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CARBON CAPTURE, UTILIZATION AND STORAGE (CCUS):

BARRIERS, ENABLING FRAMEWORKS AND PROSPECTS FOR CLIMATE CHANGE MITIGATION

INTRODUCTION

Carbon capture and storage (CCS) involves the trapping of man-made CO_2 underground to avoid its release into the atmosphere. Because of the scale with which it could be applied, CCS is identified as a critical technology to reduce CO_2 emissions to achieve global climate goals. The Intergovernmental Panel on Climate Change (IPCC) shows that most of the 1.5°C pathways assume significant use of CCS. For some energy-intensive hard-to-abate sectors such as steel and cement, technical options to reduce emissions without CCS are currently limited. CCS could reduce the cost of meeting climate targets as other sectors would otherwise have to pursue more expensive mitigation options. The Joint G20 Energy–Climate Ministerial Communiqué on July 2021 acknowledges the important role of carbon capture, use, and storage (CCUS) recognizing 'the need for investment and financing for advanced and clean technologies, including CCUS/Carbon Recycling' urging 'all members to formulate such long-term strategies that set out pathways consistent to achieve balance between anthropogenic emissions by sources and removal by sinks'.

This issue of the *Oxford Energy Forum* examines the recent trends in CCS and explores the regulatory and commercial barriers limiting the deployment of CCS at a large scale. The *Forum* opens with *Samantha McCulloch*'s article which provides an overview of the recent trends in CCUS, highlighting the immense challenge required to scale-up CCUS under net-zero pathways. The International Energy Agency (IEA) report *Net Zero by 2050: A Roadmap for the Global Energy Sector* highlights the need for an accelerated and ambitious scale-up of CCUS to meet net-zero goals. In this scenario, almost 1.7 billion tonnes (Gt) of CO_2 are captured across the global energy system by 2030 – a more than 40-fold increase from today. Also, by 2050, carbon management would be a major industry, with 7.6 Gt of CO_2 captured, transported, and used (around 5 per cent of the total) or geologically stored. On a positive note, there has been recently an increased momentum in project activity; in 2021 alone, plans for more than 100 new CCUS projects were announced, and such projects are now operating or under development in 25 countries around the world. If all these projects were to go ahead, global CO_2 capture capacity would quadruple by 2030. However, despite recent progress, the author argues that this is not sufficient for the world to be on track for net-zero goals. Even if all CCUS projects in planning were to successfully navigate the path to commercial operations, the global capture rate in 2030 would be less than 15 per cent of that needed in the IEA Net Zero Scenario. McCulloch identifies three priorities that can help scale the contribution of CCUS from tens of millions of tonnes to gigatonnes of CO_2 capture within the next decade: (i) Establish policies that create sustainable and viable markets for CCUS investment, (ii) target industrial clusters (or hubs) with shared infrastructure, and (iii) identify and develop CO_2 storage.

Ashok Belani and *Damien Gerard* argue that the world tried to deploy CCS at scale earlier this century, but a lack of sustained policy commitment, and some fundamental regulatory gaps, such as long-term liability management, have prevented this technology from large-scale adoption as a viable business opportunity. More recently, however, national net-zero commitments have repositioned CCS back on the map. The authors argue that the world is in a discovery phase, where potential players are firming up costs, testing options, navigating the regulatory environment, and looking for partners. Through this discovery phase, industries with access to streams of CO_2 are learning how to construct viable business models to establish CCS as a commercial industry on its own. The authors note that unlike renewables, CCS is not a business per se, as it does not result in selling a product or anything of value such as power. Instead, it is a climate change mitigation solution, and it allows us to keep producing commodities that are consumed each day but with a lower carbon footprint. The only way to justify investment in CCS is to create a value mechanism on decarbonization; this could be driven by a policy or a regulation, or by a market incentive such as a green premium, recognized by both governments and consumers for the decarbonized product or service. Belani and Gerard conclude that there is no choice but to establish this activity as a viable business, and when it becomes a thriving business, the size of this opportunity will be larger than the whole oil industry, with the key difference being that the demand does not need to develop over decades; the whole demand is available right now.

Adam Whitmore carries on this theme and argues that support contracts, such as carbon contracts for difference (CCfD) on the carbon price, are attracting increasing attention as a way of supporting deployment of Carbon Capture and Storage (CCS) and other low-carbon technologies. The author discusses in some detail the various elements of these contracts, including the price mechanism, the contract duration, the allocation of free allowances, and changes to payment over time. Whitmore argues that in principle such contracts that remunerate the use of low-carbon technologies can be a powerful mechanism for stimulating their deployment, because they give a firm revenue stream that enables companies to invest. However, in these contracts, as with many commercial contracts, there is always a range of risks that need to be allocated and a variety of incentives that will be created. Therefore, the author calls for a careful consideration of contract structures and terms as being necessary in designing effective policy in this area.

Paul Zakkour and *Wolfgang Heidug* present a novel supply-side climate policy to value carbon sinks. They argue that without enduring policies that attribute value to the act of storing CO_2 in carbon pools other than the atmosphere, the requisite increases in enhanced carbon sinks and reservoirs aligned to a global net-zero emissions balance will not be achieved at sufficient speed and scale to prevent dangerous global warming. They propose the establishment of a carbon storage unit (CSU) which can provide a monitored, verified, trusted, and transferable record of the addition of one ton of CO_2 to carbon sinks; primarily, geological CO_2 storage sites. Where policy creates value for CSUs, a price signal for storing carbon is generated. This price can complement the value for emission units typically applied to users of fossil fuels in demand-side climate policies – such as carbon pricing instruments like the capped emissions trading schemes applied to countries, regions, and industrial emission sources.

Enhancing public acceptance of CCUS as a viable and effective mitigation technology is another key factor for large-scale deployment. *Darrick Evensen* provides a brief overview of public perceptions research into CCUS. The author notes that a core assumption, and repeatedly empirically validated maxim, of the social scientific research on both CCUS and novel energy technologies more broadly, is that without public acceptance, technologically robust and economically viable development will fail. Evensen argues that trust in the institutional actors responsible for implementing or regulating projects is regularly revealed as the most important factor that shapes risk and benefit perceptions and has a much larger effect on risk and benefit perceptions than knowledge of CCUS does. The risk and benefit perceptions are, in turn, important determinants of support for CCUS. The author summarizes some of the key risks and benefit perceptions associated with CCUS. These have been shown to differ notably between countries, areas with potential for CCUS implementation, offshore vs onshore deployment, the source from which the carbon came, and the stage in the CCUS process. Evensen also notes that an important aspect of public interaction with CCUS is the level of public awareness and specific knowledge about CCUS, which is often quite limited. The author discusses the implications of this feature on the design of communication strategies and public acceptance.

Bassam Fattouh examines the role of CCS as an enabling technology for the production of low-carbon hydrogen from fossil fuels, which is considered by many as essential to decarbonize a wide range of sectors including heavy industry, the heat and power sectors, and transport. In a net-zero CO_2 emissions world, hydrogen plants will need to reduce residual emissions to the minimum. The higher the residual CO2 emissions, the stronger the argument that blue hydrogen can only play a transitional role before moving on to the ultimate objective of producing green hydrogen. To achieve economies of scale and technological advances, new business models need to emerge. One way to reduce risks is to disaggregate the capture, transport, and storage components of the CCS technology chain, allowing different market actors with different strengths and risk appetites to collaborate on CCS. Also, outside EOR and carbon utilization, there are no revenues associated with CCS (as is the case for renewable electricity generation) that can compensate for the upfront and operational costs. One way to generate value for such activity is for governments to introduce carbon pricing either in the form of carbon taxes and/or emissions trading schemes. However, such schemes may not be enough on their own and other forms of support – such as direct government support or developing instruments specifically to support CCS and also blue hydrogen, such as setting hydrogen portfolio standards – are needed. Also, CCS consists of a series of activities and involves multiple stakeholders (government authorities, operators, investors, and the public) and therefore a regulatory framework that assigns the different rights and responsibilities of the various stakeholders is essential.

The second part of the *Forum* focuses on regional and country experiences. *Graeme Sweeney* looks at prospects and challenges of CCS in the EU. The author argues that the 2020s are critical to setting Europe on the right track to reach climate neutrality by 2050, and CCS technologies will be key in the industrial transition towards net-zero GHG emissions. Political recognition of CCS and CO_2 transport and storage infrastructure, which is vital for European decarbonization, is key, and support for CO_2 transport and the inclusion of CO_2 storage and all modalities of CO_2 transport in EU legislation is necessary. With an increasing number of market-ready CCS projects in Europe moving towards becoming operational within this decade, there is a strong need to support this progress. An EU strategy for CCS should enable a predictable and long-term framework for investors to be put in place. The strategy should also encourage and support collaboration between the EU member states and the EU Commission, as well as European industry and the CCS community.

Malcolm Keay's article looks at the prospective development of CCUS in the United Kingdom, on which the government has recently published a number of consultation papers in the wider context of its Net Zero Review. The author argues that the government is supporting individual projects and applications without any overall strategy, thus increasing the risk of making the same mistakes as it did with electricity. In the electricity sector, the government has supported individual technologies (mainly renewables but also, less successfully, nuclear) without regard to the wider system effects, leading to a range of unintended consequences and system-wide inefficiencies. Keay concludes that unless the government starts to think about energy systems in wider strategic terms, the next stage of decarbonization will raise even greater challenges and lead to even more serious problems.

Jon C. Knudsen, David Phillips, Emil Yde Aasen, and Hallvard Valen reflect on the experience of CCS in Norway. The authors note that CCS support in Norway is higher than in other countries and is influenced potentially by two factors: (i) being an effective CO_2 abatement tool and (ii) being a future industry for Norway. The authors argue that while climate regulations including carbon pricing are not yet strong enough to make CCUS economically appealing in all cases, dismissing the technology on cost grounds would be to ignore its unique strengths, its competitiveness in key sectors, and its potential to enter the mainstream of low-carbon solutions. Beside cost, the authors note that it is important to reduce the technical and commercial complexities facing emitters wanting to implement CCS with their operations; it is thus important to develop new and innovative business model such as Carbon Capture as a Service (CCaaS) which could overcome many of the commercial challenges.

Ragni Rørtveit, *Ida Egeland* and *Eirik Wærness* continue on the same theme, focusing on CCS in Norway and drawing lessons for commercialization across Europe. The authors argue that while the technology has been in operation for over 20 years, the value chains and business models have not been in place to commercialize and subsequently build scale. The current vertically integrated value chain has not opened for other industries to leverage CCS as an effective decarbonization tool. Norway is now developing a full-scale government funded CCS value chain, called Longship and, according to the authors, the opening of the value chain from an in-house single-train CO_2 'conveyor belt' to an open source, commercially available market is where the Longship project represents a first of its kind. By modularizing the value chain to include a transport component with ships, all emitters with access to a jetty can theoretically tie in to the CCS infrastructure. The authors conclude that this full-scale demonstration project is of paramount importance as a pathfinder, but the volumes are negligible relative to the global carbon challenge and thus speeding and scaling up, based on the experience from Longship and other industry projects, will be essential.

Sanne Akerboom and *Gert Jan Kramer* reflect on the Dutch approach to CCS. An interesting aspect of the Dutch experience is the treatment of CCS as a transition technology. Industry, government, and environmental NGOs have agreed to subsidize CCS projects until 2035, after which other reduction technologies must have emerged or CCS must proceed unsubsidized. The authors argue that as a 'transition technology' CCS faces a dual challenge: First, how to scale up CCS this decade and second how to transition away from it in the longer term – the end of subsidy beyond 2035 being a milestone in this transition process. This inherent contradiction may reinforce existing uncertainties in the realization of CCS and could cause a delay in the decarbonization of industry. The authors argue that a potential successful pathway is to transition from CCS to CCU.

Ashraf Ghazzawi and Ahmad Khowaiter look at CCS opportunities and deployment enablers in the light of the Kingdom of Saudi Arabia's announcement of its ambition to achieve net-zero emissions by 2060 and Saudi Aramco's commitment to achieving net-zero Scope 1 and Scope 2 GHG emissions across its wholly-owned operated assets by 2050 by harnessing the principles of the Circular Carbon Economy (CCE). Among many other low-carbon solutions, CCUS is a key climate mitigation solution in the CCE framework. The authors note that captured carbon dioxide can be used as a feedstock that contributes to many value chains, including sustainable farming, the beverage industry, and as a solvent for many extraction processes such as decaffeinated coffee production. CCUS can also enable the production of hydrogen by capturing CO_2 at hydrogen production facilities, an area where Aramco sees a significant role for CCS. The authors argue that Aramco's experience in subsurface operations and in running large-scale CCS projects, together with its integrated and complementary infrastructure that spans the entire energy value chain, provides the company with a unique position to develop a large-scale hydrogen business. As part of its R&D activities, Aramco has been operating a large-scale CCUS project since 2015, capturing and injecting up to 0.8 MTPA for EOR. SABIC (an Aramco affiliate) has been capturing up to 0.5 MTPA of CO_2 since 2015 for methanol, urea, and food grade CO_2 production. The authors argue that these early opportunities are key to building the scale, accumulating know-how, and establishing the business models for increased CCUS deployment; however, for CCUS to deliver on its full potential in a CCE approach, government and the private sector should work together and establish the appropriate policies to enable rapid deployment of the technology. The authors conclude that the scale and continuity of capital investments in renewables demonstrates the effectiveness of policy incentives to commercialize technologies and develop innovative business models, and with a similar approach and a more coordinated global effort, CCUS technologies can develop in a similar manner.

Nnaziri Ihejirika looks at CCUS potential and prospects in Canada, which is considered a world leader in CCUS with three world-class projects built since 2014, and several more in various stages of development. The author notes that these projects had significant financial backing from the provincial and federal governments, evidence of the importance attached to demonstrating and deploying CCUS. However, there are few clearly defined policies to support the commercial scaling of carbon capture. This has led to concerns that investment will suffer on two fronts – insufficient funding for proposed CCUS-related projects, and continued divestment from the resource extraction sector. According to Ihejirika, highlighting the value of industrial CCUS as an enabler of DACCS (direct air capture with carbon storage) and BECCS (bioenergy with CCS) will be important in securing the support of environmental groups and other stakeholders. A stable regulatory climate will also provide clarity to investors, while collaborations between firms will support alignment and cost-learning on the various CCUS technologies. The author concludes that early signs on both fronts are positive, but certainty in the form of legislation and sanctioned projects is required if carbon capture is to achieve its promise of becoming a core part of Canada's energy transition.

Philip Andrews-Speed looks at China's policies and action on CCUS. He argues that the development and deployment of carbon capture technologies in China has lagged behind that of most advanced countries. Whilst the central and local governments have issued several plans and notices that mention CCUS, or address the topic in more detail, a coherent set of policies and regulations has still not been formulated. As of November 2021, China has published no detailed plan for CCUS, no targets, no commercial incentives, no law, and no specific regulations and procedures. The author argues that it is not possible, at present, to project the rate of growth of CCUS in the country, nor the manner in which the technologies will be deployed. Nevertheless, given the likelihood that coal will play a significant role in the nation's energy mix for many years to come, it is to be hoped that the government will address these deficiencies soon, due to its stated commitment to reach net-zero greenhouse gas emissions by 2060. However, there is as yet no evidence that CCUS is high on the policy agenda.

Bassam Fattouh, Wolfgang Heidug, and Paul Zakkour argue that CCS has mostly been approached from a project developer's perspective, putting in place frameworks that spread risks and costs, and enabling the deployment of CCS in specific geographical contexts. However, for oil and gas producing countries, the perspective is much wider. CCS relates to the future of oil and gas and the vital role these sectors play in shaping their economies and the welfare of their people. It also relates to maintaining and establishing key sources of competitive advantage in leading sectors. According to the authors, oil and gas exporters must take a leading role in scaling up CCS and geological storage. Also, to enable investments in CCS and minimize the adverse impact on their economies and public finances, oil and gas exporters should take a leading role in developing burden sharing mechanisms that generate new sources of revenues for CCS projects and/or allow for the costs to be shared both across the supply chain and between fossil fuel exporters and importers. The authors argue that herein lies the importance of developing frameworks and mechanisms that give value to permanently storing CO_2 away in enhanced sinks located in oil and gas exporting countries and integrating these into climate finance. This requires the introduction of innovative mechanisms and harmonization of policies, together with strong cooperation either through multilateral or bilateral agreements, or clubs of like-minded countries. Such cooperative frameworks are key to deploying large-scale CCS and to enabling oil and gas exporters on their path towards low emissions strategies and to ensuring a cost effective, inclusive, and just transition.

The final part of the *Forum* focuses on carbon dioxide removal (CDR) solutions and the increasing role these technologies will play in net-zero paths. *Hasan Muslemani* reviews some key issues pertaining to the most common forms of carbon dioxide removal (CDR) solutions with a focus on tech-based solutions – Direct Air Capture (DAC), CO_2 utilization in production processes, biochar production, and enhanced weathering. CDR (defined as the act of physically removing CO_2 from the atmosphere using natural processes, engineered technologies, or a hybrid of both) has become a vital part of the fight against the climate crisis, and action to support its deployment is now considered all but necessary. The author argues that in comparison to carbon avoidance, carbon removal enjoys an advantage as it exhibits higher additionality, more tangible effects, and a direct and immediate impact on our climate. To top it off, removals can be easily measured in absolute terms, as opposed to carbon avoidance which relies on a multitude of assumptions regarding existing and future scenarios. Muslemani argues that as there is no one silver bullet to meeting the Paris Agreement climate targets, a portfolio of different solutions – from nature-based solutions (NbS) such as forestation and soil carbon sequestration, to tech-based solutions such as DAC and storing CO_2 in building materials, or producing energy from biomass where the facilities are retrofitted with carbon capture and storage technology (BECCS) – will be needed as different solutions bring about varied advantages in terms of cost, potential for scalability, existing policy support, ease of replicability in other regions, permanence or durability of carbon removal, and transparency of role in climate mitigation – the latter of which may significantly influence the public acceptance of those solutions.

Peter Freudenstein, *Louis Uzor*, and *Christoph Beuttler* look at the role of carbon dioxide removal in achieving the goals of the Paris Agreement. They argue that it is becoming increasingly clear that removing gigatons of CO_2 from the atmosphere annually, in addition to more ambitious emissions reductions, is the only way to achieve the goals of the Paris Agreement of reaching net-zero around 2050 and net-negative greenhouse gas emissions thereafter. The authors note that policymakers and companies have begun to step up to the challenge and increasing financial commitments are being made by corporate leaders as well as governments, such as the USA, the EU, and the UK, to scale permanent carbon dioxide removal (CDR) solutions, and in particular Direct Air Capture (DAC), but there is still a lot of ground to cover. The authors argue that to unlock this potential, a more concerted effort by all stakeholders to scale up DAC is needed. Specifically, policymakers must focus on developing, and advocating for, pragmatic policy options that can be implemented in the short term to aid CDR scale up and accelerate the buy-down of costs. Delaying action would result in having to double CDR capacity every year, making an already complex challenge even harder.

In another article, *Hasan Muslemani* continues with the theme of Direct Air Capture (DAC). The author notes that the indispensability of DAC developments towards meeting international, sectoral, and corporate climate targets has recently been reflected by global public policy support, including the US's dedication of $3.5 billion in funds for DAC infrastructure hubs and the UK's pledge of £100 million to develop DAC and other removal technologies. Deploying DAC along with NbS is considered key in achieving carbon neutrality or meeting corporate net-zero targets. This is also having implications on carbon markets. Until recently, the carbon offsets market has been dominated by 'avoidance' rather than 'removal' credits. Removals tend to achieve higher scores than avoidance due to their higher additionality. The author stresses, however, that DAC requires highly innovative and expensive installations that demand higher prices than typical offsets, and as a result the costs of DAC credits in the market have been in the range of $600–1000 per tonne of CO_2 removed. For DAC to be feasible, costs would need to drop from current levels to around $100/t$CO_2$. The author concludes on an optimistic note that significant cost reductions of deploying DAC are largely expected to occur with increased deployment and modularity of the technology.

SCALING CCUS TO MEET NET-ZERO GOALS

Samantha McCulloch

A net-zero energy system requires a profound transformation in the way we produce and use energy. CCUS can play a unique and important role in this transformation, as the only group of technologies that contribute both to direct mitigation efforts as well as to removing CO_2 in order to balance emissions that are challenging to avoid – a critical part of 'net' zero goals. The value of CCUS in the climate mitigation portfolio is increasingly being realized and momentum is growing globally, with plans for more than 100 new projects announced in 2021 alone. While encouraging, CCUS developments still fall well short of the scale-up required for net zero. New policy approaches, a focus on industrial clusters, and prioritized development of CO_2 storage can help to scale the contribution of CCUS from around 40 million tonnes (Mt) of CO_2 captured today to the gigatonnes needed within the next decade.

A key technology for net-zero

CCUS can help to bridge the gap between today's energy reality and a net-zero energy system. Retrofitting CCUS to existing power and industrial facilities can enable these assets to continue to operate and contribute to energy security, energy access, and economic development objectives in a way that is compatible with climate goals. Many of the world's power and industrial assets are located in emerging economies and are relatively recent investments: for example, nearly half of the predominantly fossil-based power fleet in Southeast Asia was built in the last decade.[1] Globally, today's power and industrial facilities could still emit around 8 billion tonnes of CO_2 in 2050.[2]

CCUS is a key technology for tackling emissions from heavy industry sectors. This is particularly the case for the cement sector, which accounts for around 7 per cent of global energy-related CO_2 emissions. Two-thirds of these emissions are not associated

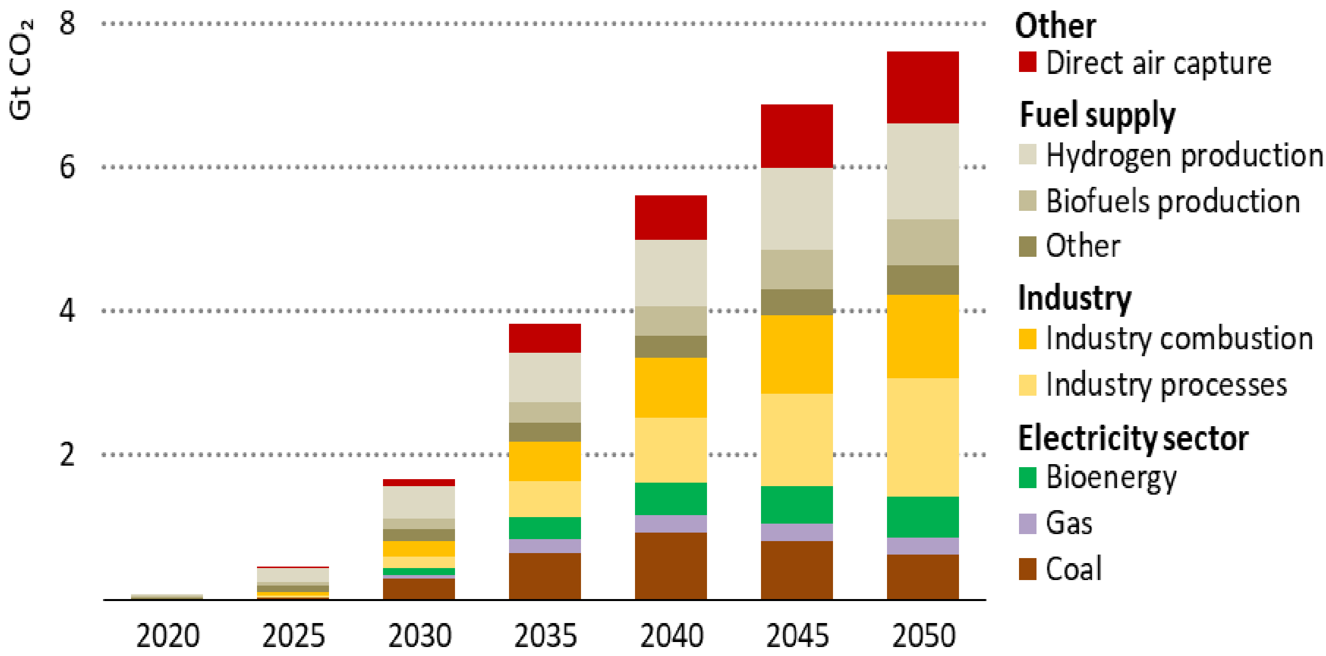
[1] 'Carbon capture, utilisation and storage: the opportunity in Southeast Asia', IEA Technology Report, June 2021.
[2] 'CCUS in Clean Energy Transitions', IEA Flagship Report, September 2020.

with the use of fossil fuels, but are chemical reactions from the calcination of limestone. These process emissions make achieving net-zero in the sector virtually impossible without CCUS.

CCUS also provides a cost-competitive pathway to scale the production of low-carbon hydrogen – an important energy vector for net-zero – and it underpins technology-based approaches to remove carbon from the atmosphere via direct air capture or bioenergy with CCS.

Reflecting this important and diverse role for CCUS, the landmark International Energy Agency (IEA) report 'Net Zero by 2050: A Roadmap for the Global Energy Sector' highlights the need for an accelerated and ambitious scale-up of CCUS to meet net-zero goals. In this scenario, almost 1.7 billion tonnes (Gt) of CO_2 are captured across the global energy system in 2030 – a more than 40-fold increase from today. By 2050, carbon management is a major industry in its own right, with 7.6 Gt of CO_2 captured, transported, and used (around 5 per cent of the total) or geologically stored.

