oil production: enhanced oil recovery with CO_2 from North Sea residual oil zones. Int. J. Greenhouse Gas Control *75*, 235–242.
36. Beck, L. (2020). Carbon capture and storage in the USA: the role of US innovation leadership in climate-technology commercialization. Clean. Energy *4*, 2–11.
37. Townsend and Havercroft (2019). Global CCS Institute Policy Report: The LCFS and CCS Protocol: An Overview for Policymakers and Project Developers (GCCSI).
38. Folger, P. (2018). Carbon Capture and Sequestration (CCS) in the United States. Congressional Research Service Report. https://fas.org/sgp/crs/misc/R44902.pdf.
39. Registry, N.D.C. (2020). Norway. https://www4.unfccc.int/sites/NDCStaging/pages/Party.aspx?party=NOR.
40. Norwegian Petroleum (2020). Norwegian Petroleum Production Forcasts. https://www.norskpetroleum.no/en/production-and-exports/production-forecasts/.
41. Price, J.P. (2014). Effectiveness of Financial Incentives for Carbon Capture and Storage (Bluewave Resources, LLC. USA. IEAGHG).
42. Kongsjorden, H., Kårstad, O., and Torp, T.A. (1998). Saline aquifer storage of carbon dioxide in the Sleipner project. Waste Manag. *17*, 303–308.
43. Tjernshaugen, A. (2011). The growth of political support for CO_2 capture and storage in Norway. Environ. Polit. *20*, 227–245. https://doi.org/10.1080/09644016.2011.551029.