Global CO_2 capture by source in the IEA Net Zero by 2050 Scenario



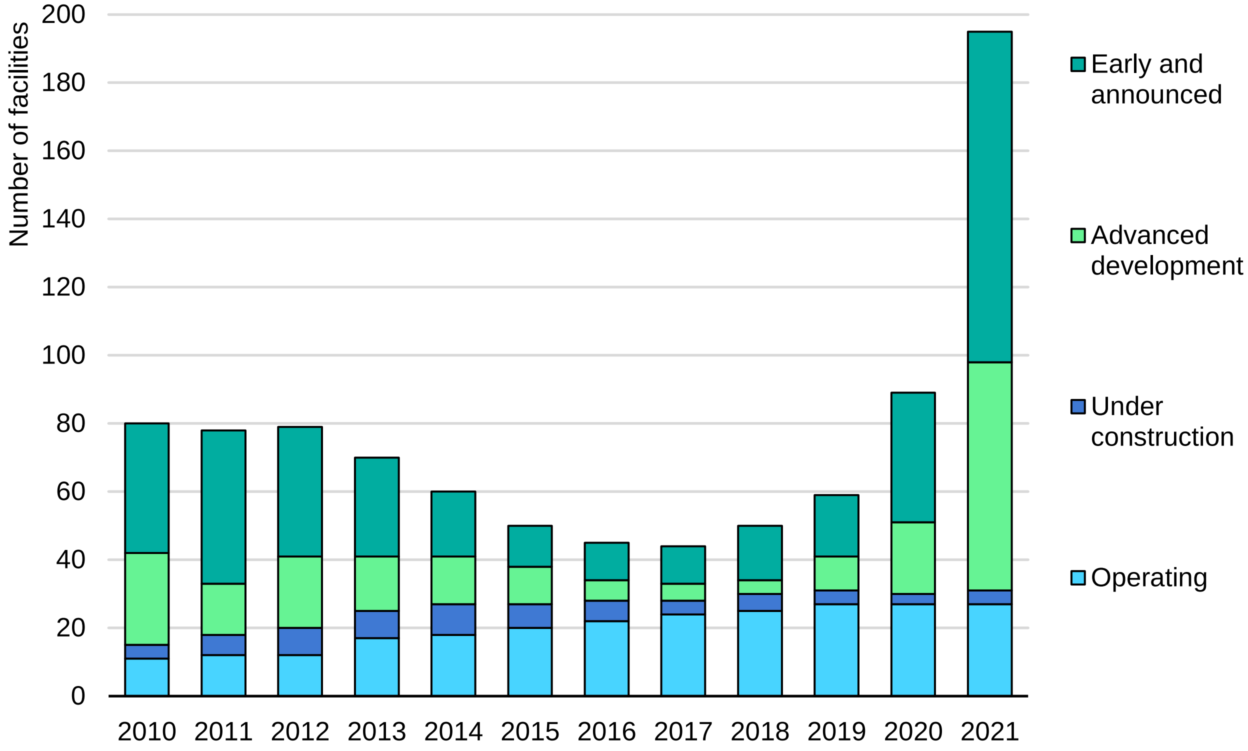
Unprecedented momentum for CCUS

Today, close to 30 commercial CCUS facilities are operating around the world, with capacity to capture over 40 million tonnes (Mt) of CO_2 a year. Some of these facilities have been operating for decades and progress has been relatively slow, with an average of around 3 $MtCO_2$ of new capacity added each year since 2010. Between 2010 and 2017, the global pipeline of planned CCUS projects shrank virtually every year.

This makes the advances for CCUS in recent years all the more remarkable. In 2021 alone, plans for more than 100 new CCUS projects were announced. CCUS projects are now operating or under development in 25 countries around the world and if all projects were to go ahead, the global CO_2 capture capacity would quadruple by 2030.

There are three key drivers for this boost in CCUS project activity. First is a growing recognition that CCUS is necessary to meet national, regional, and even corporate net-zero goals. The second relates to the growing interest in producing low-carbon hydrogen, with almost 50 planned facilities linked to hydrogen-related processes. Finally, the investment environment for CCUS has substantially improved as a result of new policy incentives, with governments and industry committing more than $25 billion in funding specifically for CCUS projects and programmes since the start of 2020.

Global pipeline of commercial CCUS facilities operating and in development



Source: IEA analysis and tracking; Global CCS Institute CCS Facilities Database https://co2re.co/

Getting to gigatonnes: priorities to scale CCUS

The recent progress for CCUS is encouraging but also not sufficient for the world to be on track for net-zero goals. Even if all CCUS projects in planning were to successfully navigate the path to commercial operation, the global capture rate in 2030 would be less than 15 per cent of that needed in the IEA Net Zero Scenario.

Further, it is almost certain that not all planned projects will proceed. Many will rely on increased policy support or are in competition for the same funding programmes, such as the EU Innovation Fund or the UK CCS Infrastructure Fund. The availability of CO_2 storage could act as a brake on investment if the identification, development, and permitting of these resources is not expedited. And public acceptance and engagement remains a major challenge in some regions, particularly for onshore CO_2 storage.

CCUS technologies are not alone in confronting a major challenge to roll out at a pace consistent with net-zero goals. Of 46 critical technologies monitored in the IEA's '[Tracking Clean Energy Progress]' analysis, only two are assessed as being on-track: electric vehicles and lighting. This sobering report card is a reflection of the unprecedented scale and pace of the energy transformation required for net-zero by 2050.

Getting CCUS on track will require an evolution in policy frameworks and a major focus on developing carbon management infrastructure, particularly geological CO_2 storage resources. Three priorities can help to scale the contribution of CCUS from tens of millions of tonnes to gigatonnes of CO_2 capture within the next decade:

1. **Establish policies that create sustainable and viable markets for CCUS investment.**

   Targeted policy support for CCUS will be critical to underpin investment at the scale and pace needed for net zero. There is no 'one size fits all' approach to effective CCUS policy design: policies may need to consider different CCUS applications, their maturity, cost, and regional preferences or circumstances. For example (and all things being equal), the level of incentive or support needed to equip a cement plant with CCUS (with costs upwards of $60 t/$CO_2$ captured) would be higher than for natural gas processing (a mature process with costs as low as $15 t/$CO_2$). In fact, new CCUS projects associated with natural gas processing are now planned in Southeast Asia without any public funding. Across the CCUS value chain, different policy approaches will be needed to facilitate early investment in CO_2 transport and storage infrastructure.

Grant funding programmes can play an important role in supporting less mature or more expensive applications of CCUS and for CO_2 transport and storage infrastructure. They can alleviate the high capital costs and commercial and technical risks for early projects. However, they can place a heavy burden on public budgets, they are typically limited to a small number of individual facilities, and can be time consuming in their implementation.

A rapid scale-up of CCUS will necessitate an increasing shift towards market-based measures that can complement grant funding and provide a stable and ongoing framework for CCUS facilities to operate over the long term. This evolution in policy is already emerging: the 45Q tax credit in the United States, which was expanded in 2018 to provide $50 t/$CO_2$ stored and $35 t/$CO_2$ used (including for enhanced oil recovery), has been a key driver of the boost in planned CCUS projects across a range of sectors, applications, and regions. In Europe, higher carbon prices are generating strong interest in CCUS, while Australia has made CCUS projects eligible for credits under the Emissions Reduction Fund, a key factor in the Moomba CCS project reaching a final investment decision in 2021.

2. **Target industrial clusters with shared infrastructure**

The development of industrial CCUS clusters with shared CO_2 transport and storage infrastructure can support economies of scale and make it feasible to capture CO_2 at a larger number of smaller industrial facilities, for which dedicated infrastructure may be impractical or uneconomic. Concentrating CO_2 infrastructure around these clusters can promote more efficient infrastructure investment in the near term and provide a basis from which to further expand CO_2 networks consistent with net-zero pathways.

Governments can play a leading role in the early planning and co-ordination of CO_2 transport and storage infrastructure, including support for the initial oversizing of capacity. The availability of excess capacity can substantially reduce lead times for future CCUS facilities and be a major factor in new facilities adopting CO_2 capture. The Alberta Carbon Trunk Line in Canada received significant government support (around $430 million), enabling it to be built with more than 90 per cent of its 14.6 MtCO_2 capacity free to accommodate future projects.

3. **Identify and develop CO_2 storage**

The availability of CO_2 storage could act as a brake on the roll-out of CCUS without a substantial increase in investment to develop geological resources. Although global CO_2 storage resources are considered well in excess of likely needs, the time to identify, characterize, and develop specific CO_2 storage sites can be in the range of 5–10 years or even longer, depending on the location, resource characteristics, and availability of existing data.

The time to develop CO_2 storage is typically much longer than the lead times for developing CO_2 capture facilities. In some regions, including Europe where CO_2 prices are rising and interest in capturing CO_2 is expanding, the demand for CO_2 storage has potential to outstrip the availability of supply in the coming decade.

The required scale-up for CCUS under net-zero pathways represents an immense challenge. However, the recent momentum in project activity together with opportunities to accelerate deployment through durable policies and strategic investment in infrastructure, including CO_2 storage, provides a strong foundation for CCUS to deliver the gigatonnes of abatement required this decade.

CARBON CAPTURE AND SEQUESTRATION – THE BUSINESS

Ashok Belani and Damien Gerard

Capturing large quantities of CO_2 and injecting it into the earth's subsurface has been done for more than 30 years. But so far, the majority of that CO_2 comes from natural gas processing as opposed to man-made emissions, and it is mostly re-used by the oil and gas industry to recover additional hydrocarbon. This process has little in common, either technically or commercially, with what CCS needs to be, if it is ever to become a solution to decarbonizing the systems of our planet.

The world tried to deploy CCS at scale earlier this century, but a lack of sustained policy commitment, and some fundamental regulatory gaps – such as long-term liability management – have prevented this technology from large-scale adoption as a viable business opportunity. More recently, national net-zero commitments have repositioned CCS back on the map. Fundamentally, no net-zero targets are achievable in a reasonable time frame without a high level of carbon abatement. A large number of scientific and economic reports issued by various agencies and financial institutions over the last twelve months, culminating recently in discourse during COP26, have all brought renewed focus and enthusiasm on the subject.

The number of projects in feasibility studies has skyrocketed from just a handful at the start of 2020, to more than 150 today. We are in a discovery phase where potential players are firming up costs, testing options, navigating the regulatory environment, and looking for partners. Very little money has been spent on building capture equipment or engineering storage resource in the subsurface; this year we will invest in CCS less than 1 per cent of the global solar spend. Through this discovery phase, industries with access to streams of CO_2 are learning how to construct viable business models to establish CCS as a commercial industry on its own.

Capture

CO_2 is rarely accessible as a standalone molecule that can be captured and disposed of. Instead, it is usually mixed with other gases produced in industrial processes, and the first step in the CCS value stream is to capture CO_2 from effluent gas streams.

A natural sequence in developing CCS projects is to start with streams that are relatively easy to access, such as those from biofuels or ammonia plants where the concentration of CO_2 in the flue gas is higher than 90 per cent and hence the capture cost is significantly lower. If economics do not work on high-concentration streams, then CCS as a business is unlikely to grow. Where possible, plants with such streams should serve as anchor tenants for the development of a hub (or cluster) and they will help build the initial infrastructure for transport and storage.

Subsequently, to deploy CCS at scale, we need to tackle hard-to-abate dilute streams, which will be made feasible if capture costs are brought down to $30/ton or lower. There are promising technology avenues using electro-swing adsorption, metal organic frameworks, and solid sorbents – all technologies in early experimentation and development phase. But these will take another decade before they become commercially available. Meanwhile we need to improve the efficiency of traditional amine solvents and create regional supply chains to reduce operating costs (including dedicated amine factories).

Beyond man-made emission streams, CO_2 can also be found in the air (in its most dilute form at 450 ppm, or 3000 billion tons). Direct Air Capture has grown in popularity over the past couple of years, and given the latest emission projections up to mid-century, it may be a much-required technology. Here we need fundamental science and technology breakthroughs to reduce costs by an order of magnitude, together with carbon trading mechanisms, to justify large-scale investment.

Sequestration

The use of CO_2 for enhanced oil recovery has been the preferred route in the US until now, but the objectives of net-zero clearly require much larger volumes of CO_2 to be sequestered permanently in the subsurface to enable the decarbonization process.

The majority of CO_2 will find its way into dedicated subsurface storage sites in deep saline formations. While there is ample storage potential globally, site selection and the permitting process are critical steps to mitigate the risks associated with safe, long-term sequestration.

Like the capture of emission streams, sequestration should also follow a natural sequence of development. Hubs will play an important role in reducing unit costs and spreading the risk over larger volumes of CO_2. At the same time, hubs are much more difficult to implement because they require the collaboration of several emitters and an alignment of incentives across the value chain. Governments could elect national champions to accelerate the overall process, as has been done in Europe in some instances.

Beyond hubs, there will still be many industrial sites where, close to an emission plant, storage will be local and still commercially viable. Further, as the costs of capture and storage technologies decrease, it will be commercially feasible to use offshore sites for storage, without being dependent on government subsidies.

The regulatory environment and the permitting process in key geographies are delaying the development of storage sites. It reflects the lack of maturity of the industry, and the lack of knowledge by regulators to establish fit-for-purpose rules of engagement. It will take a project developer three to four years just to obtain a Class VI injection permit (dedicated site) in the US, while the same process to inject CO_2 in an oil reservoir would take a few months, and a Class V permit (injection of industrial effluents) just a few weeks. The multi-million-dollar development cost of a storage site, together with a requirement to take on liability associated with carbon storage for decades post injection, are still deterrents to a rapid deployment at scale.

Business models and regulations

Unlike renewables, CCS is not a business per se, as it does not result in selling a product or anything of value such as power; it is really a climate change mitigation solution, and it allows us to keep producing commodities that we consume each day but with a lower carbon footprint. The only way to justify investment in CCS is to create a value mechanism on decarbonization; this could be driven by a policy or a regulation, or by a market incentive such as a green premium, recognized by both governments and consumers for the decarbonized product or service.

Today, established regulation providing a defined value for each ton of CO_2 captured and sequestered is only available in the United States under the 45Q Federal Regulation. In addition, California provides a specific incentive through the open market trading of low-carbon fuel credits under the LCFS state-administered market. These incentives do offer sufficient value to make projects commercial for certain CO_2 emission streams.

In Europe, the ETS (European Trading System) carbon price has been increasing steadily but remains volatile and uncertain and does not constitute – yet – a stable basis for long-term investment in CCS. It will need to be accompanied with a CCS-related policy or mandates.

A CCS project is composed of several activities that are quite different from each other, spanning the business profile of several industries, which means that few companies can claim the ability to develop the entire solution on their own. There is a component of gas separation, capture, and handling, best managed by industrial gas companies and specialized technology providers. There is an aspect of transport which is naturally owned by midstream or shipping companies. And there is the sequestration element which belongs best to the oil and gas industry or waste management players. All these activities are in addition to the capabilities of the emitter company, which owns the industrial process producing the emission stream.

In most cases, CCS will require partnerships among organizations covering all the activities of such projects, by companies that do not traditionally work together. One critical component will be to find business models that align incentives for all the participating companies to collaboratively engineer and execute the projects with large investments.

The next couple of years will be crucial for CCS to move from discovery and feasibility to development and execution. This step change will occur if governments enact attractive policies and if consumers start valuing products with a lower carbon footprint. Flagship projects will need to progress in key geographies, around the North Sea Rim, the US Gulf Coast, the Middle East, and Canada, among others. The task at hand is to construct or develop the right ecosystem, making projects technically and economically viable, and build the foundation of future large-scale networks.

It is true that CCS as a business has been attempted before, practically all over the world, and was not successful. However, we have no choice but to establish this activity as a viable business. When (and not if) it becomes a thriving business, the size of this opportunity is larger than the whole oil industry, with the key difference that the demand does not need to develop over decades, the whole demand is available right now. The rate at which this business can grow is only limited by our ability to establish viable business models and make the required investments. Because of the impact it will have on our lives and because of the large business opportunity, it will attract large investments over the coming decade. We will look back upon these years as the period which made a difference.

CONTRACTS TO SUPPORT DEPLOYMENT OF CARBON CAPTURE

Adam Whitmore

Support contracts are attracting increasing attention as a way of supporting deployment of Carbon Capture and Storage (CCS) and other low-carbon technologies. Support contracts seek, in effect, to provide payment for an environmental service (reduced emissions). They are legally binding, so they can provide certainty to investors. The counterparty will usually be government, or a government-supported entity such as a government-backed company. Such contracts have already successfully supported the deployment of renewables.

One form of contract, a contract for difference (CfD) on the carbon price, is being introduced or examined in a number of jurisdictions. CfDs are part of the Netherlands SDE++ system, the UK's planned support for Industrial Carbon Capture (though with modifications), and have been proposed for the EU's Innovation Fund. Because the contracts are written on the carbon price they are sometimes referred to as Carbon Contracts for Difference (CCfDs).

This article looks at how such contracts may be used to support industrial carbon capture. It does not consider regulation or pricing of transport and storage. It also excludes consideration of incentives or risk sharing across the chain – for example, what happens if transport or storage is unavailable – although such issues will be important in realizing projects.

Contract eligibility and the exclusion of CCU

Contracts are intended to support certain classes of technology, and there will be limits on eligibility. For example, the UK government has recently decided to exclude Carbon Capture and Use (CCU) projects at least from the first set of CCS support contracts.

The EU proposal

In July 2021 the European Commission proposed a CCfD design to support projects under the Innovation Fund, as part of its 'Fit for 55' package. The proposal illustrates the form of such a contract very clearly. It takes the form:

Yearly support = (strike price – average ETS price) * (ETS benchmark – actual emissions) * annual production

The level of price support is the difference between a set price (the strike price) and the carbon price under the EU ETS. The number of tonnes of CO_2 on which payment is made is calculated on the basis of benchmark minus remaining uncaptured emissions, per tonne of production. This represents the emissions reduction from an efficient factory.

The description of the proposals refers to a producer selling surplus allocated allowances, implying continuing free allocation of allowances to producers. However, the proposal would also be suitable under a regime of carbon border adjustment mechanisms (CBAMs).

Payments per tonne

Payment per tonne of CO_2 will likely form part of any contract because it provides incentives to operate the capture plant. Without such incentives the capture plant would risk remaining idle. This would, in turn fail to maximize the environmental benefits of the project. Technology learning would also be reduced.

An example of what can happen in the absence of such payment is given by the Petra Nova coal-fuelled power plant in the USA in 2020. The capture unit operated on the basis of revenues from enhanced oil recovery (EOR). When EOR became uneconomic because of falls in the oil price during 2020, the plant temporarily stopped capturing. It had not applied for incentives under the 45Q programme, which provides a credit of $35 per tonne stored for EOR projects (the payment is $50 per tonne stored for non-EOR projects). Had these payments been in place, the capture unit would have likely continued operating.

The design of the payment per tonne can have a significant effect on incentives. In contrast to the EU's proposal, some systems base payments on tonnes of CO_2 captured or stored. For example, the SDE++ support payments in the Netherlands are based on tonnes captured, as are volumes under the UK's proposed industrial carbon capture support contract.

However, this creates inefficient incentives, because it provides incentives for production of additional CO_2. If a factory reduces output of its main product while energy is cheap, it may continue to burn fuel and run it through the capture process because it's profitable. It may also switch to a higher-carbon fuel. It may essentially get into the CO_2 production and capture business – a

‘CO_2 factory’. Similarly, energy efficiency projects can become less profitable, because increased efficiency reduces energy use, and so leads to a loss of capture payments.

A better approach is to base payments on the reduction in emissions due to the operation of the CCS plant, as in the EU’s proposal. This represents much more closely the actual environmental benefit of the project (excluding some lifecycle emissions). Payments are not dependent directly on tonnes captured, so give no incentives for additional CO_2 to be produced. Instead, they do give incentives for increased capture rates, increased energy efficiency, or other changes that reduce residual emissions (the 5–10 per cent or so typically not captured). Residual uncaptured emissions need to continue to be priced and should not, for example, be excluded from a carbon pricing system because emissions fall below a certain volume threshold.

This approach requires the emissions that would have happened without the capture plant to be estimated (the counterfactual). This will usually be the benchmark emissions per tonne of product. However, historical emissions per tonne of product from that particular plant can also in principle be used.

Price per tonne

In principle, as carbon prices rise over time and the costs of new-build CCS decrease, avoiding paying carbon prices may be sufficient in itself to incentivize the installation of CCS at industrial facilities, provided CO_2 transport and storage infrastructure is in place. This could avoid the need for subsidy entirely, although regulatory involvement in the CCS chain will still be required and allocation of risks will remain an important issue.

While costs of CCS remain above the carbon price, payments under a CfD seek to provide support, while recognizing the value of carbon pricing to low-carbon projects. CCfD payments decrease as the carbon price rises, so there is a presumption that projects benefit from higher carbon prices. This may happen if higher carbon prices are reflected in higher product prices, for example higher steel prices. This may be the case in the following circumstances.

Non-trade exposed product. In non-emissions-intensive trade exposed sectors, carbon prices may be passed through because international competition is not enough to prevent this, and so the threat of ‘carbon leakage’ is much lower.

Carbon border adjustment mechanisms (CBAMs) may lead to the carbon price being reflected in product prices because all producers – importers and local producers – will pay a carbon price. CBAMs remain under discussion in the EU and UK.

Carbon regulation in other countries may increase the prices for a commodity. This may not necessarily be in the form of carbon pricing in other jurisdictions. Other mechanisms, for example product standards, may increase costs.

Markets for low-carbon products. There may be a market premium from regulations which limit the carbon content of a product. For example, building regulations may require the use of low-carbon steel.

Free allocation of allowances

There are various choices for whether or not the free allocation of allowances is retained, and whether these are accompanied by a CfD or a fixed-price support contract. These choices affect the required level of contract support for a carbon capture project, and create different exposures to price and volume risk. Any CfD will need to be robust in the face of regulatory changes affecting the carbon price, for example if other taxes are implemented.

> **1. Retention of free allocation – no CfD but other subsidy such as a fixed price support contract**
>
> In this case subsidy, for example a fixed price support contract or capital subsidy, meets part of the costs of the capture project. The remainder is absorbed by the project owner, or met by revenue from the sale of those free allowances that are no longer needed because the CCS plant is operating. Carbon price risk remains with the project, because the revenue from sale of free allowances depends on the carbon price.
>
> Something like this approach is applied in the Norcem capture project, part of the Norwegian Longship project. The project is subsidized by government (though not by a contractual payment per tonne), with subsidy covering 75–80 per cent of expected costs. The project retains free allowances, which can be sold to cover remaining costs. (The site will also need allowances to cover other emissions it makes, as only about half of its emissions are part of the capture project.) As there is no CfD on the carbon price, the project retains carbon price risk.

One important consideration is whether implementing CCS results in a change of benchmark for free allocation under an EU ETS, and if any resulting loss of free allocation is compensated for by additional support. If the benchmark is reduced, support based on the assumption of continuing free allocation of allowances may not provide sufficient **funding.**

2. Free allocation is retained along with a CfD

In this case a CfD in effect largely fixes the value to the project of freely allocated allowances, removing carbon price risk from the project, although risks from changing volumes of free allowances may remain. This is similar to the approach used in the SDE++ programme in the Netherlands as well as the EU's current proposals.

3. Removal of free allocation and allowances aren't issued

If free allowances are removed from the project owner, the subsidy will need to meet the cost of CCS in full. This removes carbon price risk from the project because there are no free allowances to vary in price.

If allowances are never issued, they are not available for government or others to auction. This increases the net cost to the taxpayer compared with the case where allowances are issued and can be auctioned (assuming no significant effects on the market price).

4. Removal of free allocation and allowances are issued and auctioned by government

The net cost of the subsidy to government is potentially reduced by auction revenue from selling allowances not allocated to projects. However, to secure this there is a need to ensure that the allowances are issued, and that they return to government, and can subsequently be sold.

Proposals in the UK include a provision that free allowances will be removed, but payments will be given to the project to represent the value of the removed free allowances at an assumed carbon price path. However, because this payment is determined in advance, it becomes rather like any other form of contractual payment independent of the carbon price.

Other contract terms

Other features of the contract will need to be specified. These include the following.

Whether there is an annual fixed payment. This does not depend on volumes of CO_2, but is paid anyway, for example as a fixed monthly or annual amount. It may be made unconditionally, provided only that the capture plant remains open, or it may be based on availability of the capture plant (a capacity charge). This type of payment is usually intended to allow repayment of a portion of capital costs irrespective of the utilization of the capture plant. It has some potential benefits similar to a capital grant, which may also be part of a support package.

Costs of energy used in capture. Some proportion of the per tonne payment, most likely corresponding to the energy costs of running the capture plant, may be indexed to energy prices. This can reduce financial risks to the capture plant, because energy costs may have quite different trends from other operating costs, and from general inflation.

Transport and storage costs. These will normally be set by regulation, and most likely be remunerated on a pass-through or similar basis.

Contract duration. To ensure value for money for tax payers (assumed to be the ultimate provider of funds for the contract payments), contracts should run for long enough to gain the value from operation of the plant – including the benefits of reducing emissions, and technological learning.

There is some convergence of length of support amongst existing or proposed arrangements, even though the type of support varies. Contracts for Norway's Longship project run for ten years from the start of operation, the Netherlands SDE++ runs for 15 years, the UK's current proposal is for 10–15 years although with a shorter capex repayment period. The 45Q tax credit in the USA runs for 12 years.

Some industrial investors look for shorter paybacks on investment. However, very short contract durations, for example five years, that fully remunerate total capital are unlikely to be optimal. If the plant closes after only a few years, the cost per tonne of CO_2 usually becomes very high. There will also be a loss of environmental benefits. Similarly, a short period of operation will lead to a loss of learning benefits that would come from a more prolonged operation. It risks leaving transport and storage infrastructure investment stranded if capture plants cease operation early.

Changes to payments over time

Contract parameters may change in various ways.

Changes over time. For example, payments may reduce over time to reflect expected learning both within and outside the project.

Changes in market conditions or regulation. For example, payments may change if market CO_2 prices under a carbon tax or emissions trading system go outside certain ranges. Similarly, contract provisions may change if there is a change in the form of carbon pricing, for example the introduction of carbon border adjustments.

As a means of risk sharing. For example, there may be reduced payments if rates of return exceed given levels, or outturn costs are lower than expected. Similarly, there may be an increase in payments if returns fall below a specified level, or costs are higher than expected. There may also be risk sharing through changes being passed through only in part. For example, only a portion of CO_2 prices may be passed through.

Changes may be written into the contract, or be subject to re-negotiation in certain conditions (re-openers).

Conclusion

Contracts to remunerate the use of low-carbon technologies can be a powerful mechanism for stimulating their deployment, because they give a firm revenue stream that enables companies to invest. However, as with many commercial contracts, there is a range of risks that need to be allocated and a variety of incentives that will be created. Careful consideration of contract structures and terms is necessary in designing effective policy in this area.

ACHIEVING NET-ZERO: A NOVEL SUPPLY-SIDE CLIMATE POLICY TO VALUE CARBON SINKS

Paul Zakkour and Wolfgang Heidug

The 2018 Intergovernmental Panel on Climate Change (IPCC) Special Report on 1.5°C (IPCC 2018) emphasized the necessity of deploying a wide variety of solutions to combat climate change. These include carbon capture and storage (CCS) and negative emissions technologies (NETs) such as direct air capture with carbon storage (DACCS) and bioenergy with CCS (BECCS). While the enhancement of terrestrial carbon sinks (such as afforestation and reforestation) can also be an important component of the net-zero transition, the scale of sequestration required for safe storage of CO_2 away from the atmosphere on a multi-century timescale highlights the need for secure, long-term geosequestration. Without massive deployment of geological CO_2 storage, the world will almost certainly face global temperature increases well above 1.5°C before the end of the century, which will culminate in dramatic consequences for ecosystems and societies.

A decade or so or so ago, the reaffirmation of the cumulative stock problem posed by greenhouse gas accumulations in the atmosphere – and the establishment of the associated notion of a ‘carbon budget’ – in the global climate policy debate led to the idea of setting finite limits for the total allowable global emissions under different warming limitation scenarios. A carbon budget therefore means that any commitment to a given warming limitation target also includes a tacit acceptance that once the associated atmospheric resource is exhausted, global emissions and removals must remain in balance or at ‘net-zero’ thereafter to avoid further warming. However, most modelled trajectories of Paris-compliant global emissions show significant gross emissions even after the point of net-zero (IPCC 2018). In other words, fossil fuels are likely to remain an important energy vector in industries such as maritime shipping, aviation, iron and steel, chemicals, and cement production beyond 2050. In the second half of this century, emissions from these sources will need to be continuously offset through corresponding enhancements in carbon sinks in order to restrict additional increases in mean global temperatures.

Without enduring policies that attribute value to the act of storing CO_2 in carbon pools other than the atmosphere, the requisite increases in enhanced carbon sinks and reservoirs aligned to a global net-zero emissions balance will not be achieved at sufficient speed and scale to prevent dangerous global warming.

The challenges

Presently, sequestration-based geoengineering technologies face at least two major development challenges.

First, there is no well-defined policy framework that effectively incentivizes the permanent storage of carbon in non-atmospheric pools. Present policy frameworks, such as carbon pricing under capped emissions trading schemes, are largely tied to low and volatile carbon prices. These provide only weak incentives for the deployment of CCS and no incentive for NETs. Efforts over the past decade or so to deploy CCS through carbon pricing alone suggest that a linear business model that passes the carbon price value down the chain from capture to transport and storage does not work effectively outside of niche and captive situations (for example, the Sleipner, Snøhvit, Quest, Decatur, Santos Basin, and Gorgon CCS projects are all captive, single-entity projects). Experience suggests that fully private multi-party CCS projects seem to work best where commercial markets allow prices for physical CO_2 to form between capturers, shippers, and storers, as is the case with CO_2-enhanced oil recovery operations (such as the Petro-Nova, Boundary Dam, and Jilin CCS projects). Thus, the permanent storage of carbon is a valuable activity, but few policies have explicitly recognized this in a manner that is separate from emission reductions.

Second, carbon sequestration solutions are at various stages of maturity and encompass a wide variety of costs, ranging from near-market viability to longer-term potential. These differences, in addition to technical variations in the scale and permanence of carbon storage, need to be addressed in an effective policy package. Thus, CCS and NETs need targeted policy support to be deployed in time to achieve net-zero in the second half of this century.

International collaboration

Given these challenges, a new international effort to measure and value actions to enhance geological carbon sinks is required. The concept centres on bringing geological carbon stocks under a policy target that balances fossil carbon extraction (such as fossil fuel production and limestone extraction for cement making) with carbon deposition in stable sinks (such as geosequestration). Such a policy perspective offers a unified pathway to value carbon rather than treating it entirely as a negative externality. A sequenced set of policy actions based on this concept can collectively accelerate the deployment of carbon geosequestration. This includes strengthening and expanding ongoing international efforts in support of carbon capture utilization and storage under frameworks such as the Clean Energy Ministerial (CEM), Mission Innovation, the International Energy Agency Greenhouse Gas R&D Programme, and the Carbon Sequestration Leadership Forum. It also includes developing policy and regulatory frameworks that reduce the investment hurdles for CCS.

The establishment of a carbon storage unit

One key facilitating factor is the establishment of a carbon storage unit (CSU). A CSU can provide a monitored, verified, trusted, and transferable record of the addition of one ton of CO_2 to carbon sinks; primarily, geological CO_2 storage sites. Where policy creates value for CSUs, a price signal for storing carbon is generated. This price can complement the value for emission units typically applied to users of fossil fuels in demand-side climate policies (for example, carbon pricing instruments such as capped emissions trading schemes applied to countries, regions, and industrial emission sources).

Carbon pricing policies typically employ units that measure either:

- emissions (such as allocated emission allowances or rights, such as assigned amount units (AAUs) to Annex I countries under the Kyoto Protocol or various units allocated to industrial facilities in regional cap-and-trade schemes)

or:

- emission reductions (for example, credits against a baseline in project-based instruments, such as certified emission reductions (CERs) under the Kyoto Protocol's clean development mechanism, that also avail the holder with a right to emit).

On the other hand, because CSUs measure carbon stored in the geosphere, they would be applicable for fossil fuel producers (and importers) as offsets against carbon extracted from the geosphere (and imported by major users). Consequently, they can offer a complementary climate policy tool on the supply side of fossil energy markets alongside carbon pricing policies applied to fossil fuel users. On this basis, CSUs can:

- Provide new options in the policy toolbox by offering a basis to incentivize fossil fuel producers to undertake CCS and DACCS;
- Create a new price signal for CO_2 storage activities, which can create a market for physical transactions of CO_2 among capturers, shippers, and storers, thus helping unlock new business models for geosequestration when compared with the linear approach of using carbon pricing alone;
- Tag and track fossil fuels as they move through the energy supply chain, thus allowing producers to demonstrate the degree to which their products and activities might be considered 'Paris-compliant' as either 'low-carbon' or 'decarbonized' fuels;
- Provide an additional layer of targeted finance for geosequestration technologies whose costs generally exceed the levels of incentives on offer from carbon pricing policies.

Where rates of fossil fuel production from the geosphere can be entirely balanced by corresponding additions of carbon to the geosphere as measured by CSUs, a Paris-compliant mitigation pathway can be achieved. By increasing climate action on the supply side of global fossil energy markets, new forms of cooperation between major fossil fuel producers and users can be established in order to accelerate and enhance climate ambition alongside efforts to price carbon emissions.

Cooperation on policies and actions that create and drive initial demand for CSUs

The establishment of CSUs as proposed offers several pathways to drive investment in geosequestration and to deliver more ambitious climate action. However, as this is a departure from established global climate policies, there is an inevitable need for a phased approach that provides time for the concept to develop and mature.[3] There are at least two approaches that could be taken by leading governments to pilot storage crediting concepts centred around CSUs:

- Bilateral approaches: CSUs can be piloted through existing bilateral schemes to support mutual climate goals, such as Japan's Hydrogen Strategy, or through other novel forms of cooperation based on decarbonizing fossil fuels. The latter can include piloting extraction-based carbon accounting by major fossil carbon producers (either partial or through parallel accounts) that stipulate conditions for the zero-rating of fossil fuel emissions by major users (for example, an individual importing country or sector, such as the aviation sector in conjunction with the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and its low-carbon fuels initiative).
- A wider group of countries with interest in continuing fossil fuel use in a Paris-compliant manner could establish a 'carbon storage club' that pools funding in order to procure CSUs from prospective storage site operators. The approach would essentially form a targeted international geosequestration technology support mechanism using results-based finance. The fund would be paid out to operators in return for surrendered CSUs. Rather than setting a fixed price for storage activities, as with 45Q tax credits in the US, an open tender process or reverse-auction design can be used to enhance price discovery and cost efficiency. The 'carbon storage club' can be established under existing channels and frameworks (such as CEM) or under a new initiative within the auspices of the cooperation framework under Article 6 of the Paris Agreement.

These early phase actions can accomplish several important and related goals that are presently beyond the scope of climate policies:

- Incentivize the avoidance of emissions to, or removal of carbon from, the atmosphere through its transfer into the geosphere;

[3] Zakkour, P.D. and W. Heidug (2019), *A Mechanism for CCS in the Post-Paris Era: Piloting Results-Based Finance and Supply Side Policy Under Article 6*, King Abdullah Petroleum Studies and Research Center (KAPSARC) discussion paper. April 2019.

- Provide a dedicated technology mechanism for CCS and DACCS that supports the deployment and scaling up of these essential technologies;
- Facilitate a policy pathway that supports private sector commitments to net-zero emissions on the supply side of fossil fuel value chains (for example, Occidental Petroleum, BP, Shell, Total, and Repsol 'net-zero pledges' to address scope 3 [or embedded] emissions in their products), as well as other significant actors with interest (such as Microsoft's commitment to achieve net-negative emissions, in part using geological storage). CSUs can provide a common framework to ensure that such voluntary commitments are effectively tracked using an internationally trusted and verified measurement methodology.

The pilot phase described here requires government funding to enable the CSU framework. However, if the pilots prove successful, the private sector will play a key role in scaling up, with governments exploring systematic and enduring policies built upon CSUs.

Policies and measures that drive long-term demand for CSUs toward net-zero

Establishing CSUs offers significant potential to support an orderly transition to net-zero emissions. Conceptually, a steadily increasing effort by fossil carbon extractors to offset their actions through the equivalent storage of carbon in the geosphere can ultimately lead to net-zero CO_2 emissions. The approach also presents a pathway to 'virtual' decarbonized fossil fuels, where rates of carbon extraction and deposition converge. CSUs can provide the building block on which such approaches may be based. Building on a 'SAFE-carbon' concept[4] – in other words, setting an obligation for the amount of fossil carbon extracted from the geosphere to be increasingly balanced by increasing carbon deposition in the geosphere – a coordinated transition away from pilot approaches toward more enduring and systematic policies based on CSUs can be envisaged. Approaches can be undertaken incrementally and predictably through an escalating percentage of the carbon contained in fossil fuels being offset, demonstrated by the origination of CSUs from increasing amounts of geological carbon storage. The implementation of such approaches can build from various policy pathways. Examples of these are as follows:[5]

- Fuel supply regulations such as low-carbon fuel standards (like those already in force in California, various Canadian provinces, and in the European Union). Countries employing such measures can require a portion of the carbon embedded in imported fossil fuels to be offset by a corresponding supply and surrender of CSUs.
- Voluntary sectoral pledges are made by fossil carbon producers and suppliers toward net-zero, such as those made by oil and gas companies in relation to embedded carbon (like those of Occidental Petroleum, BP, Shell, Total, and Repsol described above, for example). These companies can demonstrate progress toward their internal targets through origination and/or acquisition and holding of CSUs.
- 'Carbon take-back schemes' based on the policy principle of 'extended producer responsibility' that is widely employed in the waste management sector (for example, regulations requiring the take-back of electronics waste).[6,7,8]

National governments can employ CSUs to implement and measure the level of fossil carbon that must be 'taken back' by national fossil fuel suppliers. In these scenarios, the burden of acquiring CSUs would devolve from governments to private sector operators, who can bundle CSUs in varying proportions alongside fossil fuel supplies. Such approaches would constitute a new supply-side carbon offset market in which industries compete to store carbon at the lowest cost to satisfy a ratcheting decarbonization standard. Companies with successful CCS and NETs strategies will gain a competitive advantage through

[4] Allen, M.R., D.J. Frame, and C.F. Mason (2009), 'The case for mandatory sequestration' *Nature Geoscience* 2: 813–14.
[5] Zakkour, P.D. and W. Heidug (2020), *Supply-side climate policy for crude oil producers: exploring policy pathways for decarbonizing fossil fuels*, King Abdullah Petroleum Studies and Research Center discussion paper (KAPSARC), August 2020.
[6] Hepburn, C., T. Allas, L. Cozzi, M. Liebreich, J. Skea, L. Whitmarsh, G. Wilkes, and B. Worthington (2020), *Sensitive intervention points to achieve net-zero emissions: Report of the Policy Advisory Group of the Committee on Climate Change*. University of Oxford/UK Climate Change Committee, December 2020.
[7] Zakkour, P.D., W. Heidug, A. Howard, R.S. Haszeldine, M.R. Allen and D. Hone (2021), 'Progressive supply-side policy under the Paris Agreement to enhance geological carbon storage'. *Climate Policy*, 21:1, 63–77.
[8] Kuijper, M. E. Holleman, J-P. van Soest (2021), *Carbon Takeback Obligation. A Producers Responsibility Scheme on the Way to a Climate Neutral Energy System*, De Gemeynt.

access to major fossil fuel markets. Such a long-term mechanism can support the ongoing geological storage of CO_2 up to and beyond the net-zero date, paid for by the private sector.

Enhance support for negative emission technologies

Policies that support the removal of CO_2 from the atmosphere are limited globally, with only the US Federal 45Q tax credit and California's Low Carbon Fuel Standard currently offering targeted incentives for DACCS. However, NETs will likely be crucial in achieving net-zero emissions, particularly in offsetting hard-to-abate mobile emission sources that are not amenable to capture, or by removing the legacy CO_2 from the atmosphere.

CSUs, as proposed, can directly support the greater development of NETs by offering a direct incentive and price signal for storing carbon from any source and facilitating the development of geological CO_2 storage sites that are critical to the efficacy of both BECCS and DACCS. It can also be beneficial for countries or corporations wishing to go net-zero or net-negative to use DACCS to generate CSUs as a direct measure of action undertaken in pursuit of these goals. Technologies such as DAC are in the early stages of maturity and will thus benefit from research, development, and demonstration into different types of NETs; pilot activities to help advance to the commercial deployment stage; and from establishing regulatory policies and market-based frameworks and measures to promote investment and enhance commercial deployment.

Potential benefits and advantages of the CSU policy concept

In conclusion, the CSU policy concept would add to the climate policy toolbox as a parallel and complementary framework to manage carbon stocks, operating alongside emission reduction policies. As a suite of climate policies, the phased evolution of the CSU concept offers several advantages which include:

- *Measuring climate progress more effectively:* Restating the climate mitigation challenge in terms of ramping up sequestration to 100 per cent of the carbon extracted, rather than focusing solely on reducing net emissions to zero, offers another way of framing progress toward meeting climate goals.
- *Guaranteeing net-zero:* G20 members can ensure that net-zero is achieved by escalating the fraction of carbon stored per unit of carbon extracted. This can be a failsafe if the demand-side carbon pricing fails to deliver net-zero
- *Decarbonizing the last 30 per cent:* Conventional carbon pricing fails to incentivize abatement at the expensive end of the marginal abatement cost curve (such as for cement, steel, and aviation) until very high prices are reached. However, many technologies that will likely be required to perform this abatement are already understood and available (primarily CCS). Placing value on carbon storage using CSUs can act as a vital bridge between carbon pricing and higher-cost abatement technologies
- *Targeted support for necessary technologies:* Renewable energy technologies receive various forms of targeted support to scale up (such as feed-in tariffs in several EU member states and the US Investment Tax Credit). Similarly, carbon storage needs explicit support to drive a clear outcome: an increased volume of permanently stored CO_2 at ever-decreasing marginal cost. Just as carbon prices increase the cost of fossil fuels, targeted technology support can reduce the cost of storing CO_2.
- *Transition plan:* Directing public funds to CO_2 storage can be more easily justified when there is an 'exit strategy' to ultimately transition to an enduring model in which high-carbon industries take responsibility for storing enough CO_2 to neutralize the climate impact of their product
- *Creating opportunities to decarbonize:* Valuing carbon storage broadens the range of stakeholders that are incentivized to drive global decarbonization. Supply-side CSU-based policy frameworks can allow extractive industries to proactively contribute to climate solutions while offsetting the impacts of their product through commensurately rising CO_2 storage.

PUBLIC PERCEPTIONS OF CARBON CAPTURE, USE, AND STORAGE (CCUS)

Darrick Evensen

For a technology that has seen as little industrial-scale deployment as CCUS, a truly phenomenal quantity of social scientific research has been conducted into public perceptions of it; factors affecting its support/opposition; and awareness, knowledge, and effect of additional information on CCUS acceptance. For example, a systematic review of public perceptions of CCUS published in 2014 reveals 42 academic articles, whilst a 2019 review identifies 135 articles. A 2021 systematic review of CCS communication and trust building revealed 115 articles (several overlapping with the public perceptions sample).

In many respects, the magnitude of attention is valuable, as it can be far more beneficial to understand public reactions and influences on public attitudes/support before projects commence. Otherwise, industrial and policy actors are usually left cleaning up the mess of a project implementation gone wrong. A core assumption – and a repeatedly empirically validated maxim of the social scientific research on both CCUS and novel energy technologies more broadly – is that without public acceptance, technologically robust and economically viable development will fail. This is understood to the point of banality in the aforementioned articles in the systemic reviews. For example, despite the limited number of CCUS projects to date globally, protests have occurred to some developments and local support has been lacking in many instances (for example in Germany and the Netherlands).

In this brief overview of public perceptions research, I present some fundamental findings that are robust across many studies, and then offer recommendations for the most practically useful, academically interesting, and methodologically innovative directions for future research in this area.

Perceived risks/benefits

Nearly all research on public perceptions of CCUS examines beliefs about risks and benefits attributed to the technology and its implementation. Over a multitude of studies, key risks of CCUS have been identified as:

1. It only addresses symptoms of problematic carbon emissions and not the causes,
2. It leads to reduced policy incentives to mitigate carbon emissions further,
3. Safety concerns over leaks or explosions due to over-pressurization,
4. Cost/expense of the technology,
5. Uncontrollability of the technology,
6. Public and scientific uncertainty about the technology.

Benefits that repeatedly emerge are:

1. Reductions in carbon emissions, thereby mitigating climate change,
2. Economic investment in jobs and communities where projects occur.

Trust in institutional actors responsible for implementing or regulating projects is regularly revealed as the most important factor that shapes risk and benefit perceptions. Trust reliably has a much larger effect on risk and benefit perceptions than knowledge of CCUS does. Public perceptions research commonly alleges that risk and benefit perceptions are, in turn, key determinants of support for CCUS, with benefit beliefs being seen as more important for predicting support and acceptance to CCUS generally, and risk beliefs being seen as more important in relation to acceptance of specific local projects.

A majority of the published studies on public perceptions of CCUS, nevertheless, use online surveys as their primary form of data collection (another portion uses in-person or telephone surveys). Whilst allowing for extrapolations to broader populations than other research approaches, such data cannot demonstrate the direction of causality between beliefs and support/acceptance. Because knowledge of CCUS is generally very low, and trust in institutional actors heavily influences responses to the technology and its deployment, it is also possible that people make decisions about whether they support the technology or not (for example, based on initial emotive reactions, trust, and broad values), and then update their beliefs about the risks and benefits accordingly.

A key revelation about risk and benefit perceptions of CCUS is that whilst sometimes related to each other, these beliefs are often not highly correlated. For some other technologies, it is common to see risk perceptions highly negatively correlated with benefit perceptions. This relationship is much more ambiguous for CCUS; one could perceive high risks and high benefits, or low risks and low benefits.

Variations in beliefs

Risk and benefit perceptions, whilst consistently related to the key themes covered above, have been shown to differ notably between: (1) countries, (2) areas with potential for CCUS implementation and areas with little potential, (3) offshore vs onshore deployment, (4) the source from which the carbon came, and (5) the stage in the CCUS process – capture, transport, use, or storage. In the largest review of public perceptions of CCUS to date – the 2019 review including 135 articles – the majority of articles included examined perceptions in a single nation, with a heavy focus on Europe. Cross-national comparisons were present in 23 articles (17 per cent). These comparative studies also focused heavily on Europe, with 79 instances of European countries being compared, across 16 countries. Non-European comparisons were limited to ten instances in which the US, Japan, Canada, and Australia were included.

The comparisons that exist, as well as reviews of single-nation studies side-by-side, reveal, for example, elevated risk perceptions and lower support in Germany and the Netherlands compared to the UK. This is perhaps at least in part related to general findings of higher perceived risk, more concerns about lack of local benefits, and lack of support or acceptance for projects close to prospective development sites. A number of studies have asked members of the public to assess their support for hypothetical development close to where they live; far fewer – but still some – have evaluated support in areas close to prospective development sites (for example, in Germany, where a national assessment of viability was conducted), and in relation to actual proposed projects. The clear pattern is that less support exists for CCUS locally. Nuance does exist, with evidence of a few locations notably supporting projects where clear evidence for tangible local benefits exists.

A number of researchers, and industry actors, focused on energy development siting have termed local opposition to energy projects NIMBY – not in my backyard. Nevertheless, leading scholars in this area have recommended against such a simplistic and unnuanced description of differential acceptance levels at local and national scales. People local to a project have more awareness of things that could be threatened (or advanced) through the project – such as local tourism, cultural meanings, and job prospects. They might also have specific experiences with prior energy development – such as coal mining – which could evoke comparisons to previous industrial problems or accidents, or to loss of trust in industrial actors that were not good neighbours to local communities. The reasons for local opposition are often complex, but do mean that context-specific understanding is essential for assessing the viability of specific CCUS projects.

Few studies have specifically examined perceptions and acceptance of offshore versus onshore projects. One might expect that offshore sites would be more removed from potential local impacts, so on the basis of the foregoing discussion, they would experience higher acceptance. The data suggest this is true to some extent, but larger risk and benefit issues tied to global climate change, CCUS as a ‘techno-fix’, and addressing symptoms versus causes still apply here, so offshore siting is not the panacea it might seem at first.

This points us also to the relevance of the source of carbon. The large majority of studies on public perceptions of CCUS attend to carbon captured from use of fossil fuels, predominantly at coal-fired power plants. The studies that examine carbon captured from other sources – such as the steel industry and biomass plants – show that acceptance can be higher and risks seen as lower/fewer in such cases. Nevertheless, the paucity of such investigation suggests research opportunities.

The stage in the CCUS process has also been shown in a few key studies to strongly affect risk perceptions, support, and acceptance. Concerns, as can be seen by the key risks listed above, are generally associated with storage and transport. Higher acceptance of industrial use of carbon exists, compared to storage, and the process of carbon capture is not viewed as particularly problematic (unless the source of carbon is problematic, as above). Again, however, a substantial majority of public perceptions studies have attended to CCS broadly or storage specifically, leaving gaps in understanding of risk/benefit perceptions and support for transport, use, and capture.

Knowledge, awareness, and communication

After examination of risk/benefit perceptions, support, and acceptance of CCUS, the next most commonly assessed aspect of public interaction with CCUS is the level of public awareness and specific knowledge about CCUS. As one would expect, this also varies cross-nationally and regionally within countries (places with more exposure to industrial projects or government discourse and planning show higher knowledge). Nevertheless, across virtually all studies to date, the common finding is that public understanding of CCUS is quite limited. Even if people have heard of it, they know little about it. Over the last two decades of public perceptions research studies, knowledge and awareness are climbing, but slowly.

This lack of knowledge could be seen as beneficial for governments or industries seeking to expand deployment of CCUS. If people are poorly informed about a new technology, then this is seen in social psychology as an object to which public attitudes would generally be malleable. There might be potential for further information, and targeted communication, to influence the level of support and acceptance. Social scientific research on CCUS repeatedly champions the need for effective communication on this topic – indeed, identifying messages, messengers, visuals, dissemination pathways, and specific language that will lead to higher public acceptance of CCUS is the primary purpose of many such studies.

The focus on communication and acceptance has also been critiqued by some scholars; I discuss three reasons here. First, even in studies that reveal a genuine statistically significant empirical connection suggesting that certain information or messages can lead to, or are associated with, higher acceptance, the magnitude (and therefore real-world meaningfulness) of the effect is often small. For example, a shift in acceptance of 0.15 on a 1–5 scale of support/opposition could be statistically significant, but will mean very little for acceptance of a real project.