44. GCCS Institute (2009). Strategic Analysis of the Global Status of Carbon Capture and Storage. Report 3: Country Studies: Norway (HWL Global CCS Institute).
45. IEA (2011). Energy Policies of IEA Countries: Norway 2011 Review (IEA).
46. Ministry of Petroleum and Energy (2013). Change in Direction of Commitment to Carbon Capture and Storage, Press release No: 054/13. https://www.regjeringen.no/en/historical-archive/Stoltenbergs-2nd-Government/Ministry-of-Petroleum-and-Energy/Nyheter-og-pressemeldinger/pressemeldinger/2013/change-in-direction-of-commitment-to-car/id735970/.
47. IEA (2020c). World Energy Outlook 2020 (IEA). https://www.iea.org/reports/world-energy-outlook-2020.
48. National Development, and Reform Commission. (2007). China's National Climate Change Programme.
49. Dahowski, R.T., Li, X., Davidson, C.L., Wei, N., and Dooley, J.J. (2009). Regional Opportunities for Carbon Dioxide Capture and Storage in China: A Comprehensive CO_2 Storage Cost Curve and Analysis of the Potential for Large Scale Carbon Dioxide Capture and Storage in the People's Republic of China (No. PNNL-19091) (U.S. Department of Energy, National Energy Technology Laboratory).
50. Zhang, K., Xie, J., Li, C., Hu, L., Wu, X., and Wang, Y. (2016). A full chain CCS demonstration project in northeast Ordos Basin, China: operational experience and challenges. Int. J. Greenh. Gas Control *50*, 218–230. https://doi.org/10.1016/j.ijggc.2016.04.025.
51. Gibbs, M.K. (2016). Effective Enforcement of Underground Storage of Carbon Dioxide (HWL Ebsworth Lawyers).
52. Jiang, K., Ashworth, P., Zhang, S., Liang, X., Sun, Y., and Angus, D. (2019). China's carbon capture, utilization and storage (CCUS) policy: a critical review. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2019.109601.
53. IEA (2016b). Energy Policies of IEA Countries: Japan 2016 Review (IEA).
54. Reuters. (2021). Japan to Tighten Rules on Coal Power Exports to Meet G7 Vow. https://www.reuters.com/business/sustainable-business/japan-tighten-rules-coal-power-exports-meet-g7-vow-2021-06-18/.
55. Mission Innovation, Saudi Arabia. http://mission-innovation.net/participating-countries/saudi-arabia/
56. World Coal Association (2016). Coal in the Energy Mix of India. https://www.worldcoal.org/coal-energy-mix-india.
57. IEEFA (2020b). No Foreign Players Will Bid in India's Auction of Coal Blocks. https://ieefa.org/ieefa-update-no-foreign-players-will-bid-in-indias-auction-of-coal-blocks/.
58. Government of India. (2018). India: Second Biennial Update Report to the United Nations Framework Convention on Climate Change. https://unfccc.int/sites/default/files/resource/INDIA SECOND BUR High Res.pdf.
59. Gupta, A., and Paul, A. (2019). Carbon capture and sequestration potential in India: a comprehensive review. Energy Proced. *160*, 848–855.
60. Zahasky, C., and Krevor, S. (2020). Global geologic carbon storage requirements of climate change mitigation scenarios. Energy Environ. Sci. https://doi.org/10.1039/D0EE00674B.
61. SCCS (2020). Global CCS Map. Scottish Carbon Capture and Storage. https://www.sccs.org.uk/expertise/global-ccs-map.
62. IEA (2009). The IEA CCS Roadmap. Contributing to Global Climate Goals. Technology Roadmap Carbon Capture and Storage (IEA).
63. GCCS Institute (2018a). 2018 Thought Leadership Report. The Carbon Capture and Storage Readiness Index 2018: Is the World Ready for Carbon Capture and Storage?. https://www.globalccsinstitute.com/archive/hub/publications/202108/ccs-readiness-index-2018global-ccs-institute-2018digital.pdf.
64. GCCS Institute (2018b). 2018 Thought Leadership Report. CCS Storage Indicator (CCS-SI). https://www.globalccsinstitute.com/archive/hub/publications/202110/ccs-storage-indicatorglobal-ccs-institute2018digital.pdf.
65. Consoli, C.P., and Wildgust, N. (2017). Current status of global storage resources. Energy Proced. *114*, 4623–4628.
66. GCCS Institute (2016). Global Storage Portfolio: A Global Assessment of the Geological CO_2 Storage Resource Potential. https://www.globalccsinstitute.com/wp-content/uploads/2020/01/Consoli_Global-CCS-Institue_2015_Global-Storage-Portfolio-1.pdf.
67. Ringrose, P.S., and Meckel, T.A. (2019). Maturing global CO_2 storage resources on offshore continental margins to achieve 2DS emissions reductions. Sci. Rep. Nat. Commun. *9*, 17944.
68. IEAGHG (2017). CCS Deployment in the Context of Regional Developments in Meeting Long-Term Climate Change Objectives (IEAGHG). https://ieaghg.org/docs/General_Docs/Reports/2015-TR3.pdf.
69. Transition Pathway Initiative (2020). Carbon Performance of European Integrated Oil and Gas Companies: Briefing Paper (TPI). https://www.transitionpathwayinitiative.org/publications.
70. Fletcher, L., Crocker, T., Smyth, J., and Marcell, K. (2018). CDP Report: Beyond the Cycle. Which Oil and Gas Companies Are Ready for the Low-Carbon Transition?.
71. Shell Sky Scenario (2020). Sky Scenario. https://www.shell.com/energy-and-innovation/the-energy-future/scenarios/shell-scenario-sky.html.