Second, although appeals for effective CCUS communication are nearly universal in the literature, there are also a number of claims about 'information deficit' – an empirically invalid assumption that people simply lack information and will necessarily change their views when gaining additional knowledge. The actual evidence from the public perception and communication studies shows a broad mix of additional information marginally increasing support for CCUS, decreasing support, or having no effect. There is, of course, strong potential for the effect of additional information on support/acceptance to be mediated by factors such as those discussed in the 'variations in beliefs' section above, but this level of nuance has rarely been explored.

Third, even if communication were to increase acceptance, some scholars question whether this should be the goal of researchers. Several studies point to communication as one step in a public engagement process, but only an incremental stage that follows understanding of perceived risks/benefits; it is followed by robust and credible public engagement and a transparent decision-making process that reflects the engagement. The relational context matters for any energy project, and CCUS deployment is no exception; recall the aforementioned influence of trust.

The engagement process should also be thought of as continual and iterative, not a one-off sharing of information. Indeed, as members of the public learn more about CCUS, they understand the technology better, but they also understand its role in society and in their community better, and they understand how its effects intersect in complex ways with their core values. The role of CCUS in their community will touch on a number of values and beliefs that are best considered in processes that offer a range of ways in which public stakeholders can be heard, learn more, and contribute in a non-trivial way to decision making.

Recommendations

The foregoing brief summary of CCUS public perceptions research on perceived risks/benefits, support, acceptance, variations in beliefs, knowledge, communication, and public engagement points to a few clear academic gaps and opportunities for focusing future studies, despite the considerable social scientific research to date.

Because of the clear differences between countries and between locations proximate to, versus distal from, prospective development, more comparative studies would help further elucidate the mechanisms behind cultural differences in beliefs and attitudes towards CCUS. Comparisons could also include investigation of different carbon sources for CCUS, and explicit views on the different stages – capture, transport, use, and storage.

There are a very large number of ways in which country, region, sources, and stages could be combined. Some of this could be explored in the large online surveys common to CCUS research. The methodology is well established, but could be innovative if including national samples along with regional sub-samples across countries, or if paired with in-depth qualitative understanding. In one sense, I would like to advocate for research beyond Europe, considering how heavily the research literature has attended to this continent. Conversely, I would like to see more understanding of processes at local levels in areas exposed to prospective development. If those areas happen to be predominantly in Europe, then perhaps the manifest geographic focus is appropriate.

A final recommendation relates to public engagement. Although an expansive literature exists on how to engage effectively with communities and public stakeholders in relation to siting of energy projects, there is certainly more room to see this approach applied to CCUS, and engagement strategies tested empirically in locations dealing with deployment of CCUS projects and technologies. Deliberative workshops and iterative, interactive engagement with members of the public in areas affected by prospective CCUS development would help plug academic gaps and simultaneously contribute to the full engagement process, beyond just persuasive communication.

ENABLING CCS IS VITAL FOR BLUE HYDROGEN

Bassam Fattouh

CCS is identified as a critical technology to reduce CO_2 emissions to achieve global climate goals. It refers to the process of separating the CO_2 from a gas stream and then storing it underground. In addition to offering a solution to the problem of CO_2 emissions from hard-to-abate sectors such as the cement and the steel industries and reducing emissions from existing energy infrastructure, CCS is required in the production of low-carbon hydrogen from fossil fuels (often referred to as blue hydrogen) which is considered by many as essential to decarbonize a wide range of sectors including heavy industry, the heat and power sectors, and transport.[9]

Most of the hydrogen produced in 2020 used natural gas as a feedstock through a well-established and technologically mature process known as Steam Methane Reforming (SMR). It is estimated that of the 90 million tons (Mt) of hydrogen currently produced globally, around 80 per cent is produced from natural gas and coal (the bulk of the remaining is produced as a by-product from refineries) resulting in close to 900 Mt of CO_2 emissions per year.[10] The challenge for SMR is not its cost competitiveness, as it remains the cheapest method to produce hydrogen. The key challenge for SMR is the high CO_2 emissions linked with the process. Every ton of unabated hydrogen produced from natural gas is associated with the emission of 9 tons of CO_2. In the case of coal-based hydrogen, the emissions are higher: 20 tons of CO_2 are emitted for every ton of hydrogen produced. However, even though fossil fuel-based hydrogen plants with CCS have been in operation for many years, there are few such plants operating – representing a combined annual production of just 0.4 Mt of hydrogen capturing around 6 Mt of CO_2.[11] These plants produce hydrogen for use in fertilizers, in the refining sector, and in bitumen upgrading.

The CCS chain

If hydrogen is to contribute to a cleaner transition, it is essential to develop routes to produce clean hydrogen either through water electrolysis or fossil-based hydrogen with CCS (or CCUS). CCS projects have been in operation for decades but have not achieved the scale required to meet climate targets. The factors often cited behind the lack of deployment of CCS at a large scale are: the absence of a supportive regulatory framework and incentive schemes, and a lack of suitable commercial arrangements that are essential for developers to recover their upfront and operating costs in a stable environment. These costs include:

- The cost of capturing and conditioning CO_2.
- The cost of compressing/liquefying CO_2 for transport.
- The cost of transporting CO_2 via pipelines and ships (or trucks in the case of short distances and small volumes).
- The cost of injecting CO_2 into storage sites.
- The cost of monitoring and verifying the amount of CO_2 stored underground.

[9] IEA (2020), Special Report on Carbon Capture Utilisation and Storage; CCUS in Clean Energy Transitions. Paris: International Energy Agency.
[10] IEA (2021), Hydrogen, IEA, Paris.
[11] IEA (2020).

The cost of each of these activities varies widely depending on project-specific factors (location, plant size, type of activity, the technology in use, just to mention a few) and the literature reports a very wide range of estimates of these costs. But it is generally accepted that capturing CO_2 constitutes the biggest cost component for CCS and the area where significant cost reductions, efficiency gains, and further technological innovations could be achieved. One of the ways to measure the cost of CCS is in terms of the cost of avoided CO_2 (often expressed in $/t$CO_2$). A recent techno-economic study on a hydrogen plant in Norway[12] finds that CO_2 capture and CO_2 conditioning represent 57 per cent of the total CO_2 avoided cost, while pipeline transport and storage represent 17 per cent and 26 per cent of the total CO_2 avoided cost respectively. In terms of CO_2 avoided cost, CO_2 capture and conditioning is estimated at €38/ton compared to €11.3/ton for pipeline transport and €17.5/ton for CO_2 storage.

CO_2 capture

CCS could be categorized according to the capture process (post combustion, pre-combustion, and oxy-combustion) and the separation technology (absorption, membranes, direct separation, and chemical looping). By far the most common separation process is chemical absorption, which has been used for decades and is considered to have a 'technology readiness level' (TRL) of 9 (in other words, the technology is commercial). In the chemical absorption process, CO_2 in a gas stream reacts with a chemical solvent (often an amine-based solvent). The process is performed using an ***'absorption'*** column in which CO_2 reacts with the chemical solvent and a ***'separation'*** column where pure CO_2 is released and the chemical solvent is regenerated to be reused in the absorption process. These columns are a costly component of a plant's capital expenditure.

A key factor in the cost of CO_2 capture is the concentration of CO_2 in the source gas, with costs typically decreasing with the increased concentration in the flue gas flow. In some applications such as ethanol production or natural gas processing, CO_2 concentration is quite high. In contrast, in applications such as power generation, CO_2 is quite dilute and therefore it is more challenging and costly to capture it. Currently, the most expensive application is capturing CO_2 directly from the air (Direct Air Capture). For SMR used in hydrogen production, the process involves capturing CO_2 from different gas flows. The process of separating CO_2 from hydrogen benefits from a high concentration of CO_2 in the gas stream, making it easier and less costly to capture. The Hydrogen Council estimates that for the SMR process, about 60 per cent of total CO_2 captured comes from this gas process stream.[13] The remaining 40 per cent comes from the flue gas, where CO_2 is much less concentrated. To achieve a high capture rate of 90 per cent or more, CO_2 should be captured from both streams, but this results in a much higher overall CO_2 avoidance cost. The IEA estimates that capturing CO_2 from a 'concentrated' stream costs around $50/t and this increases to around $80/t if a hydrogen plant seeks to capture 90 per cent of the CO_2 emissions.[14]

The literature emphasizes two other aspects related to carbon capture which impact cost and adoption. The first is the amount and the cost of energy used in the process of carbon capture, which is provided in the form of steam. This is often expressed in terms of energy penalty (defined as the amount of energy that must be dedicated to CCS for a fixed quantity of output). A recent techno-economic study on a hydrogen plant in Norway finds that the highest individual contributor to CO_2 avoidance cost is the energy penalty linked to capture (15.3 per cent of the total cost) and conditioning (7.3 per cent of the total cost).[15]

The second aspect relates to the amount of CO_2 captured and its implications on fossil fuel consumption. In many of the models with climate-constrained scenarios, the volumes of fossil fuels consumed depend on assumptions about CCS availability: models that assume higher CCS availability are associated with higher fossil fuel consumption. However, even though most models don't assume restrictions on CCS either in terms of its abatement cost or technical issues, the uptake of CCS in these models is lower than might otherwise be expected given the centrality of CCS in achieving net-zero emissions. Budinis et al.[16] attribute this to the residual emissions from CCS installations, where models usually assume that about 10–15 per cent of CO_2 is not captured.

[12] Roussanaly S., Anantharaman R., Fu C. (2020), 'Low-Carbon Footprint Hydrogen Production from Natural Gas: A Techno-Economic Analysis of Carbon Capture and Storage from Steam-Methane Reforming', *Chemical Engineering Transactions*, 81, 1015–20.
[13] Hydrogen Council (2020), *Path to hydrogen competitiveness: A cost perspective*.
[14] US Department of Energy (2020), 'Hydrogen Strategy: Enabling A Low Carbon Economy', Office of Fossil Energy, Washington.
[15] Roussanaly et al. (2020).
[16] Budinis, S., et al. (2018), 'An assessment of CCS costs, barriers and potential', *Energy Strategy Reviews*, 22: pp. 61–81.

CO_2 transport and storage

After capturing, conditioning, and compressing the CO_2, the next step involves transporting it to storage sites. CO_2 transportation technologies are mature, especially via pipelines – for example in the USA, many pipelines are already in operation linked with EOR operations. Large-scale transportation of CO_2 via ships is not yet well established, but the gas industry has plenty of experience in transporting gaseous fuels and this is unlikely to present a technical barrier, especially as the technology required is already in use for the transport of other cryogenic liquids such as LPG and LNG.[17] Like natural gas, the cost of transport is project specific and would depend on factors such as distance to the storage site, the volumes of CO_2 transported, and flowrates. And like natural gas, shipping CO_2 could become cost effective if transport distances are long and if players desire flexibility.

The final stage is injecting and storing CO_2 underground. The industry has been using CO_2-enhanced oil recovery (EOR) for many decades. While the main objective of EOR is to maximize oil recovery, the process involves permanent storage of CO_2 in oil fields, though this should be monitored and verified if CO_2-EOR is to play a role as a mitigation technology. CO_2 can be stored in saline formations and in depleted oil and gas fields. According to the Global CCS Institute,[18] storage in saline solution has a TRL of 9 and existing projects have shown that CO_2 could be injected, monitored, and stored permanently. Storage in depleted oil and gas fields has a lower TRL (5–8) as projects are yet to operate at a commercial scale. While storage of CO_2 scores highly in TRL, the underperformance of some key projects such as the Gorgon CCS project has caused some observers to doubt whether the deployment of CO_2 storage at a large scale and across the globe could be achieved.[19]

Cost of CCS and blue hydrogen

The biggest contributor to the cost of natural gas-based hydrogen is the fuel cost – namely the price of natural gas which is used both as a feedstock and as a fuel to generate steam. Most technical studies assume that the cost contribution of CCS to the production of blue hydrogen is relatively small. This implies that the difference between SMR with and without CCS is not large. For instance, the US Department of Energy estimates the cost of producing hydrogen by SMR with CCS at $2.27 per kg ($17.62/MMBTU) compared to $2.08 per kg ($16/MMBTU) for SMR without CCS. These are higher than the cost of natural gas but are well below the cost of producing green hydrogen through electrolysis (via nuclear, wind, or solar).[20] The Hydrogen Council puts the cost of blue hydrogen at just 10–20 per cent higher than conventional grey hydrogen, with the cost of CO_2 capture estimated to be only about $0.2–0.3 per kg for an SMR plant[21] and these costs are expected to fall as the technology is scaled up and learning-by-doing effects kick in.[22]

If the cost differential is marginal, then this raises the question as to why there are not more fossil fuel-based hydrogen plants in operation, as the cost of investing in CCS and/or internalizing the environmental cost through a carbon tax does not seem to be a significant barrier. The latter option may not be viable, as using hydrogen from unabated fuel is not likely to be acceptable in most jurisdictions as the environmental benefits are lower in most applications even when compared to the fossil fuels they are replacing. But if the cost of converting grey to blue hydrogen through CCS is low, why is the production of blue hydrogen not developing at a more rapid pace?

This could be due to a number of reasons. First, although the cost is low, it is still a cost and if there are no requirements/incentives to replace current unabated production by clean hydrogen, then plants will not make the shift. Second, the actual cost of CCS added to SMR depends on many factors and it is not possible to give a precise estimate of these costs. For many places in the world, the cost may be sufficiently high to prevent an automatic shift. Third, the technical costs do not necessarily encompass all costs including the integration cost and the high risks involved in coordinating the various activities of the CCS chain. In the absence of a well-designed and a stable regulatory framework that ensures coordination of the various activities and suitable commercial arrangements that allow players across the chain to recover costs, there will be no incentive to implement large-scale CCS, especially for plants where hydrogen is a by-product. What makes it more challenging is that

[17] Brownsort, P. (2015), 'Ship transport of CO_2 for Enhanced Oil Recovery-Literature survey', January, Scottish Carbon Capture & Storage (SCCS).
[18] Kearns, D., H Liu, and C. Consoli (2021), 'Technology Readiness and Costs of CCS', Global CCS Institute.
[19] See for instance, C. Goodall (2021), 'The struggles to make CCS work', Carbon Commentary.
[20] US Department of Energy (2020).
[21] Hydrogen Council (2020).
[22] Kearns et al. (2021).

different frameworks and business models need to evolve depending on where and how hydrogen is being used. Finally, there is the possibility that new markets for blue hydrogen and demand centres are not sufficiently developed to justify the cost of investing in CCS, and the outlook for growth from existing industries is limited or even declining. While many expect a strong demand for hydrogen in a climate-constrained world, some governments may also decide to support blue hydrogen only temporarily until green hydrogen is developed at a scale, or some industries may decide to make the shift directly to green hydrogen. Treating blue hydrogen as a transition technology generates much uncertainty. However, given the relative high cost of green hydrogen, most projections expect a rapid growth in clean fossil-based hydrogen, at least for the next decade in certain industries such as steel and ammonia. The lack of demand may therefore be less of a limiting factor in the current context, though this would require putting in place supportive regulatory frameworks to unlock new markets for hydrogen (a topic beyond the scope of this article) and enable CCS as a key technology for scaling up blue hydrogen production (discussed below).

Some key issues shaping CCS deployment

The above discussion highlights few key issues:

- In a net-zero-CO_2-emissions world, hydrogen plants will need to reduce residual emissions to the minimum and capture 90 per cent+ of CO_2. The higher the residual CO_2 emissions, the stronger the argument that blue hydrogen can only play a transitional role before moving on to the ultimate objective of producing green hydrogen. This has implications for the share of natural gas in the energy mix. Budinis et al. (2018) find that as capture rates reach high levels, natural gas can retain market share especially from 2050 onwards.
- While all parts of the CCS supply chain would benefit from a decline in cost, the biggest gains in cost reduction could be achieved in CO_2 capture. Pipeline transport and storage are the segments of the value chain which are most technologically mature and where large technical advancements are not expected (except in some areas such as automation and digitalization, which could contribute to cost reduction), and recent experience with the Gorgon CCS project also suggests that a deep understanding of geological formations, injections methods, and site selection is essential.
- Despite their technical maturity, pipeline networks and CO_2 storage display significant economies of scale and monopoly characteristics, and thus coordination among the various activities together with putting in place an appropriate regulatory framework is required, which could be a challenging task.
- Outside EOR and carbon utilization, there are no revenues associated with CCS (as is the case for renewable electricity generation) that can compensate for the upfront and operational costs. Also, so far, there has not been a viable business model available that could secure large-scale financing of CCS by the private sector.

A recent peer-reviewed article[23] examined the life cycle emissions of blue hydrogen and reached the conclusion that ‘blue hydrogen is best viewed as a distraction, something that may delay needed action to truly decarbonize the global economy’. The article also argues that because of the increased natural gas use in powering CO_2 capture, blue hydrogen production has higher fugitive methane emissions than hydrogen production without CCS. Interestingly, a key assumption behind the analysis is the low capture rate of 85 per cent even though ‘there is no evidence that these capture rates represent the maximum technically achievable, and indeed the basis for this assumption is rarely discussed’.[24] Similarly, the IEA points to several studies showing that a high capture rate, approaching 100 per cent, is ‘technically and economically achievable’. For sure, the energy industry is highly optimistic about its efficiency in capturing CO_2. For example, Equinor’s large blue hydrogen project at Saltend in the UK is projected to achieve a ‘minimum carbon capture efficiency of 95 per cent’ by using autothermal reforming (ATR) technology (in ATR, the required heat is produced in the process itself, resulting in higher CO_2 recovery than SMR). Also, the steam required in SMR can be produced by renewable energy, and while natural gas will continue to be required as a feedstock, the dilute CO_2 stream could be eliminated. Project developers are yet to demonstrate the technical feasibility of such solutions.

23 R.W. Howarth and M.Z. Jacobson (2021), ‘How Green is Blue Hydrogen?’, Energy Science and Engineering, Volume 9, Issue 10.
24 Budinis et al. (2018).

Regarding cost, CO_2 capture constitutes the highest-cost component of CCS and where most of the technical advances could still be achieved. As with other technologies, learning-by-doing and economies of scale are key for cost reduction, especially when the CO_2 concentrations in gas streams are low.[25] Modularization is also of key importance; it can enhance economies of scale and reduce costs, for instance by shortening planning and construction periods. Also, as discussed above, the energy penalty for CO_2 capture is high, and therefore technological advances that allow utilizing energy resources more effectively will result in significant reduction in cost and enhance CO_2 recovery.

To achieve economies of scale and technological advances, new business models need to emerge to allow the deployment of CCS at a large scale. One way to reduce risks is to disaggregate the capture, transport, and storage components of the CCS technology chain, allowing different market actors with different strengths and risk appetites to collaborate on CCS. In this arrangement it will be necessary to manage the interdependency risk, as the performance and commerciality of each part of the chain depends on the performance of other components. Governments will also need to accept long-term liability for CO_2 retention in the subsurface, although the probability of leakage of CO_2 from well selected and managed storage is very low. Also, governments can encourage the creation of hubs, so infrastructure such as pipelines and storage sites can be jointly utilized and optimized, reducing costs for individual firms and enhancing economies of scale. These hubs could be created around already existing infrastructure such as natural gas pipelines and depleted oil and gas fields. A good example is the Alberta Carbon Trunk Line (ACTL) system in Canada which involves multiple players – a fertilizer plant, a refinery, a mid-stream company operating the pipeline, and an operator which injects CO_2 for EOR.

Government support is key

But these arrangements are not sufficient on their own to de-risk investments, and government support would be required to help cover the upfront and operational costs of CCS, as disposal of CO_2 does not generate any revenues unless there is a requirement/obligation to do so. One way to generate value for such activity is for governments to introduce carbon pricing either in the form of carbon taxes and/or emissions trading schemes. Such schemes would give the incentive for operators to reduce their emissions, to avoid paying the carbon tax and/or allow operators to trade emission reduction certificates and generate revenues from these certificates to offset part of the cost. Although such price-based policy instruments receive wide support from policy makers and have played a key role in international climate treaties, the economic signal such instruments provide may not be sufficient to incentivize the deployment of large-scale CCS. A case in point is that the European ETS has so far not been able to offer a sufficiently stable incentive to deliver any CCS project, even though CCS was introduced into the system around 2010. Additional instruments may be needed to provide more certainty – such as Carbon Contracts for Difference (CCfDs) where governments cover the cost differential between the cost of CCS and the market carbon price.

Given that business models around CCS are still immature and upfront capital costs are high, governments can provide an additional layer of support by directly funding hydrogen plants with CCS, for instance by offering capital grants. In the ACTL example, the Government of Canada provided funding through the eco-Energy Technology Initiative and the Clean Energy Fund, while the Government of Alberta provided support under the Carbon Capture and Storage Fund (this government support was needed despite the fact that EOR generates revenue streams). Another example is the Carbon Capture and Storage Infrastructure Fund (CIF) in the UK which will contribute to the capital costs of establishing T&S infrastructure and early industrial capture projects. Governments can also reduce the cost of financing by providing loan guarantees to project developers.

Such direct funding, however, is not sustainable in the medium term, and alternative market-based support schemes need to be developed to specifically support CCS. As in the case of renewables, these could come in the form of 'hydrogen' portfolio standards where the government mandates companies to buy clean hydrogen with the aim of increasing the share of clean hydrogen in the energy mix. This would allow project developers to sell hydrogen tradeable certificates, providing an additional source of revenues to offset their cost. Another instrument discussed in this issue of the *Forum* is the Carbon Storage Unit (CSU), which provides a monitored, verified, transferable record of the addition of a tonne of CO_2 to a carbon sink. A key challenge is how to link such instruments to regional carbon trading schemes and to climate finance mechanisms under Article 6 of the Paris Agreement.

[25] Kearns et al. (2021).

In short, there are multiple policy instruments that can be used for stimulating CCS and the choice of instrument depends on the context. However, experience shows that carbon pricing alone may not be sufficient to induce deployment at a large scale, at least in the initial phases; a mix of market and non-market polices may be required and some of this support may need to be directed to the hydrogen fuel itself.

A stable regulatory framework and strong political support

In addition to these supportive schemes, governments must show political commitment and offer a stable yet flexible regulatory environment as the technology is changing fast. CCS consists of a series of activities and involves multiple stakeholders (government authorities, operators, investors, and the public) and therefore a regulatory framework that assigns the different rights and responsibilities of the various stakeholders is essential. Issues such as ensuring safety and protection of the environment are also key.

Finally, there is the issue of public perception. Many remain sceptical about the role of CCS as a climate mitigation technology, citing factors such as its high cost, its viability, and fears around the safety and permanence of storage. Sceptics argue that CCS can also perpetuate the use of fossil fuels, discourage change in societal behaviour, and reinforce existing dependencies. It is also argued that CCS could divert funds away from clean technologies.

In short, CCS is a key enabler for fossil fuel-based hydrogen to play a bigger role in decarbonization. To enable CCS at large scale this requires:

- Proving that high capture rates could be technically achieved so net-zero emissions targets could be reached.
- Accelerating cost reductions and enhancing efficiency, especially in the activity of CO_2 capture.
- Enhancing public acceptance of CCS as a viable and effective mitigation technology.
- Providing an incentive structure specifically targeted at CCS projects.
- Putting in place a stable but flexible regulatory framework to enable CCS projects.

As in the case of CCS, where there is interdependency among the various activities, getting any of these pieces wrong would limit the potential role that CCS and fossil-based clean hydrogen can play in climate change mitigation.

CCS IN THE EU: PROSPECTS, CHALLENGES, AND EU POLICY MEASURES NEEDED

Graeme Sweeney

Carbon Capture and Storage (CCS) will be crucial in the industrial transition towards net-zero greenhouse gas (GHG) emissions, helping to safeguard and create jobs and industrial activity, and boost economic growth. CCS technologies will be an important tool to both deliver climate change mitigation and safeguard European industrial competitiveness. For energy-intensive industries, including sectors such as cement, lime, steel, and chemicals, that are at the core of Europe's economy, pathways including CCS represent the lowest-cost route to decarbonization, as stated in the ZEP report 'Climate Solutions for EU industry'.

This decade is critical to set Europe on the right track to achieve climate neutrality by 2050, and it will be crucial to urgently develop, deploy, and scale up CCS technologies and CO_2 infrastructure for a just and cost-efficient climate transition. With this 2050 target enshrined in EU legislation, and an increased 2030 target to reduce GHG emissions by 55 per cent compared to 1990 levels, low-carbon technologies such as CCS have an important role to play in decarbonizing energy and industry sectors, and can also offer the possibility of achieving carbon dioxide removals (CDR). Now, political support is crucial; policymakers at European and national level have a critical role to play in driving the successful development and deployment of CCS and setting the foundations for a cost-efficient trajectory to reach climate neutrality by 2050.

The role and value of CCS in climate change mitigation

The 'CCUS Roadmap to 2030', developed by the CCUS SET Plan (European Strategic Energy Technology Plan) Implementation Working Group on Carbon Capture Utilisation and Storage, highlights that all net-zero-compliant technologies should be developed and scaled up to support this cost-efficient pathway to 2050. CCS will have an important part to play in the deep decarbonization of industry – in particular for hard-to-abate sectors and emissions that cannot be avoided – in a timely, cost-effective, or technical manner. Therefore, reaching net-zero GHG emissions cost efficiently by 2050 will require low-carbon technologies to be scaled up, as they will be critical in the transition to low-carbon industrial activity.

For the EU to achieve this 2050 target, the large-scale deployment of cross-border CO_2 transport and storage infrastructure is crucial. CO_2 infrastructure is a no-regret investment opportunity to pave the way for a climate-proof European economy and is vital for European decarbonization. Deploying CO_2 infrastructure would allow industrial emitters from all corners of Europe to connect to permanent geological storage, where CO_2 would be safely stored without re-entering the atmosphere, thus mitigating climate change. To enable successful deployment of such infrastructure, recognition of CO_2 storage and all modalities of CO_2 transport – such as pipeline, ship, barge, truck, and train – in EU legislation is necessary. To be consistent with other EU legislation such as the EU Taxonomy for Sustainable Activities (EU Taxonomy) and the EU Emissions Trading System (ETS) Directive, it is key that this is also the case for the Trans-European Networks for Energy (TEN-E) regulation.

CO_2 transport and storage infrastructure will also be instrumental in delivering early, large-scale volumes of low-carbon hydrogen, enabling the redesign of many industrial processes to avoid CO_2 emissions. Low-carbon hydrogen can enable many energy-intensive industries to decarbonize, especially those relying on high-temperature operations. Initially, an EU hydrogen economy will depend on large volumes of low-carbon hydrogen, requiring the development of cross-border CO_2 infrastructure. Under the EU Taxonomy, the manufacturing of low-carbon hydrogen from natural gas with CCS is recognized as a sustainable economic activity, delivering a benefit for climate change mitigation. The recognition of CO_2 infrastructure and parallel development of hydrogen infrastructure, are key points for the upcoming Hydrogen and Decarbonised Gas Package.

Investing in shared CO_2 infrastructure is the ultimate European project, and it represents a strategic and instrumental policy decision to preserve Europe's welfare and to make European society future-proof for a climate-neutral economy.

In addition to facilitating industrial decarbonization, CCS (and CO_2 infrastructure) can enable European industrial regions to remain competitive in a net-zero landscape. CCS will help to retain existing jobs and to create new jobs, by supporting the decarbonization of European energy-intensive industries that will be impacted by climate change. With the right framework, CCS applied to industrial processes can secure jobs and incomes and ensure European industrial competitiveness in international markets while delivering sustainable growth. By providing a low-carbon alternative, existing jobs in those industries will be preserved.

The current status, progress, and challenges for CCS

There is significant potential for CCS in Europe today.

In its report 'Global Warming of 1.5°C', the Intergovernmental Panel on Climate Change (IPCC) analyses several pathways that limit global warming to 1.5°C, in which a median figure of approximately 15 Gt CO_2 is captured using CCS and CCU in 2050. It is also important to note that for all pathways that limit global warming to 1.5°C with limited or no overshoot, there is a reliance on CDR. CO_2 emissions captured and stored from bioenergy with carbon capture and storage (BECCS) are planned to reach a median level of 5 Gt CO_2 in 2050. The International Energy Agency (IEA) report 'Net Zero by 2050' echoes the IPCC's conclusions, foreseeing that 2.4 Gt CO_2 in total is captured from the atmosphere by 2050, and approximately 80 per cent of this total is permanently removed through a combination of BECCS and Direct Air Capture (DACCS).

Commercial, full-chain CCS projects have been operational since the 1980s, with more than 260 million tonnes of CO_2 emissions from human activity captured and stored over 40 years and an overall estimation of around 40 million tonnes of captured and stored CO_2 per year at present, outlined in the Global CCS Institute's 'Global Status of CCS Report'.

There is an increasing number of market-ready, European CCS projects – detailed on the ZEP CCS/CCU market-ready projects map – that are moving towards becoming operational within this decade, and this is also evident from the fourth list of Projects of Common Interest (PCIs) – cross-border infrastructure projects linking the energy systems of EU countries – and the fifth list, presented by the European Commission in November 2021. There is now a strong need to support this positive progress and emphasize the role of CCS as an important enabler for a cost-efficient transition to net-zero. Supportive policy and financial frameworks need to be put in place to ensure these market-ready projects become operational before 2030.

There are a number of funding opportunities available that are coordinated in support of CCS and CCU. Horizon Europe is a major pillar for public funding for CCS and CCU in Europe. It features an area for research and innovation (R&I), and in its recently launched work programme for 2021–2022, the main calls of relevance for CCS and CCU focus on CO_2 capture, storage, conversion, integration in hubs and clusters, and CDR. The 2023–2024 Horizon Europe work programme is expected to include calls for CO_2 transport and storage infrastructure. The Innovation Fund seeks to support projects that aim to bring breakthrough technologies to the market in energy-intensive industries, hydrogen, carbon capture, use, and storage, and renewable energy. In November 2021, the results of the Innovation Fund's first call for large-scale projects were announced, with over €1.1 billion to be invested in seven large-scale projects, four of which feature a CCS component. This is a very positive result and a clear indication that the interest to support CCS projects in Europe is there. However, this first call was over-subscribed, which demonstrates the strong need for further funding support for projects. This decade is crucial to set Europe on the right track to reach climate neutrality by 2050, and it is time to scale up development and deployment of CCS technologies. Furthermore, for PCIs, there is the possibility to apply for funding from the Connecting Europe Facility (CEF).

Overall, it is crucial to align European and national funding mechanisms.

Policy measures needed to support CCS deployment

Besides putting enabling funding mechanisms in place, political recognition of CCS and CO_2 infrastructure is also critical.

In July 2021, the European Commission presented the 'Fit for 55' Package, a set of proposals which aim to ensure that the EU's climate, energy, land use, transport, and taxation policies are in line with a net GHG emissions reduction of 55 per cent by 2030 compared to 1990 levels. Of the 13 legislative proposals presented under the first part of the package, one of the most relevant pieces of legislation for CCS is the EU Emissions Trading System (ETS) Directive. The revised EU ETS Directive proposes inclusion of all modalities for CO_2 transport under the scope of the EU ETS, and in accordance with this, the Monitoring and Reporting Regulation (MRR) should be updated to reflect this important inclusion of all modalities of CO_2 transport.

In December 2020, the EU Commission presented a proposal for the revision of the TEN-E regulation; a revision aims to ensure that the EU's energy infrastructure policy is consistent and aligned to reach climate neutrality by 2050. It is crucial that all modalities of CO_2 transport and CO_2 storage are included in the revised regulation. In the revised EU ETS Directive and the EU Taxonomy, the EU Commission stated that it is expected that the transport of CO_2 will be operated by pipeline and ship. Therefore, recognizing CO_2 transport by ship in the TEN-E Regulation will be vital for upcoming CCS projects that will rely on transporting CO_2 by ship, and this should be reflected across all EU legislation. At the same time, CO_2 storage plays a crucial role in delivering real climate change mitigation, is a key aspect of CCS projects and CO_2 infrastructure, and should also be included in the revised regulation.

In October 2021, the high-level CCUS Forum organized by the EU Commission took place. This initiative was very timely; CCS and CCU technologies must be part of the equation for European decarbonization, and given Europe's 2050 and 2030 targets, in this decade a European approach for development and deployment of CCS and CO_2 infrastructure is necessary. The CCUS Forum should become the basis for an EU strategy for CCS and CCU, which should outline the role of CCS and CCU technologies in the EU's 2030 and 2050 vision, proposing targets, enabling policies, business models, and the research and innovation needed to achieve these targets.

The central focus on the strategy should be the successful development and large-scale deployment of cross-border, European CO_2 transport and storage infrastructure. The EU Taxonomy and revised EU ETS proposal both clearly outline cross-border transport of CO_2, considering all modalities of CO_2 transport, and this should be reflected across EU legislation, particularly in the revision of the TEN-E regulation, where all modes of CO_2 transport and CO_2 storage should be included.

The strategy should also seek to put in place an enabling policy framework for long-term investment. Funding opportunities and mechanisms for projects should be clearly mapped out and coordinated between EU member states, and coherence between national and EU frameworks must be developed further. Carbon contracts for difference (CCfD), announced as part of the revised EU ETS Directive, will be an important tool to support the deployment of low-carbon technologies, giving certainty and predictability to industrial stakeholders.

In conclusion, this decade is crucial to set Europe on track to climate neutrality. The 2020s are critical to set Europe on the right track to reach climate neutrality by 2050, and CCS technologies will be key in the industrial transition towards net-zero GHG emissions.

Political recognition of CCS and CO_2 transport and storage infrastructure, which is vital for European decarbonization, is key and support for CO_2 transport and the inclusion of CO_2 storage and all modalities of CO_2 transport in EU legislation is necessary. In particular, with an increasing number of market-ready CCS projects in Europe moving towards becoming operational within this decade, there is a strong need to support this progress. For CCS to get to where it needs to be in 2030 for a cost-efficient transition towards climate neutrality in the EU, several crucial items will be required, which an EU strategy for CCS could address.

An EU strategy for CCS should enable a predictable and long-term framework for investors to be put in place. The strategy would also encourage and support collaboration between the EU member states and the EU Commission, as well as European industry and the CCS community, and would provide opportunities to address challenges that may arise.

The role of CCS as an essential enabler for a cost-efficient and just transition to net-zero must be considered.

CCUS IN THE UK – WHERE IS THE STRATEGY?

Malcolm Keay

This article looks at the prospective development of CCUS in the United Kingdom, on which the government has recently published a number of consultation papers in the wider context of its Net Zero Review. It argues that the government is supporting individual projects and applications without any overall strategy, and that in doing so the government risks making the same mistakes as it did with electricity. In that sector, it has supported individual technologies (mainly renewables but also, less successfully, nuclear) without regard to the wider system effects, leading to a range of unintended consequences and system-wide inefficiencies. Unless it starts to think about energy systems in wider strategic terms, the next stage of decarbonization will raise even greater challenges – and lead to even more serious problems.

Electricity turned upside down

Electricity has been the main focus of decarbonization policy to date. In the UK, emissions from the electricity sector fell by 66 per cent between 1990 and 2019, compared with a 5 per cent fall in transport emissions and 14 per cent in residential emissions. The process has accelerated in recent years – since 2010 electricity emissions have more than halved and have accounted for three-quarters of the total UK emissions reduction during that period.

The reasons for the 'electricity first' approach are, in essence, simple – low-carbon technologies are available and can be installed upstream, requiring no immediate action or behaviour change from consumers, who can continue to use their appliances in the normal way. In that sense electricity offers 'low hanging fruit' for emissions reduction. But that does not mean that the process has been straightforward. The electricity sector is changing fundamentally.

In particular, the sources of generation are changing as a result of government support schemes. Since 2000, the share of renewables in the electricity mix has increased fifteenfold, while microgeneration (units of below 5 MW) increased many hundredfold, from virtually nothing in 2000 to nearly 7 GW today. But the introduction of these new sources is not just a question of replacing one set of assets by another. The new sources have a different set of economic and operating characteristics. Their cost structure is mainly capital and they are not dispatchable (in other words, they cannot be called on to operate as and when required).

The consequences have been profound. Among them is that traditional market structures based on short-run marginal costs are no longer effective in generating new investment, providing meaningful signals to consumers, or in managing short-term operation. Governments have been struggling to fill the gap with measures such as capacity markets to ensure reliability. This support for conventional plants, added to the support for renewables and nuclear, means that the government is in effect underpinning all new generation investment, despite its commitment to free markets.

But the investment takes place without any overall optimization strategy. Offshore wind has emerged as the main component because it combines relative cheapness and public acceptability, rather than because it meets any specific system or consumer needs; approvals are given to individual projects without considering how they fit in to the wider system.

The consequences are being felt across the electricity sector – in the words of the UK System Operator, a zero-carbon system will require it to 'fundamentally change how we plan, analyse and operate the electricity system'. Other stakeholders – businesses, policy makers, and even consumers – will also have to change in fundamental ways.

New means of system optimization will be needed. Because of the increasing penetration of intermittent generating sources, it will become ever more important to find the most efficient ways of meeting demand peaks and balancing supply and demand. There are at least six or seven different options (including various sorts of generation, network development, storage, and demand response).

But to get the right balance between them, and optimize the system overall, there will need to be either efficient market signals or an overall strategic framework. Neither exists at present. This could prove expensive – a report from the National Infrastructure Commission in the United Kingdom estimated that getting the right mix could save £8 billion a year.

Future decisions – carbon capture and hydrogen

The next stage of decarbonization will involve even greater challenges. Governments will need to optimize across the energy system as a whole. The different parts of the energy sector have in the past been treated independently and tax rates on different energy sources vary hugely (high for motor fuel, low for heating fuels) while the costs of decarbonization have been incorporated in electricity prices rather than spread across the whole energy sector. As a result, there are no price signals to guide consumer choice towards low-carbon sources.

Decarbonization of transport (at present dominated by oil) and heat (predominantly natural gas) will almost certainly involve greater use of electricity, but it may also require the development of CCUS and/or hydrogen. Indeed, on many scenarios, it would involve both technologies working together. However, little progress has been made in either area. Nearly two decades ago, a widely cited paper[26] by Pacala and Socolow on the 'stabilization wedges' which would be needed to bring an end to the growth of carbon emissions treated both options as 'current technologies', which could realistically supply two of the 'wedges' needed.

But in the years since then, little has happened, as compared with the rapid development of renewables. The reason seems to be that both technologies face similar problems, and that the problems are not narrowly technical in nature but socio-economic. They include gaining public acceptance; securing the economic viability of, and coordination of, the activities of the large number of different parties who would be involved in any project; and developing significant new infrastructure in an efficient manner.

An additional complication is that in the UK the prospects for hydrogen are inevitably affected by the future viability, or otherwise, of CCUS. Without CCUS, hydrogen generation would have to rely on other low-carbon sources – like renewable electricity – which would call into question whether there was really any need for hydrogen as a carrier, given the ubiquity of electricity supply. Although the reverse is not necessarily the case (in other words, CCUS could be viable for electricity generation and industrial combustion), in practice, the prospect of a hydrogen-based energy system could prove a clinching argument for the development of CCUS.

Finally, there is the question of deciding what networks need to be built and where. These networks will have to meet several functions and straddle different markets. Some way will have to be found to ensure that they are available in the right places and for the right uses.

At present, markets are unlikely to give appropriate signals, because of the distorted energy taxation system. Meanwhile, the government is not considering these overall strategic issues, but rather focusing on bottom-up support on the same general lines as with electricity.

As regards CCUS, separate mechanisms are suggested for different sectors:

- For **industry**, the aim is to set up four industrial CCS clusters, capturing 10 $MtCO_2$ a year by 2030. To ensure that companies participating in these pilots are not disadvantaged, the extra costs involved will be reimbursed. The

[26] 'Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies', S. Pacala and R. Socolow, *Science*, 13 Aug 2004, Vol 305, Issue 5686, pp. 968–72.

arrangements include a £1 billion CCS Infrastructure Fund, which will primarily support capital expenditure on transmission and storage networks and industrial carbon capture projects.

- A different approach is being used for **electricity generation**. CCS-equipped power plants will be eligible for 'Dispatchable Power Agreements'. These will operate in much the same way as Contracts for Difference (CfDs) in electricity, with the difference that the reference price will be a carbon price rather than the electricity price – in other words, the power plant will in effect be guaranteed a carbon price sufficiently high to justify the installation of CCS. As with renewables and nuclear support, the extra costs will be borne by electricity consumers.
- CCS linked to **hydrogen production** will be treated differently again, as described below.

The hydrogen strategy has also been elaborated on a step-by-step and sector-by-sector basis. Hydrogen is seen as central to the low-carbon system of the future (the government's Hydrogen Strategy suggests that 250–460 TWh of hydrogen could be needed in 2050, making up 20–35 per cent of UK final energy consumption).

However, there is huge uncertainty, not only about the total volume, but also about precisely where the hydrogen will be used (for instance, for 2035, a range is given for hydrogen in heating buildings of 0–45 TWh) and how it will be produced (at the moment, the UK has committed to a 'twin track' approach to hydrogen production, supporting both electrolytic and CCUS-enabled hydrogen production).

The proposals for funding hydrogen development are similar to the CfD approach in electricity described above. The general aim is to support producers, rather than consumers, via a 'strike price', intended to enable hydrogen producers to cover their production costs, and a 'reference price', intended to represent the market value of hydrogen (which could vary in different applications). The cost of this support would apparently be borne partly by the taxpayer and partly by energy consumers, though little is said about the potential size of such a levy or how to ensure social equity and avoid aggravating fuel poverty.

These still leave many questions open. For instance, on the development of infrastructure, the 'strategy'[27] says in effect that strategic decisions will be taken in due course:

> 'This decade will see key policy decisions taken that will influence how hydrogen networks develop and are operated.'

The government seems to recognize that this might cause problems – without, however, at this stage suggesting any solutions. It recognizes that

> 'it will be important that initial investments and later evolution of the network are achieved in a coordinated manner'

but proposes no mechanism, saying only

> 'We will need to consider whether and what policy mechanisms, such as incentives or regulation, are needed to ensure that network infrastructure is developed to allow later build out and interlinkages. We will also need to manage or mitigate the risk of stranded assets'.

It is not even clear whether it will ever attempt to take a cross-sectoral overview. While the document implies that Government is looking at system operation and network planning across the energy sector it adds only that this work **may** shape their long-term vision for network planning.

In other words, there seems to be no effort at present to address the wider questions of infrastructure development. For instance:

- if the CO_2 infrastructure has to be designed around the needs of carbon users, rather than just sent to storage, its structure and functioning could be very different;
- if hydrogen for transport is going to be critical, that will influence the overall design of the system;

[27] Quotations taken from: 'UK Hydrogen Strategy', HM Government, August 2021.

- if electricity, rather than CCUS-equipped gas, is to be the main source of hydrogen that will affect system architecture;
- if environmental concerns are to be the priority rather than economic value, that might significantly affect hydrogen use.

Hydrogen in electricity or transport is likely to have higher market value (because of the tax anomalies described above) but home heating might offer the greatest scope for emissions reduction.

The list of such questions is potentially very long – but all are overshadowed by the fundamental question of whether hydrogen and CCUS will be needed in the first place. The government has said it will not make a decision on hydrogen until 2026, which might both be too late (for development of the necessary infrastructure in time to reach the net-zero target) and too early (in terms of the proposed pilots of hydrogen in residential heating which will not reach town level until 2030).

Alternative policy approaches

While it would be unreasonable to expect any detailed strategy from the government at this stage, the failure to develop any overview, however high-level, or even to decide whether any overview is needed, is worrying. Time is short. Although energy transitions need not necessarily take centuries, a coordinated and efficient new system will not evolve in response to uncoordinated individual interventions with specific objectives.

A better approach might be to focus on outcomes – such as lower emissions – rather than specific technological inputs. Many economists favour carbon taxes or trading schemes as a means to this end. The problem is that it takes time for fiscal measures to bed in and influence expectations. It is virtually impossible for governments to commit themselves to tax levels 10 or 20 years out; credibility only comes after an extended period of operation.

This author therefore favours tradable carbon intensity targets. Carbon emissions limits (g/kWh) would be set for each year on a scale descending to 0g/kWh by 2050 or earlier, probably with separate scales for each sector. Failure to achieve these targets would result in fines, but compliance could be achieved by buying credits from producers who remained below their target for the year in question.

The advantages of the approach include the fact that it is transparent (including to investors, who will be able to penalize companies for plans which do not follow an appropriate trajectory) and that it provides incentives for over-achieving. There is a partial parallel in the US automobile market, where a broadly similar system applies. Tesla, the electric vehicle manufacturer, has generally made most of its net income via selling carbon credits, rather than by selling cars.

But the main advantage of the approach is that it does not specify technologies. That does not necessarily mean that support for new technologies and infrastructure will not be needed. Some of the schemes listed above may indeed have a useful function to perform in taking technologies towards viability, testing consumer acceptance, and identifying major pitfalls. But they should not drive the shape of the future system – as they have with electricity. Even at the end of the proposed trial stages listed above, the answers to the big strategic questions will be no clearer. The support schemes are essentially artificial and designed to make the technologies concerned viable within present structures, rather than to develop new structures in which the best technologies, and those which best reflect consumer preferences, would be self-sustaining.

Conclusions

The government needs to learn from its experience with electricity in considering measures to encourage CCUS and hydrogen. It is not just a matter of introducing a new set of sources into a system which will then continue much as before. The government cannot therefore take a piecemeal approach, dealing with individual problems as they arise; it needs to set a clear overall direction for the energy sector as a whole and to evolve mechanisms for optimization and coordination between the various sub-sectors. This is a new frontier and the government has not even started to develop appropriate policy tools. The efficient development of the country's future energy system will depend on how successfully the government rises to these challenges.

CARBON CAPTURE AND STORAGE (CCS) IN NORWAY: EXPERIENCES AND CHALLENGES FROM WITHIN

Jon C. Knudsen, David Phillips, Emil Yde Aasen, and Hallvard Valen

There has been some debate over the deployment of CCS in some industries, but research – and increasingly market consensus – shows that CCS is likely necessary on a large scale. This is especially the case for sectors like power generation and industrial manufacturing, as well as in the use of fossil fuels and biofuels. To ensure CCS is deployed at the appropriate scale (and speed) to make a substantial contribution to the Paris Agreement's 'well below' target of 2°C, government support for CCS is likely to be required alongside broader climate policies.

CICERO, The Center for Climate Research, a Norwegian interdisciplinary research institute, lists three main reasons why CCS is likely to be required to stay 'far below 2°C'.

1. CO_2 emissions have a cumulative effect on the climate, necessitating net-zero CO_2 emissions to prevent further global temperature rises. It may be difficult to reach net-zero emissions without using CCS to remove direct emissions or for CO_2 removal.
2. There are no competitively priced technologies that reduce emissions to zero in most hard-to-abate industries (such as steel and cement). It may be less expensive to reduce emissions in these industries by direct use of CCS or through CCS utilized in CO_2 removal.
3. Reducing emissions in some industries using CCS or CO_2 removal may be less expensive, and the resources saved may be utilized for other social goals.[28]

What are the challenges in the commercialization of CCUS?

Since carbon capture technology has already been validated, a widely held belief is that the major business obstacle to enabling widespread CCS deployment is commercialization.[29] CCS involves the construction of capital-intensive, long-lived assets. Aside from the capture plant, these assets include CO_2 transport pipelines or shipping, as well as geological storage resources.

According to the IEA, the concern held by some – that carbon capture and storage (CCUS) is the costliest emission-reduction technology – is incorrect. For industry, CCUS technologies are among the cheapest abatement options, or in some cases the only option. As an example, CCUS is currently the most cost-effective method of decreasing emissions in the manufacturing of important chemicals such as ammonia, which is widely used in fertilizers.[30]

A number of factors can explain the low adoption of CCUS so far, but one of the most frequently mentioned is its perceived high cost. According to the IEA, this explanation ignores the bigger picture. However, market views routinely highlight CCUS as being excessively expensive, and unable to compete as a tool for CO_2 mitigation with major areas of renewables like wind and solar power generation, due to the considerable cost reduction realized in those areas over the last decade.

While climate regulations, including carbon pricing, are not yet strong enough to make CCUS economically appealing in all cases, dismissing the technology on cost grounds would be to ignore its unique strengths, its competitiveness in key sectors, and its potential to enter the mainstream of low-carbon solutions.[31]

To reduce the technical and commercial complexities facing emitters wanting to implement CCS with their operations, Aker Carbon Capture (ACC) has recently developed a new and innovative business model: Carbon Capture as a Service (CCaaS). This model addresses several of the key challenges mentioned in this study. From an emitter's perspective, with CCaaS there is no need to wait for government financing, no large investments are necessary, and the whole value chain is simplified. The CCaaS model sees ACC take the risk of building and operating, and the customer pays a price per ton of CO_2 that is linked to some measure of forward-looking ETS pricing curve. To date, the CCS industry generally lacks the well-established and identifiable business models, processes, and procedures that exist in mature industries and which help to play a vital role in minimizing perceived investment risk. With the launch of CCaaS, many of these commercial shortfalls are potentially resolved.

[28] Peters, G. & Sognnæs, I. (2019), 'The Role of Carbon Capture and Storage in the Mitigation of Climate Change', Center for International Research.
[29] IEA (2020), 'CCUS in Clean Energy Transitions', IEA Flagship Report, Paris.
[30] IEA (2021), 'Is carbon capture too expensive?', IEA, Paris.
[31] IEA (2021).

Is there public support for CCS in Norway?