72. Shell. (2020). Nature Based Solutions. https://www.shell.com/energy-and-innovation/new-energies/nature-basedsolutions.html.
73. Zimmermann, A.W., Wunderlich, J., Müller, L., Buchner, G.A., Marxen, A., Michailos, S., Armstrong, K., Naims, H., McCord, S., Styearing, P., et al. (2020). Techno-economic assessment guidelines for CO_2 utilization. Front. Energy Res. *8*, 5. https://doi.org/10.3389/fenrg.2020.00005.
74. Stewart, R.J., and Haszeldine, R.S. (2014). Carbon Accounting for Carbon Dioxide Enhanced Oil Recovery (Scottish Carbon Capture & Storage).
75. World Bank Group (2020). Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org.
76. IEA (2020d). China's Emissions Trading Scheme. Designing Efficient Allowance Location (IEA).
77. European Comission (2021). Carcon Border Adjustment Mechanism. https://ec.europa.eu/taxation_customs/green-taxation-0/carbon-border-adjustment-mechanism_en.
78. Havercroft, I., and Macrory, R. (2014). Legal Liability and Carbon Capture and Storage, A Comparative Perspective. https://www.globalccsinstitute.com/archive/hub/publications/179798/legal-liability-carbon-capture-storage-comparative-perspective.pdf.
79. Havercroft, I. (2019). Lessons and Perceptions: Adopting a Commercial Approach to CCS Liability (GCCSI report). https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Adopting-a-Commercial-Appraoch-to-CCS-Liability_Thought-Leadership_August-2019.pdf.
80. Haszeldine, R.S. (2011). 'Geological Factors in Framing Legislation to Enable and Regulate Storage of Carbon Dioxide Deep into the Ground' in Havercroft, Macrory and Stewart Carbon Capture and Storage – Legal and Regulatory Issues (Hart Publishing), Oxford at 13.
81. Budinis, S., Krevor, S., Mac Dowell, N., Brandon, N., and Hawkes, A. (2018). An assessment of CCS costs, barriers and potential. Energy Strategy Rev. *22*, 61–81.
82. McQueen, N., Psarras, P., Pilorgé, H., Liguori, S., He, J., Yuan, M., Woodall, C.M., Kian, K., Pierpoint, L., Jurewicz, J., et al. (2020). Cost analysis of direct air capture and sequestration coupled to low-carbon thermal energy in the United States. Environ. Sci. Technol. *54*, 7542–7551.
83. Pilorgé, H., McQueen, N., Maynard, D., Psarras, P., He, J., Rufael, T., and Wilcox, J. (2020). Cost analysis of carbon capture and sequestration of process emissions from the U.S. industrial sector. Environ. Sci. Technol. *54*, 7524–7532.
84. Psarras, P., He, J., Pilorgé, H., McQueen, N., Jensen-Fellows, A., Kian, K., and Wilcox, J. (2020). Cost analysis of carbon capture and sequestration from U.S. natural-gas fired power plants. Environ. Sci. Technol. *54*, 6272–6280.
85. Commission (EU) (2015). 'European Commission Report on Review of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide of 11 November 2015' (Communication) COM (2015) 576 Final, Annex 2.
86. Weber, V. (2018). Uncertain liability and stagnating CCS deployment in the European Union: is it the member states' turn? RECIEL *27*, 153–161.
87. Alcalde, J., Flude, S., Wilkinson, M., Johnson, G., Edlmann, K., Bond, C.E., Scott, V., Gilfillan, S.M.V., Ogaya, X., and Haszeldine, S. (2018). Estimating geological CO_2 storage security to deliver on climate mitigation. Nat. Commun. *9*, 2201.
88. IEAGHG (2012). Quantification Techniques for CO_2 Leakage.
89. Koornneef, J., Ramírez, A., Turkenburg, W., and Faaij, A. (2012). The environmental impact and risk assessment of CO_2 capture, transport and storage—an evaluation of the knowledge base. Prog. Energy Combust. Sci. *38*, 62–86.
90. Reiner, D., Curry, T., deFigueredo, M., Herzog, H., Ansolabehere, S., Itaoka, K., Aka, M., Johnsson, F., and Odenberger, M. (2006). An international comparison of public attitudes towards carbon capture and storage technologies. In Paper presented at GHGT-8, 8th International Conference on Greenhouse Gas Control Technologies, Tronheim, Norway, June 19-22, 2006.
91. Whitmarsh, L., Xenias, D., and Jones, C.R. (2019). Framing effects on public support for carbon capture and storage. Palgrave Commun. *5*, 17.

92. Kearney Energy Transition Institute (2021). Carbon Capture Utilization and Storage (Towards Net-Zero).

93. Ragden, P., Irons, R., and Schoenmakers, H. (2013). Too early or too late for CCS—what needs to be done to overcome the valley of death for carbon capture and storage in Europe? Energy Proced. *37*, 6189–6201.

94. IEA (2021). After Steep Drop in Early 2020, Global Carbon Dioxide Emissions Have Rebounded Strongly. https://www.iea.org/news/after-steep-drop-in-early-2020-global-carbon-dioxide-emissions-have-rebounded-strongly.

95. Consoli, C.P. (2019). Bioenergy and Carbon Capture and Storage (Global CCS Institute report).

96. UKRI (2021). UKRI Awards £171m in UK Decarbonisation to Nine Projects (United Kindom Research and Innovation). https://www.ukri.org/news/ukri-awards-171m-in-uk-decarbonisation-to-nine-projects/.