A study conducted by Palgrave Communications analysed the level of public support for CCS. This survey was conducted in the United Kingdom, the United States, Canada, Norway, and the Netherlands, expanding the geographic reach of earlier research (which was largely undertaken in a single nation or within Europe) and allowing for cross-regional comparison. The data revealed significant cross-national disparities in CCS awareness and support, with Norway being the most aware and the UK being the most favourable. The survey showed that fewer than 10 per cent of Norwegians have never heard of CCS, and 50 per cent have heard something about it, which is relatively high when compared to the next closest country, where less than 40 per cent have heard anything about it. Though public acceptance of CCS in Norway is actually lower than in the UK, there has been no large media outcry against the operation of the carbon capture test centre at Mongstad, even in the context of proprietary solvents such as those used by ACC.[32]

However, popular opinion in Norway is divided. When addressing the Longship project, former Prime Minister Erna Solberg told the Norwegian newspaper Enerwe that the long-discussed work must now proceed, and that she believes she has widespread support for the project.[33] In addition, Gasnova, a Norwegian state enterprise for CO_2 management, and First House, a Norwegian communications and consulting firm, carried out a poll. The topic presented was whether Norway had a special responsibility for decreasing global greenhouse gas emissions. More than half of those polled answered 'Yes'. This could imply that CCS technology based on Norwegian current technical understanding makes sense, because technology transfer from our existing oil and gas sector to a new industry would be widely accepted. On the other hand, a few centre-right parties were opposed to the initiative because they claimed that private corporations were carrying too little of the cost.[34]

This analysis shows that CCS support in Norway is influenced potentially by two factors:

> **1. Being an effective CO_2 abatement tool**, without being a risk for the neighbouring environment. The Aker group started testing its CO_2 capture technology at Technology Centre Mongstad (TCM) in 2012.[35] This occurred at the same time as a series of substantial advancements in the understanding of amine emissions and nitrosamine chemistry. SOLVit, an eight-year research and development programme (funded by Gasnova and Aker Clean Carbon, now ACC, in 2008) had the purpose of making CO_2 handling using amine-based solvent technology more cost effective. The solvent was assessed for 2,090 hours during the campaign, and many outstanding Health, Safety, and Environment (HSE) properties of the solvent were identified. These included minimum emission, non-toxicity, biodegradability, liquid waste reduction, and corrosion minimization. With the UK having one of the strongest focuses on health and safety records in the world, it is possible that the high HSE standard of ACC is equally relevant in the UK and comparable regions.[36]
>
> **2. Being a future industry for Norway**; CCS is currently expensive; Longship is an example of public money being spent on such projects, nonetheless, there is optimism that this will be part of Norway's new industry adventure. According to Sintef, an independent non-profit Norwegian research institute, large-scale CO_2 management in Norway could provide 30,000–40,000 new jobs by 2050, with ripple effects potentially adding up to 200,000 jobs. Sintef also states that, along with the investment in large-scale CO_2 management, hydrogen may also become a major player, potentially creating 35,000 jobs in hydrogen production from natural gas.[37]

What role can CCS play in negative emissions?

In recent years, negative emissions technologies, or NETs, have arisen as a major topic in climate policy debates.

Direct air capture (DAC), afforestation, land management, ocean fertilization, and bioenergy with CCS (BECCS) are some of the NETs estimated to be necessary to accomplish the ambitious climate goals. Indeed, it is projected that NETs will need to be

[32] Whitmarsh, L., Xenias, D. & Jones, C.R. (2019). 'Framing effects on public support for carbon capture and storage', Palgrave Communications 5, 17.
[33] Enerwe (2020). 'Solberg: Regjeringen setter av 2 milliarder kroner til karbonfangst', enerWE.
[34] Krekling, D. (2020). 'Frp sier nei til forslaget til karbonfangst og -lagring', enerWE.
[35] Koeijera,G. Engea,Y. Sanden, K. Graffb, O. Falk-Pedersen, O. Amundsen,T. Overå, S. (2011). 'CO_2 Technology Centre Mongstad–Design, functionality and emissions of the amine plant', *Energy Procedia*, 4, 1207–13.
[36] Hackit, J. 'A guide to health and safety regulation in Great Britain. Health and Safety Executive'.
[37] Størset, S. Tangen, G. Wolfgang, O. Sand, G. (2018). 'Industrielle muligheter og arbeidsplasser ved CO2 -håndtering i Norge' Sintef.

widely deployed by the end of the century to cut greenhouse gas emissions to the levels necessary to satisfy the Paris climate goals.

According to the IEA's Net Zero by 2050 (NZE) article, Switzerland expects to employ negative emissions technology to balance a portion of its residual emissions in 2050. It also claims that NETs such as bioenergy and DAC equipped with CO_2 storage are critical to providing global emissions reductions. According to the Intergovernmental Panel on Climate Change (IPCC), without extensive usage of NETs, no forecast can achieve a 1.5–2 degree scenario by the end of the century.

It is not only an issue of improving or aiding the current situation; achieving the Paris Agreement would be impossible without some sort of NET. Although it looks as if NETs will play an important part in fulfilling future carbon reduction targets, several experts have lately questioned their future usage, emphasizing deployment limitations. They argue that NETs are not a 'silver bullet' solution to climate change.[38] Despite the fact that NETs are included in the NZE and IPCC scenarios for net zero, they have not been widely discussed in Norway, either in the media or in politics.

The importance of government funding

Various governments in Norway have collaborated to develop a full-scale programme for CCS. In the state budget for 2021, the Norwegian Parliament authorized the Solberg government's full-scale CO_2 management project Longship – collection, transport, and storage of CO_2. The project will cost a total of NOK25 billion. In the first phase of the project, the government will fund around two-thirds of the expenditure, while the industry will cover the remainder.

The socio-economic effects of this initiative have the potential to significantly benefit Norwegian industry. In addition to the value creation from the full-scale project itself, the initiative has the potential to employ up to 5,000 people in Norway. Norwegian companies will be able to position themselves for the global market and potentially gain a competitive advantage over nations with no domestic market, because of Norway's technical development and deployment. Furthermore, the project has enormous technological and information distribution potential, and it may provide critical knowledge for the development of the next generation of CO_2 management programmes.

Since the CCS market is still in its early phases, the need for ongoing government financial backing cannot be overstated. In most initiatives, we still see a need for government assistance. Several governments now provide 'Contracts for Difference' to help new initiatives get started while simultaneously contributing to long-term cost reductions.

Conclusions regarding the Norwegian experience

While working with CCS in Norway, ACC encountered a variety of challenges, gained great expertise, and would like to highlight three essential points.

- A major promotion of the HSE and capture efficiency at the core of the technology is required in order to apply it to other locations, such as the United Kingdom.
- There is also a need for commercial innovation. This is exemplified by the new business model, CCaaS, which has seen a strong market pull, suggesting that the market desires new forms of business.
- As funding is so critical for CCS, new ways of acquiring funds are essential. The most recent EU Innovation Fund (IF) award is an example of this. Seven projects were chosen for grant discussions and ultimate funding award from the 66 submissions submitted in the second stage of the IF. This represents a 2.3 per cent success rate when compared to the original 311 applications, and emphasizes the importance of additional financing.

There will undoubtedly be many challenges to overcome in the next few years, in order for profitable large-scale carbon capture plants to become a reality, but ACC is convinced that a solution can be found by working together!

[38] Global CCS Institute (2018). 'Let's talk negative emission technologies'.

CCS IN NORWAY: LESSONS FOR COMMERCIALIZATION ACROSS EUROPE

Ragni Rørtveit, Ida Egeland, and Eirik Wærness

Carbon Capture and Storage (CCS) is gaining acceptance as an effective and necessary tool to reach the world's ambitious climate targets. The technology is a means to decarbonize existing and necessary industry, and it can contribute to negative emissions through bioenergy with CCS (BECCS) and Direct Air CCS (DAC(CS)). However, CCS is an infant industry, thus it needs support to gain size and reach commercialization. This includes everything from legislation, access to storage locations, and political acceptance to incentivizing funding and taxation schemes. The Glasgow Climate Pact illustrates that significant action is still needed to realize global climate goals. Combined with an increasingly tight carbon budget, there is an obvious need for speed in the development of this critical piece of the climate puzzle.

Experience

The CCS adventure in Norway started as a practical way to handle excess CO_2 in the gas coming from the offshore field Sleipner in 1996. The next part of the story was a project with a solution to separate CO_2 from the liquified natural gas (LNG) at the Snøhvit processing plant in 2008. Both projects have been full-scale operational CCS projects since their start-up, but have had little global attention. This is probably partly because both projects are fully owned, operated, and controlled by the same company.

But the adventure did not stop there. Norway is now developing a full-scale CCS value chain, called Longship,[39] spearheaded by the transport and storage operator, Northern Lights,[40] and building on the Sleipner and Snøhvit experience. The technology applied to handle CO_2 is not new. However, while the technology has been in operation for over 20 years, the value chains and business models have not been in place to commercialize and subsequently build scale. The current vertically integrated value chain has not opened for other industries to leverage CCS as an effective decarbonization tool. As an example, no cement or waste-to-energy factory has access to an appropriate storage reservoir. Furthermore, the cost of emissions has also been too low to incentivize emitters to search for such opportunities.

Opening the value chain from an in-house single-train CO_2 'conveyor belt' to an open source, commercially available market is where the Longship project is the first of its kind. By modularizing the value chain to include a transport component with ships, all emitters with access to a jetty can theoretically tie into the CCS infrastructure. The emitter needs to capture, purify, and liquify the gas before it can be stored and transferred to the vessels, and then shipped to the receiving terminal on the Norwegian west coast. From the terminal the liquid CO_2 will be pumped through a 100 km pipeline before being injected into a subsea saline aquifer in the North Sea.

An important challenge for an emerging market is identifying commerciality. Previously, no emitter could justify capturing CO_2 with nowhere to store it, and no storage provider would develop expensive infrastructure for a non-existing market. The government-funded Longship project has unlocked this long-standing chicken-and-egg stalemate, which could accelerate commerciality for CCS. By funding the entire value chain, from capture, through transport, to storage, a mutual and coordinated commitment to project realization is ensured. Northern Lights phase 1 has a capacity to transport and store 1.5 million tonnes of CO_2 per annum (MTPA) by 2024, of which only 2 x 0.4 MTPA are reserved for the government-funded volumes. This allows the Northern Lights Joint Venture to approach the market with available capacity, and consequently emitters to consider CCS as a realistic option for decarbonization.

This full-scale demonstration project is of paramount importance as a pathfinder, but the volumes are of course negligible relative to the global carbon challenge. Speeding and scaling up, based on the experience from Longship and other industry projects, will be essential.

Hurdles in the development of CCS as an industry in Europe

The Global CCS Institute has been reporting yearly growth in the number of CCS projects since 2017, and although the market for CCS is growing, there are many elements that need to fall into place for it to continue this trajectory. The export, import, transport, and storage of CO_2 is a new industry, which brings a demand for appropriate legislation. CO_2 is, correctly, labelled as

[39] Longship – The Norwegian government's full scale CCS demonstration project.
[40] Northern Lights – an open-source CO_2 transport and storage project in Norway, owned by Equinor, Shell, and TotalEnergies in equal share.

a waste product. This has had challenging implications in, for example, the London Protocol, which prohibited the export of waste for dumping in marine environments. Not until 2019 were amendments added to allow for CO_2 to be transported between countries for the purpose of permanent subsea storage. The difficulties of being a first mover become apparent through this example. This proves the need for a demonstration project like the Norwegian Longship.

In the energy transition so far, the public opinion, engagement, and push for actions have been an important driving force to influence businesses, markets, and policymakers to speed up development. The renewables industry is one such example. Public perception of CCS is currently very varied, in Europe and elsewhere. Scepticism mainly comes from safety concerns and the fear of a lock-in effect of the fossil fuel industry. The 'not in my backyard' mentality against CCS has been particularly prominent in Germany, coincidentally the biggest emitter in Europe.

A main concern from the public is leakage of CO_2 from the reservoir. However, this is well addressed through years of operations, research, and development, and will be closely monitored. In the preceding value chain, the key difference between CO_2 and hydrocarbons is the non-explosiveness and non-toxicity of the former. This means that any value chain leaks would be considerably less impactful and dangerous. An accidental release of CO_2 is of course mitigated.

Safety concerns and public perception of this risk may be smaller in countries with an oil and gas industry. In Norway, the offshore and onshore experience over many years (refinery and processing), has given the public a high level of trust in the industry's ability to ensure safety. Also important is that most of the political parties in Norway share a support and confidence in CCS as a key decarbonization technology. This view is also supported by environmental NGOs. This public, governmental, and NGO support has thus been instrumental in the development of the Longship project, and the consequent availability of a commercial CO_2 sink. This broad alignment on the decarbonization toolbox is an early step towards real climate action in hard-to-decarbonize sectors, and a lesson to follow for the main emitting countries in Europe.

How could CCS become commercially attractive?

A large-scale demonstration project is a key start, but in order to reach the scale required, CCS must become a self-sustained industry, driven by regulation and the cost of carbon. There are three key factors that accelerate the commercialization of CCS;

- carbon pricing,
- carbon markets,
- drive from consumers for climate-neutral products.

What sets CO_2 apart from other liquified gases is its value, or lack thereof. This implies that an artificial, regulatory, value must be imposed to incentivize the reduction in CO_2 emissions. For the EU this is being done through the EU ETS (Emissions Trading System), a cap-and-trade system built to ensure the commercialization of emission-reducing measures. By allowing businesses a fixed number of quotas annually and allowing surplus quotas to be sold, or deficiencies to be bought, the idea is that the most effective decarbonization measures will be taken first. By subsequently reducing the number of free allowances/quotas each year, emissions should also be reduced.

The EU ETS and other local/national carbon taxes implement a cost of emitting CO_2 directly to the atmosphere, and thus reduce the price gap between the alternatives – cleaning up or emitting. The marginal cost of releasing CO_2 saw a historic high on 8 December 2021 above 90€/t. In Norway, this price comes on top of carbon taxes at different levels for industries that are part of the EU ETS. This drives companies to invest considerably in energy efficiency or decarbonization measures. The prospect of even higher carbon prices in the future is a strong driving force in the development of CCS. Whereas some industries like shipping – which is not part of EU ETS today – await the availability of low-carbon fuels, with an intermittent lack of options, other sectors are quickly electrifying. For some industries, especially those requiring high temperatures, such as steel production or waste treatment, electrification is not an option. Carbon Capture and Storage will be the inevitable solution for these industries to continue producing their products, but with much lower emissions. This will be key for the global carbon budget, as demand for industrial products has substantially increased over the last years, along with the industries' energy use and GHG emissions. Today, manufacturing industry counts for a third of global energy use.[41]

[41] Tracking Industry 2020 – Analysis - IEA

Removing carbon from within a value chain is a way to *avoid* emissions that would have otherwise happened if no action was taken. With the possibility of capturing and storing CO_2, negative emissions, namely the removal of historic emissions, also become a possible part of the equation and is deemed an inevitable tool by the IEA and others in aiming for a future net-zero world.

Negative emissions can be achieved by capturing carbon in a natural lifecycle, in other words, through wood. If a tree dies naturally in the forest, it will emit CO_2 through the decomposition phase. If the same tree is burned in a closed system to generate energy, and the CO_2 which otherwise would have been released to the atmosphere is captured, we have been able to extract CO_2 from the air through the tree's lifetime and avoid the residual emissions from the natural decomposition. This is coined BECCS (bioenergy with Carbon Capture and Storage). Negative emissions can also be achieved by 'sucking' the CO_2 directly from the air using DAC (Direct Air Capture), with subsequent CCS. Though not available at scale yet, innovation and development are on a rapid trajectory. With the prospect of more available storage locations, the possibilities continue to grow.

Negative emissions already have a value on the voluntary carbon market (VCM). Not all emissions can be removed within the activity's own value chain, and carbon off-setting is a way to compensate for own emissions by investing in carbon removals somewhere else. Projects eligible for credits can be both nature-based, and technology-based. Technology-based solutions include credits sourced from BECCS and DAC but are not common in the VCM today, as these technologies are still in the early stages of development. Today, the VCM consists of mostly nature-based solutions, where offset credits are being generated through investments in projects for forest preservation and reforestation, among others. However, the lack of international regulation has contributed to undermine the legitimacy, and subsequent development, of the VCM. Article 6 in the Paris Agreement outlines the mechanism for carbon emission trading between host countries and was one of the main topics at COP26. One of the main outcomes was an agreed regulation of international carbon markets, which may have implications for the VCM, as it may bring a stronger sense of legitimacy and increase companies' attention to voluntary measures to abate emissions. In the future, technology-based credits enabled by CCS for negative emissions could play a larger role, and there is a possibility that we will see a strong voluntary market based on certified and verified CO_2 removals that could unlock further investment in commercialization of the technology.

The third commercial enabler for CCS is consumer power. Sustainable products are in high demand, and for some segments the tolerance for a 'green premium' could be considerable. One example could be the global market for high-end electric cars. The low-emissions component is key to many customers, and by using steel produced with carbon capture, a large part of the vehicle's life cycle emissions is removed. Consumer power as an enabler has grown stronger with increased public knowledge and attention to climate change, but a more direct focus on consumer habits is needed. This is another big piece of the climate puzzle we must seek to solve.

Need for speed

Different energy scenarios consistent with sustainable development all point to the need for massive growth in CCS capacity over the next decades. Norway has decided to lead the way in the development of CCS, building on years of offshore experience. With the Longship project, the commercial market is being unlocked, and customers far beyond the project's capacity are flagging their interest. This indicates the possibility for other open-source CCS projects in Europe, and competition should be welcomed, as the need to scale up is massive. A multitude of capture sites, transport options, and storage locations are needed to provide a stable and reliable CCS value chain. In addition to the logistics benefits, cost saving will also follow with increased sink availability and proximity, by reducing the transportation need. On top of this, experience shows that when access to new markets opens, so does innovation and technology development.

We are, however, still a considerable distance from where we need to be for CCS to be commercially viable on its own. Going forward, governments must continue to incentivize and support all parts of the value chain – through targeted and effective funding, reduced barriers to entry from a legislation standpoint, and higher carbon prices. In November 2021, the EU demonstrated that CCS was considered to be an important lever to the decarbonizing agenda, when it was seen that four out of the seven projects which were awarded funding through the Innovation Fund were planning to use CCS. The funding round amounted to a total of €1.1 billion and shows the EU's willingness to speed up, and also a technological readiness worth taking note of. Simultaneously across the Atlantic, similar signals were also expressed when President Biden signed the US infrastructure bill. It included over $12 billion allocated to carbon removal technologies, projects, and infrastructure which will be the largest investment in CCS ever made.

As COP26 is over, we are reminded yet again of the criticality of moving quicker and in the right direction in terms of energy efficiency and emission reductions. We are seeing a plethora of solutions, but no silver bullet; this implies the need to develop all solutions, and do it concurrently. CCS has a definite place in the future by being the only solution for decarbonizing heavy industry and enabling negative emissions. It is also a necessary component in the development of markets for hydrogen as an energy carrier, believed to be an important part in the future energy mix. As with all good adventures, the quest for CCS is well defined, with further commercialization as an important and inevitable enabler for a net-zero world. There is little doubt that we have only seen the beginning of the CCS adventure yet.

THE DUTCH APPROACH TO CARBON CAPTURE AND STORAGE

Sanne Akerboom and Gert Jan Kramer

As the world runs out of time to meet its climate targets, the old saying that energy policy should be ‘all of the above’, namely that we should not rule out options, comes ever closer to being a hard truth. This has particular implications for carbon capture and storage (CCS). For well over a generation the world has had a wavering stance towards it, recognizing its value on paper, but resisting or shunning it in practice. Large-scale projects are still comparatively rare and most of them are tied to oil and gas production rather than to power or industrial end use. It looks as if the Netherlands will break the spell and proceed with CCS deployment with a determination not seen anywhere before.

In a public–private Dutch Climate Agreement, more than 100 parties have agreed to measures and transition pathways to reduce CO_2 emissions by 49 per cent by 2030, relative to 1990. To divide tasks and responsibilities, the 2030-target has been itemized into sector-specific targets. The Dutch industrial sector is tasked to reduce its emissions by 14 million tons (Mt) annually, with half of that relying on CCS. This completes a shift away from use of CCS in the power sector to an exclusive focus on CCS in industry. The political decision to phase out coal-fired power plants in the Netherlands by 2030 leads to exclusion of CCS as a reduction measure in electricity production. The decarbonization of the power sector will now fully rely on renewables. Also, following a public outcry over two previous onshore CO_2 storage projects, CO_2 storage will be done exclusively in offshore depleted gas fields.

Several emissions reduction technologies are available for industry. In earlier decades, efficiency improvement was the prime route for emissions reduction. The deep cuts required now require more radical measures. Electrification of both motive power and heat is an important technology, both short term and long term. But electrification has its limits, so that the remainder requires a fuel shift, for which green hydrogen is the preferred long-term choice. Yet it will not be available at scale for a long time, making CCS an almost unavoidable option to deliver significant emission reduction this decade. For this reason, industry, government, and environmental NGOs have agreed to subsidize CCS projects until 2035, after which other reduction technologies must have emerged or CCS must proceed unsubsidized.

As a ‘transition technology’ CCS faces a dual challenge: how to scale up CCS this decade and how to transition away from it in the longer term – the end of subsidy beyond 2035 being a first marker in the transition process. This inherent contradiction may reinforce existing uncertainties in the realization of CCS and could cause a delay in the decarbonization of industry.

How to realize CCS in the Netherlands?

On paper the Dutch policy to stimulate CCS in industry offers a hopeful perspective. To start with, regulation on the exploration and realization of CCS projects has existed since 2009, when the Netherlands transposed Directive 2009/31/EC on the geological storage of carbon dioxide into its existing Mining Act. The specific chapter on permanent storage of carbon dioxide regulates under which conditions – such as monitoring and compensation for potential damages – permits for exploration and CCS projects can be granted.

In 2017, a newly elected government in the Netherlands presented their ‘most ambitious climate policy yet’. This policy laid down for the first time a new 2030 target, a 49 per cent reduction of CO_2 emissions (relative to 1990), and the challenge to work within the European Union (EU) towards an EU-wide target of 55 per cent, which has been adopted by the European Commission in the European Climate Law (EU 2021/1119). To meet the Dutch target, a new public–private agreement, a successor to the Energy Agreement, would be negotiated. As tools and guidance, the new elected government coalition suggested a division of five sectors and corresponding targets in the form of reduction of Megatons (millions of tons, Mt) of CO_2.

The industrial sector would have to reduce 22 Mt CO_2 annually and had the ability to reduce 18 Mt with CCS projects. This was, at the time, surprising. Most parties did not mention CCS in their election programmes, but rather used vague terms such as 'innovation' or technique-neutral terms such as 'emissions reduction technologies'.

How this target could or should be met was then left to negotiations between the executive branch of government, industry, and societal and environmental organizations like NGOs. During these negotiations, the industry target was lowered to 14 Mt annually in total. Environmental NGOs resisted the employment of CCS to fully meet this target, especially when subsidies would be used to enable these projects. As a compromise, subsidies were capped quantitively and for a certain period: no more than 7.2 Mt annually, with an end date in 2035.

On paper, there is a supporting regulatory and policy framework to realize CCS in the Netherlands, especially since the Porthos project was awarded a subsidy of €2.1 billion in 2020. Moreover, in September 2021 the government announced an increase in the level of subsidies in the upcoming years. Yet not a single CCS project has been realized in the Netherlands so far. They only exist on paper. There is still no guarantee that projects, even the subsidized Porthos, will in fact be realized.

Different uncertainties persist. To start with, there is no guarantee that the Porthos project will be granted a permit for the permanent storage of CO_2. The requests have been submitted, which follow the exploration permit that was granted in 2020. Upon the public review of the permit requests and the draft decision, a case has been brought before the Judicial Division of the Council of State, the highest administrative court in the Netherlands. This is in relation to the nitrogen disposition during the realization of the CO_2 infrastructure. The Netherlands is already coping with a nitrogen crisis, as the Judicial Division ruled that the Programmatic Approach to nitrogen was void due to direct contradiction with EU habitat regulations. The NGO, Mobilisation for the Environment, which brought that case before the Judicial Division has now appealed the draft decision to grant the permits. If the Judicial Division rules in favour of Porthos, the permits most likely will be granted. In that situation, it is likely that Porthos will initiate the injection of CO_2 before 1 January 2026, which it will be allowed to do for 15 years.

There has been less progress on other new projects, which still have to request exploration permits. All projects face stringent rules pertaining to the monitoring of the sites, including leakages and possible compensation requirements for damages, including the transfer of emission trading rights.

Whether Porthos is the only viable CCS project in the Netherlands remains to be seen. Tata Steel, the company with the biggest CO_2 footprint in the Netherlands, has recently announced that it would cancel its CCS plans, and instead focus on green hydrogen. This prolongs the use of the coal-fired powered production processes, and its emissions. It could be argued that the realization of green hydrogen in the Netherlands is surrounded by even more uncertainties, due to a lack of clear regulatory frameworks, policy instruments to incentivize, and a standstill in the roll-out of offshore wind energy, which will hopefully be resumed once the new cabinet takes office.

Given the uncertainties in other sustainable pathways towards decarbonizing Dutch industry, this begs the question of whether the Netherlands should mandate CCS, or potentially risk not meeting its emissions reduction targets. The PBL Netherlands Environment Assessment Agency, which monitors (projected) progress of climate policy, has indicated that the 49 per cent emissions reduction target is currently unlikely to be realized. To this end, there should be more policy instruments to facilitate progress. From this perspective, CCS offers one of the most cost effective technological solutions for emissions reduction until 2030.

This has become all the more pertinent, now that the new Dutch coalition has announced to aim for a CO_2 emission reduction target of 55 per cent by 2030 (relative to 1990) in its coalition agreement of December 2021. This new target will put more pressure on parties, possibly through CCS. In line with the September 2021 announcement, the coalition parties mention in their agreement that they will increase the incentives if necessary.

How to transition away from CCS in the Netherlands?

Whilst the Netherlands may face the choice of mandating CCS as an emissions reduction technology, to meet its targets until 2030, it simultaneously faces the need to think through its phase-out before it has even started. There is a clear choice in the Netherlands not to prolong CCS until 2050 but to realize CCS as a transition technology and rely instead on other technologies to achieve a carbon-neutral society by 2050. The transition towards large-scale electrification, CCUS, green hydrogen, and new renewable sources such as geothermal heat is, as sketched above, rather uncertain.

At the moment, CCS competes with these technologies under the most important Dutch subsidy scheme, SDE++. Given the evaluation criteria, namely CO_2 emission against the most cost-effective measures, CCS is a clear winner in the competition with green hydrogen for instance. This pushes the progress of green hydrogen further on the timescale, as it does not receive any governmental subsidies yet, which are essential for its development. This may *de facto* prolong the lifespan of CCS, and risk the viable development of alternative emissions reduction technologies. There are debates about splitting the subsidies for emissions reduction technologies, to guarantee that green hydrogen will be eligible for subsidy, but the political decision has not been made yet.

A potential successful pathway is to transition from CCS to CCU. This is, for instance, included in the sustainable cluster plans of the Port of Rotterdam. In these plans, industrial clusters make explicit which targets they aim to realize by 2030, and which measures they will use to realize this. The Port of Rotterdam envisions CCS as being ultimately replaced by CCU, but does not yet emphasize how or when to realize this goal.

The question arises here, who is responsible for envisioning and realizing the transition away from CCS to other emissions reduction technologies? The government aims to be technology-neutral, despite *de facto* favouring certain technologies over others. The government has at least the ability to take away these limiting factors for other technologies. Currently companies and industrial clusters enjoy competence over emissions reduction choices, and can opt for CCS or other technologies. Should this persist, or should the government take a more active role in steering this transition?

To CCS or not to CCS?

In the short term, the Netherlands opts to employ CCS to enable deep decarbonization in industry. Whether projects will be successful depends on a number of factors, some of which could be addressed by the Dutch government, yet the willingness to realize CCS is stronger than ever. The more important question is whether CCS will remain as part of the decarbonization palette in the Netherlands beyond 2035, and whether projects will then be self-reliant in terms of finances, in other words, unsubsidized.

To achieve this, the Dutch government can also opt to create conditions by new subsidy grants. In 2015 it was, for instance, decided to reduce the costs of offshore wind farms by 40 per cent. Coordinated tendering and permits procedures, centralized construction of offshore infrastructure, and connection to the existing onshore electricity infrastructure ultimately resulted in a cost reduction of 70 per cent in only five years. Today, offshore wind farms no longer require subsidies. For CCS, a similar target could be envisioned. This could ensure that CCS projects can take place unsubsidized beyond 2035, without having to make a political decision to phase out CCS, whilst alternatives have not yet matured. This at least allows for emissions reduction trajectories to progress under the uncertainties laid out above. This indicates that the Dutch policy framework, albeit one of the most complete, still requires additional decision making for the short and long term.

CCUS OPPORTUNITIES, GLOBAL CHALLENGES AND DEPLOYMENT ENABLERS

Ashraf Ghazzawi and Ahmad Khowaiter

The past few years have seen unprecedented global momentum addressing the challenge of climate change. Major economies, including the United States, China, the United Kingdom and the European Union have set out their ambitions to reach net zero emissions at various points during the century. Most recently, the Kingdom of Saudi Arabia announced — during the Saudi Green Initiative held in Riyadh — its ambition to achieve net-zero emissions by 2060, by harnessing the principles of the Circular Carbon Economy (CCE) and its four Rs: Reduce, Reuse, Recycle, and Remove. Among many other low carbon solutions, Carbon Capture, Utilization and Storage (CCUS) is a key climate mitigation solution in the CCE framework. Following the Kingdom's announcement, Saudi Aramco, the world's leading energy and chemical company, committed to achieving net-zero Scope 1 and Scope 2 GHG emissions across its wholly-owned operated assets by 2050.[42] To achieve these ambitions, CCUS technologies will play a vital role in managing GHG emissions – both from in-process and combustion applications – at the required scale. Indeed, in its summary for policymakers, the IPCC Special Report concluded that all credible climate mitigation pathways that limit global warming to 1.5°C make use of Carbon Dioxide Removal (CDR) technologies, with Carbon Capture and Storage (CCS) being the key removal technology.[43]

[42] Saudi Aramco press release, Aramco expands climate goals, stating ambition to reach operational net-zero emissions by 2050 | Aramco. (October, 2021)
[43] IPCC Special Report: Global Warming of 1.5 ºC, Summary for Policymakers, https://www.ipcc.ch/sr15/chapter/spm/.

Global Developments in the CCUS market

Today, global CCS capacity stands at 37 million tonnes of CO_2 per year (Mtpa), with 27 plants in operation. In the last decade we saw a stagnation of investment flows into CCUS projects. However, there has been a healthy rebound in the past few years. In the first nine months of 2021, the global CCS project pipeline grew by 45%, from 75 Mtpa at the end of 2020 to 111 Mtpa (this includes projects under operation, construction, advanced development and early development). This amounted to an addition of 71 projects, with most of the projects (36) being in the United States.[44] While this positive momentum is encouraging, CCUS investments remain low compared with other low-carbon technologies. According to Bloomberg New Energy Finance (BNEF), global investments in low-GHG energy sectors amounted to $500 billion in 2020.[45] Of these investments, almost $300 billion were in renewables projects, compared with about $3 billion for CCS, a two-fold order of magnitude lower and significantly below the level needed to meet climate goals. For example, the IEA 2021 World Energy Outlook (WEO) outlines the Announced Pledges Scenario (APS), which models a case where global net-zero pledges are met timely and in full. Under this scenario, global CCUS capacity will need to grow to 350 Mtpa by 2030 to achieve climate ambitions.[46] Given the long lead-times of CCS projects (usually 7-10 years), projects will need to reach the FID stage soon to meet these targets.[44] All in all, it is clear that supporting policies and incentive schemes must develop in a more globally coordinated and timely manner, to ramp up investments and create a business case for projects to move forward and achieve the desired scale.

Carbon dioxide utilization

Captured CO_2 can be used to enhance the production of hydrocarbons or as a feedstock for many industrial processes. In the CO_2-based enhanced oil recovery (EOR), injected CO_2 interacts with the in-situ oil, facilitating its flow and extraction, while retaining a significant part of the CO_2 in the reservoir as permanently stored. Current CO_2-EOR practices aim to optimize oil production; however, innovative approaches seeking to optimize both CO_2 utilization and oil production will enable better outcomes. Synthetic hydrocarbons (e.g., chemicals, e-fuels) can be produced by chemically reacting captured carbon dioxide with low carbon hydrogen, providing a solution for many hard to abate sectors, such as heavy-duty transport, aviation, maritime and heat for industry. Numerous chemicals such as methanol or urea can also be produced through similar processes, enabling carbon circularity. Captured CO_2 can also be utilized for curing concrete materials and reducing water and energy used in the traditional concrete curing process. This CO_2-based technique reduces the concrete curing time, improves its mechanical strength, and reduces its life-cycle emissions. CO_2 can be also combined with waste (municipal waste ashes, steel slags, cement dust, etc.) to produce carbonated rocks (e.g., synthetic aggregates) that replace the naturally mined limestone rocks. This contributes to reducing waste disposal while storing CO_2 and reducing the environmental footprint and cost of aggregate production.

CCUS can also enable the production of hydrogen by capturing CO_2 at hydrogen production facilities. This is an area where Aramco sees a significant role for CCS, in the production of low carbon hydrogen and its energy vectors, such as ammonia. The demand for hydrogen is set to rise as the pace of the energy transition accelerates, and the production of hydrogen from hydrocarbon sources (e.g., natural gas) will be essential to establishing and sustaining this market due to its competitiveness with other production routes. This is a big focus area for Saudi Aramco's clean energy strategy and emission reduction targets. Indeed, our experience in subsurface operations, running large-scale CCS projects, and our integrated and complementary infrastructure that spans the entire energy value chain (upstream production from low-carbon intensity assets, processing, transmission, hydrogen production, and CO_2 capture and storage) provides us with a unique position to develop a large-scale hydrogen business. Recently, Aramco, in collaboration with SABIC and Japan's Institute of Energy Economics, demonstrated the production and shipment of high-grade low-carbon ammonia, from Saudi Arabia to Japan, for use in zero-carbon power generation.

Global challenges to CCS scale up and key enablers

The early deployments of CCUS technology have been linked with R&D or economic drivers such as enhanced oil recovery (EOR), or government incentives in a few countries, such as the U.S., with the 45Q tax-credit mechanism. For example, as part of its R&D activities, Aramco has been operating a large scale CCUS project since 2015, capturing and injecting up to 0.8

[44] Global CCS Institute, Global Status Report (October, 2021)
[45] BNEF, Energy Transition Investment Trends 2021 (January 2021). BNEF defines Low-GHG energy sectors as renewables, electrified heat, electrified transport, energy storage, CCS and hydrogen.
[46] IEA 2021 World Energy Outlook (page 174).

MTPA for EOR. SABIC (an Aramco affiliate) has been capturing up to 0.5 MTPA of CO_2 since 2015 for methanol, urea, and food grade CO_2 production. The challenge remains with addressing a wider scope and scale of CO_2 emissions (especially in hard-to-abate sectors), which will be primarily driven for climate change mitigation purposes. The success of these subsequent projects will be dependent on the feasibility of the ventures and the creative methods of generating cash flows and scale to secure their long-term feasibility. That said, these early opportunities are key to building the scale and know-how, and establishing the business models for increased CCUS deployment. Another challenge is the potential mismatch between major emission-emitting centers and CO_2 storage availability. These challenges can be mitigated by considering each market's unique circumstances, deploying the right fiscal and policy incentives at the right stage in the market's development, and commercializing more innovative CCS business models. Some of the key enablers to address these challenges include:

- **Additional benefits of CCUS**: An important factor that must be considered is comprised of the additional benefits of CCUS deployments. There is global consensus among energy and climate bodies on the need to scale-up CCUS to address the negative impacts of climate change. Stakeholders should seek to capture economy-wide impacts beyond emissions mitigation and pursuit collaborations, which aim at improving societal outcomes across the economy (e.g., GDP, jobs), the environment (e.g., net-zero, air quality, and health) and the energy system (e.g., optimal use of existing infrastructure). That said, these societal benefits are not accessible to private developers through the market, due to many factors, including uncertainty and horizon mismatch. Hence, there is a clear case of a positive externality where the social benefits significantly exceed the private benefits, establishing a compelling case for government intervention. In particular, firm policy drivers must be in place to sufficiently encourage investments with long-term visibility and the growth of international collaboration between governments, academia and the private sector. With steady investment in both and through the creation of financial incentives to commercialize the technology and allow for a competitive market to develop and innovate, competition will subsequently pick up as the primary driver.
- **Collaboration on Infrastructure**: Public investment in infrastructure will be necessary as the capital intensity of construction of CO_2 transport and storage infrastructure remains a key barrier that prevents the linkage of CO_2 emitters and CO_2 storage sites. In addition, some industrial players lack sufficient emission capacity to justify investment in full CCS deployment. For these reasons, the development of CCS hubs could present a key enabler, where multiple industrial players and the government share the cost of CO_2 transport and storage infrastructure, and build collective knowledge in CCS operations. There is a lot of potential for regional collaboration, for example GCC cooperation on CCUS and working together by creating a hub utilizing the regional advantages while creating large-scale infrastructure. However, as this type of cross-industry collaboration is relatively recent and carries many associated risks, governments will have to play a key role in coordinating the development of the necessary CO_2 transport and storage infrastructure to kick-start these models. As seen in Norway's Longship project, government and industry collaboration was catalytic for the development of the project. One component of Longship is the Northern Lights project, which will establish the pipelines, ocean carriers and sequestration infrastructure to support Longship. The first phase of Northern Lights will be completed in 2024, and will support 1.5 Mtpa of permanent CO_2 storage in depleted oil fields in the North Sea, with future increments targeting to provide access to CO_2 storage across Europe.[47]
- **Finance**: CCUS deployment is more feasible when the finance structure increases cash flows and ensures long-term certainty. This can be most readily achieved when the policy structures enable the environment for investment in public and private sector CCUS projects. Financial mechanisms for CCUS include: production tax credits (PTC), investment tax credits (ITC), public investment in infrastructure, and reduced finance costs, such as through government guarantees. These mechanisms affect cash flows in different ways and allow sharing of costs among government, industry and the public. Production tax credits increase revenue for the capturing entity. Investment tax credits, public investment in infrastructure, and reduced finance costs (e.g., reducing the discount rate and relying more on external financing) translate to cost reductions for the capturing entity. Other mechanisms that could incentivize CCUS include: master limited partnerships, tax exempt private activity bonds, accelerated or bonus depreciation schedules, mandates, direct cash grants, or direct payments.

[47] Nothern Lights CCS, About the Longship project - Northern Lights (northernlightsccs.com).

There is no single finance structure that guarantees successful CCUS implementation. The most effective combination of incentives evolves as the deployment schedule progresses.

- **Innovation**: In addition to financial mechanisms, research and development can be effective at reducing costs for all parties. Strong investment in R&D can be very effective at reducing costs to all parties. Specifically, increasing R&D expenditure this decade will be key to reducing the future capture cost, improve process efficiency and develop new ways to utilize CO_2, which will be critical for later deployment stages and scale ramp up, as it will allow for gradual phasing out of fiscal incentives. The U.S. National Petroleum Council (NPC) study on CCUS deployment estimates that investment in research and development could lead to a 10-30% improvement in the cost of large-scale CCUS projects.[48]

Conclusions

Through CCUS, emissions can be sequestered underground or utilized to produce a wide range of high value low carbon products, contributing to mitigating GHG emissions, while generating socio-economic value (GDP, jobs, and new industries) – all essential elements of the circular carbon economy framework contributing to the 4Rs through:

- Reducing the flow of emissions entering the atmosphere by capturing CO_2 at power stations and industries, such as cement, iron and steel, chemicals, and many other hard to decarbonize sectors, where proven low carbon solutions are not available. Capturing CO_2 from hydrogen facilities also provides a means for a low carbon energy source across many sectors, including transport, power and industry.
- Reusing emissions as a work fluid, for food and beverage, greenhouses for agriculture, or for enhancing the production of oil and gas while storing CO_2.
- Recycling emissions in the form of synthetic fuels, chemicals, polymers or concretes.
- Removing emissions stock in the atmosphere through Direct Air Carbon Capture (DACC) or Bioenergy with Carbon Capture and Storage (BECCS) while contributing to global carbon balance or net-zero emissions.

However, for CCUS to deliver on its full potential in a CCE approach, government and the private sector should work together and establish the appropriate policies that enable rapid deployment of the technology. Such policies should include a revenue stream for CCUS project developers to facilitate private investments, and reduce risks by mutualizing CO_2 transport and storage infrastructure. The financial sector should ensure CCUS is part of their climate strategies and is eligible for sustainable finance, and more governments need to include CCUS in their climate strategies as they set more ambitious emission mitigation targets.

The recent investment momentum in CCUS is encouraging, but much more needs to be done to fully realize emissions reduction at scale and contribute to achieving climate goals, while ensuring the principles of economic development and energy access are not compromised. The scale and continuity of capital investments in renewables further demonstrates the effectiveness of policy incentives to commercialize technologies and develop innovative business models. With a similar approach and a more coordinated global effort, CCUS technologies can develop in a similar manner, where all players across the CCUS value chain are incentivised to participate and benefit.

CCUS IN CANADA: POTENTIAL AND PROSPECTS

Nnaziri Ihejirika

With the third-largest oil reserves and the fourth-largest natural gas deposits in the world, Canada has often found itself in the increasingly polarized roles of advocating for deep cuts in global greenhouse gas (GHG) emissions, while continuing to support the extraction of fossil-based energy sources domestically. Although it has one of the lowest-emission electricity grids in the world, continued increase in the global demand for oil and natural gas – Canada's largest source of export revenue – means that its energy reserves are viewed as a mainstay of the economy for years to come. CCUS offers a potential pathway for the sustainment of this economic sector, but potential challenges with finance, infrastructure, regulatory support, and various

[48] National Petroleum Council, Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage, (March 2021)

stakeholders threaten to derail its momentum in Canada.

CCUS is not new to Canadian industry, as it is used by some firms for enhanced oil recovery (EOR) from oilsands *in situ* reservoirs. CCUS for EOR has many critics but has also proved to be a low-risk way to demonstrate that CO_2 can be securely stored underground or in reservoirs with no losses. The 240 km long Alberta Carbon Trunk Line (ACTL), commissioned in 2020, was justified in part on its role in stimulating depleted wells in Central and Southern Alberta, minimizing the financial and environmental liabilities associated with abandonment; while unlocking low-cost oil with near-zero Scope 1 and 2 emissions. Future growth of CCUS in Canada is expected to be spurred by increased deployment of capture technologies in mature industries such as oilsands extraction, refining, fertilizer, and cement manufacturing.

Emissions intensity in Canada's oil and gas sector has decreased by over 30 per cent since 2000, driven by improvements in energy efficiency, yet significant production growth during that period has resulted in sector emissions increasing from 157 $MtCO_2e$ in 2000 to 194 Mt CO_2e in 2019. This has led to an often-contentious environmental and socio-political debate about the sustainability of a sector that appears challenging to decarbonize. These ESG (environmental, social, and governance)-related concerns have also been at the heart of decisions made by banks or investment funds like Norge Bank and HSBC to stop investing in, or lending money to, firms that operate in the oilsands. There has been less focus on GHG emissions from other heavy industries, but the impact is significant nonetheless, with electricity generation and heavy industry contributing 138 $MtCO_2e$, or 18 per cent of all Canadian emissions in 2019. The commercialization of CCUS is attractive to these industries, with few other options for achieving deep decarbonization. This also applies to the Canadian electricity sector. While natural gas is still considered a bridge fuel to enable the energy transition, it is likely to face the scrutiny that coal underwent over the last two decades. Utilities making investment decisions on natural gas-fired plants are looking at CCUS as an option to not only maintain investor and public support in the short term, but also to secure long-term viability and economic value.

While carbon-negative green hydrogen produced by combining hydrolysis with processes like bioenergy with carbon capture and storage (BECCS) or electrolysis offset by direct air carbon capture and storage (DACCS) are the ideal end-state in Canada's journey to net zero by 2050, there is pragmatism in the desire to leverage existing grey hydrogen production in heavy industry and the expertise that comes with it. Combining current hydrogen production with CCUS technologies is expected to reduce upstream oil and gas emissions by as much as 50 per cent, and up to 90 per cent in secondary heavy industry. Given the relatively high ratio of energy extraction, utilities and heavy industry sector emissions in the Canadian total, CCUS has the potential to set Canada well on the way to meeting its Paris climate targets. The resultant blue hydrogen is touted as a low-emission source of energy in Canada that can accelerate the commercialization of fuel cell vehicles, be blended into natural gas for heat and power, and spur increased economic activity in the manufacturing and chemical sectors. It's also worth noting that the use of natural gas in power generation is expected to *grow* until 2040, even under the Canadian government's current plan for meeting the Paris Agreement.

Earlier in 2021, several projects were announced covering the production of hydrogen from decarbonized natural gas and the transportation of CO_2 for sequestration, together with promises of future green hydrogen projects. The most important of these announcements was the alliance of the six largest oilsands-based energy firms to form the Oilsands Pathways to Net Zero Initiative. Together, these firms – Cenovus, CNRL, ConocoPhillips, Imperial, MEG Energy, and Suncor – control over 95 per cent of Canada's oilsands production. While they have previously demonstrated a willingness to collaborate, as seen with the technology-driven Canada's Oilsands Innovation Alliance (COSIA), this marks the first partnership to deliver megaprojects of this size and scale. If all the announced projects are sanctioned, Canada's CO_2 capture capacity would nearly double from 7 $MtCO_2$/year to 13 $MtCO_2$/year by 2028. Leveraging this, pipeline transport capacity for captured carbon will increase five-fold from the current 14.6 $MtCO_2$/year to 74 $MtCO_2$/year by the end of this decade.

CCUS in Canada: challenges to commercialization

Finance There is broad acknowledgement of the role played by CCUS in significantly reducing emissions in industries that are hard to decarbonize, but there has been a hesitancy – particularly from oil and gas firms – to invest heavily in the technology. This is due to the belief that CCUS alone is not profitable, since it doesn't add reserves or increase the netback on a barrel of oil, two key balance sheet metrics for oil and gas firms. Integrated projects like the ACTL which delivers waste CO_2 streams from a fertilizer plant and upgrader/refinery to depleted reservoirs in Central and Southern Alberta for EOR, are an option. However, the likely exclusion of EOR as a designated use of captured CO_2 under the government's investment scheme means that most new projects will be based on sequestration, or carbon utilization. Cost learning that has occurred since the 2015 commissioning of Quest, the first oilsands-based CCUS project, will enable improved project economics, but that alone is not enough. For this reason, firms have been advocating for stronger funding support from the government. In 2021, the Canadian government promised C$319 million over seven years for the development and commercialization of CCUS, and an additional C$5 billion over seven years for decarbonizing heavy industry. The government also announced that it would work with stakeholders to design an investment tax credit to stimulate non-EOR CCUS development activity. In this regard, the credit is likely to differ from the 45Q production credit that has been implemented in the United States for CCUS projects, where a reduced tax credit is provided for CCUS projects used for EOR.

Infrastructure The proposed build of CO_2 pipelines addresses a key infrastructure concern. Heavy industry firms which deploy carbon capture will be able to leverage those egress pathways without the burden of contributing to high upfront capital costs. The deployment of CCUS in Canada has shown that the sequestration of CO_2 is safe and effective, while storage locations appear plentiful. Yet, there is still significant cost involved in ensuring these reservoirs remain safe, especially when EOR is not an option and new injection wells have to be drilled. Finally, the decision around retrofitting existing facilities or building new ones is likely to pose the largest infrastructure challenge. While a retrofit is likely to be less expensive in the short term, building new facilities may allow for the use of the most efficient CCUS technologies and better economics long term. These infrastructure challenges mean that the maximum penetration of CCUS in tackling Scope 1 and 2 emissions from the oil and gas sector is expected to be less than 50 per cent.

Regulatory Support The Canadian government has put a high-level framework in place for the broad adoption of CCUS. The carbon price hike from C$50/t$CO_2$ in 2022 to C$170/t$CO_2$ in 2030, the Clean Fuel standard, and the hydrogen strategy have sent a clear message about where industry's attention should be directed. However, there are concerns that these policies are aspirational, and are not backed by enabling support or practical targets. The lack of regulatory support for EOR-based carbon capture projects increases the risk that potential investment will be diverted to other jurisdictions with friendlier policies, like the United States. The various Federal and provincial political parties in Canada also have different approaches to carbon pricing and energy regulation. There is a risk that firms invest significant amounts in CCUS, only for the goalposts to shift or for the government to focus its support on DACCS or BECCS instead. To counter this, firms are seeking guarantees in the form of credits and grants from the government before proceeding with investment decisions. In addition, there is uncertainty about investing heavily in hydrogen production when its status as a solution for long-distance road transportation and peak power shaving is still uncertain. This could act as a barrier to entry for small and medium-sized firms, even if they could afford to capture carbon. A carbon price on its own does not guarantee that such firms implement CCUS, without the guarantee that the resultant hydrogen and CO_2 can be taken off their hands or a viable market built for both.

Indigenous, environmental and social acceptance Some Indigenous communities are exploring nature-based carbon capture solutions, relying on Canada's vast forests which hold some of the largest carbon sinks in the world. Collaborating in these developments could provide a carbon offset mechanism that is preferentially purchased by heavy industry, while contributing towards a restoration of the natural environment. Whether in exploring these opportunities, or the already announced CCUS and blue hydrogen projects, the relationships that have been built with Indigenous groups will be critical to project sanction.

Concerns have been expressed by citizen and environmental groups that CCUS development erodes financial support intended for renewable energy, especially with the apparent focus on blue hydrogen over green hydrogen in the short term. Some researchers have also suggested the risk of CO_2 leakage, higher than actual fugitive emissions rates from increased natural gas production and lower-than-advertised carbon capture rates, make the technology environmentally unfriendly. Canadian CCUS projects have demonstrated that these challenges can be met with the right technological and financial input. However, since Scope 3 emissions dominate the transport sector, there are those who insist that the only meaningful emissions reduction in this sector will come from significant declines in the use of fossil fuels.

Energy efficiency has not significantly altered overall emissions in the resource extraction sector, and there are worries that the success of CCUS could lead to an increase in the consumption of oil and gas. The recently announced plan to eliminate the sale of new fossil fuel-powered vehicles in Canada after 2035 may allay some of those concerns, but this resistance is one that is likely to continue until there is a meaningful reduction in Canadian GHG emissions.

Industrial decarbonization using CCUS: a strategic opportunity

Despite these challenges, there is significant momentum in the Canadian CCUS space. The experience that Canadian oil and gas firms gained from using technology to unlock unconventional and costly resources in a harsh environment is driving a high degree of confidence in the widespread operational deployment of CCUS. The performance of Quest and ACTL, the two heavy industry and/or oilsands-based projects, demonstrates that operational execution is unlikely to be an issue if the major CCUS projects currently under development in Canada are sanctioned.

For firms, CCUS adoption in heavy industry will enable two energy transition pathways – one focused on emissions reduction and the other focused on profitability. To reduce emissions, firms will utilize carbon capture to reduce total Scope 1 and 2 emissions by up to 50 per cent, with further reductions from carbon credits associated with variable renewable energy projects. Scope 3 emissions for oil and gas firms are likely to be reduced by introducing a higher share of biofuels but also through reduced combustible fuel sales, as the government's ban on new gasoline and diesel powered vehicles comes into effect in the middle of the next decade. To sustain and grow current profitability levels, firms will need to identify new business opportunities and markets. This is increasingly challenging in an environment where Canadian firms, already unsure of the government's commitment level, are struggling to secure international funding and will need to get creative with project finance. In that sense, it's worth pointing out that CO_2 storage has economic value, especially when tied to the regulatory framework the project operates under. Shell Canada has reported that the cost of carbon avoided at the Quest project is higher than the cost of capturing and storing the carbon.

With the planned carbon price hike, capturing and storing carbon could become an unlikely source of profitability for heavy emitters. Lower fuel sales can be offset by an increase in electricity sales, the creation of CO_2-based products, and the development of non-combustible uses for bitumen and crude oil. The biggest opportunity likely lies in the development of a hydrogen-based economy in Canada, but it also carries a lot of risk and uncertainty. Despite the hype surrounding hydrogen, it is a long way from displacing natural gas as a primary fuel. Its lower energy content means that it can only be blended into natural gas in small amounts, while the high pressures it operates at leads to its use in residential applications being limited. That said, there is a strong focus on developing and unlocking new hydrogen markets, particularly for power production and long-distance freight transportation.

Conclusion

Canada is considered a world leader in CCUS, with three world-class projects built since 2014, and several more in various stages of development. These projects had significant financial backing from the provincial and federal governments – evidence of the importance attached to demonstrating and deploying CCUS in Canada. However, there are few clearly defined policies to support the commercial scaling of carbon capture. This has led to concerns that investment will suffer on two fronts – insufficient funding for proposed CCUS-related projects and continued divestment from the resource extraction sector. Highlighting the value of industrial CCUS as an enabler of DACCS and BECCS will be important in securing the support of environmental groups and other stakeholders. Carbon capture may not be a cure-all for the global climate challenge, but it has a major role to play in decarbonizing heavy industry. In Canada, where industrial emissions make up over a third of total emissions, it can play an even bigger role than in other countries. A stable regulatory climate will provide clarity to investors, while collaborations between firms will support alignment and cost-learning on the various CCUS technologies. Early signs on both fronts are positive, but certainty in the form of legislation and sanctioned projects is required if carbon capture is to achieve its promise of becoming a core part of Canada's energy transition.

CHINA'S POLICIES AND ACTIONS ON CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

Philip Andrews-Speed

Coal has long been the principal source of primary energy in China on account of the abundant domestic resource. Until the 1990s, coal provided around 75 per cent of the country's primary energy needs. Since 1990, this share has steadily declined, to 56 per cent in 2020. The nation accounts for about 50 per cent of the world production of coal and 54 per cent of its consumption. Oil remains a significant source of energy and its share of the energy mix rose from 17 per cent to 19.6 per cent between 2020 and 2020. The use of natural gas continues to rise rapidly. It now accounts for about 8 per cent of the primary energy mix, up from 4 per cent in 2010. In all, fossil fuels account for about 84 per cent of China's primary energy supply, though this share is declining slowly as the availability of renewable and nuclear power grows. As a result, China has the highest level of carbon dioxide (CO_2) emissions from energy in the world at about 9.8 billion tonnes, accounting for 31 per cent of the total. This is only slightly less than those of the 38 member countries of the Organisation for Economic Cooperation and

Development combined.[49]

The greatest need for CCUS is in the power industry, in which coal provides 63 per cent of the energy. Other high-emission industries include steel, cement, and chemicals. Despite this great need, the country currently (November 2021) hosts only just over 2.0 Gt of operating CCUS capacity spread across at least 16 projects (see Table 1). There are more than 11 additional projects under development with an aggregate annual capacity of about 10 million tonnes (Table 2). This compares with the 13 large-scale projects (greater or equal to 1.0 million tonnes) that were in already operation in other countries in 2020, in the USA, Canada, Brazil Australia, and Norway.[50] The slow pace of development of CCUS in China results from the failure of the government to put in place a framework and incentives for investment. This sits in sharp contrast to the measures deployed to promote renewable energy, electric cars, nuclear fission power, and nuclear fusion.

Policy development

The government appears to have given no systematic thought to the development of CCUS technologies until 2005. A project to assess the viability of using CO_2 to enhance the production of coalbed methane had just shown that coal seams could store CO_2 effectively. At that time, annual consumption of coal had been rising at an annual rate of about 17 per cent and the country was fast becoming the world's largest emitter of CO_2 from energy.[51]

The *National Programme for Medium and Long-Term Science and Technology Development (2006–2020)* highlighted the need to develop low-carbon technologies but failed to mention CCUS. Subsequent documents relating to combatting climate change that were issued during the Eleventh Five-Year Plan Period (2006–2010) addressed the need to develop CCUS technologies.[52]

Only in the following Five-Year Plan period (2011–2015) was CCUS explicitly identified as being a critical technology in various plans, including those for scientific research and development. Over this period, the amount of scientific research into CCUS increased markedly, as shown by a dramatic increase in the number of scientific publications on the topic from Chinese institutions. The number of international collaborations in this field also rose, reflecting the fact that China was some years behind the leaders, notably the United States. At the same time, the banking institutions began to recognize CCUS as being qualified for green credits and green bonds.[53]

In 2011, the Ministry of Science and Technology (MOST) issued a technology roadmap for CCUS spanning the period 2011–2030. This covered technologies for capture, storage, and use, as well the need to develop plans and standards for the long-distance transport of CO_2. Specific aims to be achieved by 2020 included the establishment of projects with annual capacities of one million tonnes for capture, two million tonnes for use (specifically enhanced oil recovery), and one million tonnes for storage. By 2030, supply chains for these technologies were to be fully developed and commercialized, each being allocated specific cost targets.[54]

The MOST followed up in 2013 with a more detailed CCUS plan for the period to 2015. In the same year, the National Development and Reform Commission issued a document promoting CCUS pilot and demonstration projects that included the need to support research, develop economic incentives, establish standards, and build human capacity. Two years later the Ministry for Environmental Protection issued draft guidelines for assessing the environmental risk related to CCUS.[55]

The level of direct support for CCUS rose significantly during the Thirteenth Five-Year Plan period (2016–2020). The technology was mentioned in a number of national and subnational plans relating to energy, technology, and climate change mitigation. An explicit aim was to invest 37.5 billion Yuan in CCUS in order to reduce emissions by 390 million tonnes per year.[56] In 2019, the MOST published a new CCUS Roadmap that envisaged the country having an operating CCUS capacity of 100 million tonnes by 2035 and 300 million tonnes by 2040. But this would abate only about 4 per cent of current thermal coal consumption.[57]

[49] BP (2021), *BP Statistical Review of World Energy 2021*.
[50] Global CCS Institute (2021), *Global Status of CCS 2021,* Melbourne: Global Carbon Capture and Storage Institute.
[51] Jiang et al. (2020), 'China's carbon capture, utilization and storage (CCUS) policy: A critical review', *Renewable and Sustainable Energy Reviews* 119, 109601.
[52] Jiang et al. (2020).
[53] Jiang et al. (2020).
[54] Zhang et al. (2013), 'Technology roadmap study on carbon capture, utilization and storage in China', *Energy Policy* 59, 536–50.
[55] Zhang (2021), 'Regulations for carbon capture, utilization and storage: Comparative analysis of development in Europe, China and the Middle East', *Resources, Conservation & Recycling* 173, 105722.
[56] Jiang et al. (2020).
[57] Wan (2019), 'Carbon capture and storage in China', CRU, 30 July.

Recently, in October 2021, the Central Committee of the Communist Party of China and the State Council issued an *Action Plan for Carbon Dioxide Peaking before 2030*.[58] It mentioned CCUS five times. Whilst the focus was on basic and applied research, development, and deployment, it also highlighted the need for international cooperation. No more specific plans aimed at CCUS for the Fourteenth Five-Year Plan period (2021–2025) had been published as of late 2021.

Technologies and project development

The development and deployment of carbon capture technologies in China has lagged behind the most advanced countries.[59] The principal technologies applied for capturing CO_2 are chemical absorption and physical separation, both pre- and post-combustion. Other technologies such as membrane separation and chemical looping are at early stages of development.[60] Carbon capture has been applied in China to a variety of industrial processes including power generation, natural gas processing, the production of cement and chemicals, and coal liquefaction (Table 1). Only one operational project is linked to a steel plant and that has an annual capacity of only 90,000 tonnes. None of the projects currently under development involve capturing CO_2 from steel production (Table 2).

The principal use of captured CO_2 in China is for enhanced oil recovery (EOR), although a few projects are operating which use the CO_2 for other purposes, such as the production of chemicals and cement and for the food and beverage industry. The application of CO_2 to EOR dates to the 1960s in both the US and China. The China National Petroleum Corporation (CNPC) applied this technique successfully to the Daqing oilfield in the far north-east of the country. From the 1990s onwards, a growing number of other oilfields followed suit as well productivity started to decline. However, the approaches taken by the Chinese suffer from two key deficiencies that limit their effectiveness. First, the permeability of some of the reservoirs is so low that the effect of CO_2 stimulation on productivity is often small. Second, and related to this, is the practice of using CO_2 in a gaseous or liquid phase rather than in a supercritical form.

The first pilot projects to demonstrate the application of EOR to CCUS came onstream in different oilfields between 2006 and 2008.[61] There are now at least nine such projects, of which three are in commercial operation (Table 1). At least four additional projects with a total annual capacity of 2.3 million tonnes are under development and due to be commissioned during the 2020s (Table 2).

China possesses large sedimentary basins with saline aquifers that can be used for the storage of CO_2, both onshore and offshore. As of late 2021, only two projects are dedicated purely to the long-term storage of CO_2 and both are small in scale (Table 1). However, three large-scale projects are due to be commissioned during the 2020s with a planned aggregate annual capacity of 5.0 million tonnes (Table 2).

Most transport of CO_2 is by truck and, in a small number of cases, by barge. Only in the Jilin oilfield is a pipeline used, and this is only 53 km long. The CO_2 captured at Sinopec's Qilu petrochemical plant in Shandong Province will be transported to the Shengli oilfield by pipeline when it is commissioned in 2021.[62]

The policy and regulatory gaps

Whilst the central and local governments have issued several plans and notices that mention CCUS or address the topic in more or detail, a coherent set of policies and regulations has still not been formulated as of November 2021. Further, financial support available has been directed mainly at R&D and demonstration projects, not at commercialization.[63] The construction of large-scale CCUS infrastructure requires a high level of capital expenditure. This is unlikely to happen to any extent without financial support or incentives, even with the major energy companies being state-owned. The price of carbon in the national emissions trading scheme was around 42 RMB/tonne (US$6.50/tonne) in November 2021, far below what might be required to incentivize the companies. Various mechanisms are open to the government. It could provide financial support in the form of

[58] National Development and Reform Commission, *Action Plan for Carbon Dioxide Peaking before 2030*, 27 October 2021.
[59] Xu et al. (2021), 'Carbon capture and storage as a strategic reserve against China's CO_2 emissions', *Environmental Development* 37, 100608.
[60] International Energy Agency (2021), *An Energy Sector Roadmap to Carbon Neutrality in China*, Paris; IEA.
[61] Hill et al. (2020), 'CO_2-EOR in China: A comparative review', *International Journal of Greenhouse Gas Control* 103, 103173.
[62] International Energy Agency (2021).
[63] Wei et al. (2021), 'A strategic framework for commercialization of carbon capture, geological utilization, and storage technology in China', *International Journal of Greenhouse Gas Control* 110, 103420.

low-interest loans, tax allowances, or other subsidies. Alternatively, power generators operating CCUS facilities could be offered priority despatch, additional operating hours, or an enhanced tariff.[64] The absence of incentives, explains why most CCUS projects are targeted at EOR, which generates a stream of revenues for companies.[65]

Table 1 Operating CCUS projects in China at late 2021[66]

Project	Year of Operation	**Capture/use/storage**	Type	Capture capacity (Mt/year)	Status	Industry
Sinopec Zhongyuan Carbon Capture Utilization and Storage Pilot Project	2006	EOR	Commercial	0.12	Operational	Chemical Production
Huaneng Gaobeidian Power Plant Carbon Capture Pilot Project	2008	Food	Pilot	0.003	Completed	Power Generation
Jilin Oil Field EOR Demonstration Project	2008	EOR	Demonstration	0.10–0.35	Operational	Natural Gas Processing
Sinopec Shengli Oilfield Carbon Capture Utilization and Storage Pilot Project	2008	EOR	Pilot	0.04	Operational	Natural Gas Processing
Shanghai Shidongkou 2nd Power Plant Carbon Capture Demonstration Project	2009	Beverage	Demonstration	0.10–0.12	Operational	Power Generation
Chongqing Hechuan Shuanghuai Power Plant CO_2 Capture Industrial Demonstration Project	2010	Chemicals	Demonstration	0.10	Operational	Power Generation
Sinopec Shengli Oilfield Carbon Capture Utilization and Storage Pilot Project (2)	2010	EOR	Pilot	0.03–0.04	Operational	Power Generation
Shenhua Group Ordos Carbon Capture and Storage (CCS) Demonstration Project	2011	Storage	Demonstration	0.1	Completed	Coal-to-liquids
ITRI Calcium Looping Pilot	2013	Capture	Pilot	1 tonne/hour	Operational	Cement Production
Daqing Oil Field EOR Demonstration Project	2014	EOR	Demonstration	0.20	Operational	Chemical Production
Karamay Dunhua Oil Technology CCUS **EOR** Project	2015	EOR	Commercial	0.10	Operational	Chemical Production
PetroChina Changqing Oil Field EOR CCUS	2017	EOR	Demonstration	0.05–0.10	Operational	Coal-to-liquids
Beijing Shuangang LanzaTech New Energy Technology	2018	Ethanol	Commercial	0.09	Operational	Steel Production
CNPC Jilin Oil Field CO_2-**EOR** (2)	2018	EOR	Commercial	0.60	Operational	Natural Gas Processing
Haifeng Carbon Capture Test Platform	2018	Capture		0.03	Operational	Power Generation
Guohua Jinjie CCS Full Chain Demonstration	2021	Storage		0.15	Operational	Power Generation

[64] Jiang et al. (2020); Wei et al. (2021).
[65] Zhang (2021).
[66] Jiang et al. (2020).

Just as important is the current absence of a law or overarching regulatory framework for CCUS. Such a framework is needed to provide predictability for investors and confidence to the general public. One of the most important issues is the liability of operators for environmental damage resulting from leaks of CO_2, including the prerequisites for transfer of the storage site to the state after an agreed period.[67] China lacks a standard set of procedures for permitting and supervision of CCUS projects. Project operators must apply to several agencies for approval. Those procedures that are in place are too general, are directed solely at onshore CCUS, are focused principally on storage, and are not adapted to unpredictable circumstances.[68] Similarly, there is a lack of standards for technology and for environmental management.[69]

Despite the slow development of a domestic legal framework, China is a contracting party to the London Convention and the London Protocol, which regulate the offshore disposal and dumping of waste and other materials from the land. Two subsequent amendments in 2006 and 2009 provided frameworks for the storage of CO_2 offshore and for its international transport respectively. Only the first of these two has entered into force.[70] However, a meeting of the contracting parties in 2019 permitted the provisional application of the second of these amendments.

Table 2 CCUS projects under construction 2021[71]

Project	Year of Operation	Capture/use/storage	Type	Capture capacity (Mt/year)	Status	Industry
Sinopec Qilu Petrochemical CCS	20221	EOR		1.0	In construction	Chemical Production
Yanchang Integrated CCUS Demonstration	2020–2021	EOR		0.41	In construction	Chemical Production
Chinese-European Emission Reducing Solutions (CHEERS)	2022	Capture	Pilot and demonstration	-	Advanced development	Oil refining
Australia-China Post Combustion Feasibility Study Project	-	Capture	Pilot and demonstration	1.00	Advanced development	Power generation
Guodian Taizhou Power Station Carbon Capture	2020s	EOR		0.3	In construction	Power generation
China Resources Power (Haifeng) Integrated CCS Demonstration	2020s	Storage		1.00	Early Development	Power Generation
Huaneng GreenGen IGCC Large-scale System (Phase 3)	2020s	Storage		2.00	Early Development	Power Generation
Huazhong University of Science and Technology Oxy-fuel project	2020s	Capture	Pilot and demonstration	0.10	In construction	Power generation
Shanxi International Energy group CCUS	2020s	Not defined	Large-scale CCS	2.00	Early development	Power generation
Shenhua Ningxia Coal-to-liquids Project	2020s	Storage	Large-scale	2.00	Early Development	Coal-to-liquids
Sinopec Eastern China CCS	2020s	EOR	Large-scale	0.50	Early Development	Fertilizer Production
Sinopec Shengli Power Plant CCS (3)	2020s	EOR	Large-scale	1.00	Advanced Development	Power Generation

Aside from these critical financial, legal, and regulatory matters, a number of other issues need to be addressed if the deployment of CCUS is to accelerate in China. These include establishing a knowledge-sharing platform along the full supply chain, capacity building to extend technical expertise beyond a small number of state-owned enterprises, and enhancing public understanding.[72]

[67] Zhang (2021).
[68] Jiang et al. (2020); Zhang (2021).
[69] Zhang (2021).
[70] International Maritime Organization, *Status of IMO Treaties*.
[71] Global CCS Institute (2020); Jiang et al. (2020); Xu et al. (2021); Global CCS Institute (2021).
[72] Wei et al. (2021).

Outlook for CCUS in China

As of November 2021, China has published no detailed plan for CCUS, no targets, no commercial incentives, no law, and no specific regulations and procedures. Thus, it is not possible, at present, to project the rate of growth of CCUS in the country, nor the manner in which the technologies will be deployed. Nevertheless, given the likelihood that coal will play a significant role in the nation's energy mix for many years to come, it is to be hoped that the government will address these deficiencies soon, due to its stated commitment to reach net-zero greenhouse gas emissions by 2060. However, there is, as yet, no evidence that CCUS is high on the policy agenda.

Published projections of China's future CCUS capacity span a large range. In a 2021 report, the Chinese Academy of Environmental Planning forecast an annual need for 0.6–1.45 Gt of capacity by 2050 and 1.0–1.83 Gt by 2060.[73] The International Energy Agency envisaged an annual capacity of 2.6 Gt by 2060.[74] This range of possibilities is also captured by another study in a 'necessary' and 'ideal' pathway.[75] In contrast, Tsinghua University's 1.5°C scenario for achieving net zero greenhouse gas emissions by 2060 included only 0.88 Gt/year of CCUS in 2050 and, instead, was heavily reliant on non-fossil fuels.[76]

THE ROLE OF CCS IN OIL AND GAS EXPORTERS' TRANSITION POLICIES[77]

Bassam Fattouh, Wolfgang Heidug and Paul Zakkour

Carbon capture and storage (CCS) involves the trapping of CO_2 underground to avoid its release into the atmosphere. Because of the scale with which it could be applied, CCS is identified as a critical technology to achieve global climate goals. Also, CCS could play a central role in oil and gas exporters' low-emissions development strategies. The deployment of CCS could provide them with an opportunity to continue to monetize their reserves while meeting climate goals and retain the competitiveness of their oil and gas sectors and energy-intensive industries in a net-zero emissions world. CCS is a climate mitigation action which caters to the assets (in terms of geological storage capacities and existing infrastructure) and the technical skills (namely expertise in subsurface technology) of oil and gas producers.

Given that CCS is intrinsically linked to the future of oil and gas and the key role these sectors play in producers' economies and enhancing the welfare of their people, oil and gas exporters have an incentive to take a leading role in scaling up CCS and geological storage and developing successful regulatory and business models to enable this technology. While such a strategy could result in lower returns when compared to the current one of exporting unabated oil and gas given the costs associated with CCS, it may prove essential to maintain the competitiveness of the oil and gas sector in a world transitioning to net-zero emissions.

But this strategy is not without risks. A low-emissions strategy centred around CCS alongside changes in the trade system associated with carbon pricing could have macroeconomic consequences beyond project economics. While CCS is a technology that oil and gas exporters could develop, the cost of adjustment could be too high, causing a massive reduction in these countries' incomes. Therefore, to enable investments in CCS and minimize the adverse impact on their economies and public finances, oil and gas exporters should also take a leading role in developing burden sharing mechanisms that generate new sources of revenues for their CCS projects and/or allow for the costs to be shared both across the supply chain and between fossil fuel exporters and importers. Since the benefit of reduced emissions and of CO_2 storage accrues to all the stakeholders along the oil and gas supply chain, it is reasonable that the cost for large-scale CCS deployment should be shared rather than be focused on one part of the supply chain, as this could result in sub-optimal deployment of the technology.

[73] Cai et al. (2021), China Carbon Dioxide Capture, Utilization and Storage (CCUS) Annual Report 2021 (in Chinese).
[74] International Energy Agency (2021).
[75] Oil and Gas Climate Initiative (2021), *CCUS in China: The Value and Opportunities for Deployment*.
[76] Tsinghua University (2020), *Launch of the Outcome of the Research on China's Long-term Low-carbon development Strategy and Pathway*.
[77] This is based on Bassam Fattouh, Wolf Heidug, and Paul Zakkour (2021), 'Carbon Capture and Storage: The perspective of oil and gas producing countries', OIES Energy Insight 101, Oxford: Oxford Institute for Energy Studies.

The challenge of financing CCS

Several characteristics make financing CCS projects challenging for governments and the private sector alike:

- Deployment of CCS is exclusively driven by climate change mitigation goals. Unlike the case for renewable electricity generation, there are no revenues associated with CCS (except for enhanced oil recovery activities) that can compensate for the high upfront and operation costs. Given the squeeze on governments' budgets in most oil and gas exporting countries, especially as they look to diversify their economies into new non-energy sectors, diverting public funding towards large-scale CCS projects could have a high opportunity cost.
- There is currently no business model available that could secure large-scale financing of CCS by the private sector. Without governments putting in place a supportive regulatory framework and incentives, the private sector will find it difficult to justify large-scale investment in CCS given the cost and risks of the technology. A commercial arrangement could be built by disaggregating the capture, transport, and storage components of the CCS technology chain, allowing different market actors with different strength and risk appetites to collaborate on CCS. In this arrangement it will be necessary to manage the interdependency risk, and governments will need to accept the long-term liability for CO_2 retention in the subsurface, although the probability of leakage of CO_2 from well-selected and managed storage is very low.

The limits of carbon pricing

Carbon pricing, in other words putting a price on the CO_2 emitted into the atmosphere, is the main market-based instrument for reducing CO_2 emissions in the policy toolbox. It is an effective instrument, in the sense that it induces emission reduction at the lowest macroeconomic cost, while also raising revenues to support fiscal reform and climate reduction goals. Carbon pricing could be implemented either through a tax on carbon emissions or via an emission trading scheme (ETS), and both options are presently in use. Because of their attractive features, price-based policy instruments have played a key role in international climate treaties.

However, the economic signals these instruments provide are not sufficient to incentivize the type of large-scale investment needed for deploying CCS at scale. A point in case is that the European ETS has so far not been able to offer a sufficiently stable incentive to deliver any CCS project, even though CCS was introduced into the system around 2010. Since CCS is a pre-commercial technology, investors will find it hard to accept the financial and technical risks associated with investment in these types of technology without a sustained and stable flow of revenues. Public policies that aim at de-risking investment are required to promote the adoption and deployment of CCS at scale. These policies need to provide technology-specific support and not rely on technology-neutral carbon pricing to trigger investment in CCS. As far as policy design is concerned, the situation is rather similar to that faced by low-carbon electricity generation. Feed-in tariffs and renewable portfolio standards have been among the instruments policy makers instituted to specifically increase the share of renewable energy in electricity markets, even in countries (such as Germany and the UK) with operational emissions trading systems covering electricity generation.

Innovative mechanisms

At a time when many countries are aspiring to achieve carbon neutral economies over the coming decades, designing policies to support CCS is key. Terrestrial sinks (involving afforestation and reforestation) and geological sinks could provide capacity to achieve carbon neutrality. This in turn requires effective incentives for the permanent geological storage of carbon to complement policies that are used for enhancing terrestrial sinks.

There have been some proposals to enhance this objective. For instance, the Low Carbon Technology Partnerships initiative (LCTPi) proposes the creation of a Zero Emission Credit (ZEC) awarded for each tonne of CO_2 stored in the geosphere by a storage operator.[78] ZECs would be purchased by a Zero Emission Credit Development Fund (ZDF) formed by like-minded investors to drive early demand and to ensure that price signals are generated in the early stages of the mechanism. In the long term, as the market matures, ZECs would transition to an emitter obligation scheme – in other words, ZECs could be traded or surrendered against governments' obligations or commitments to reduce emissions.

An alternative proposal, which only at first glance looks similar to the ZEC approach, has been put forward by Zakkour and

[78] World Business Council for Sustainable Development (2015), 'Innovative Solution to Accelerate CCS', November.

Heidug[79] (also discussed in this issue by Zakkour and Heidug in more detail). There the policy focus is on the storer of CO_2 and not the emitter as is the case for the ZEC scheme. For each tonne of CO_2 that is submitted to permanent storage the storer is awarded a Carbon Storage Unit (CSU). A CSU provides a monitored, verified, transferable record of the addition of a tonne CO_2 to a carbon sink. Zakkour and Heidug propose the creation of a CCS club of countries with interest in CCS to pool resources to establish a fund for purchasing CSUs. It is important that CSUs only quantify the amount of CO_2 stored, not an emission reduction, and hence cannot be counted towards emission reduction targets. Thus, CSUs provide an additional layer of financing for CCS but would not undermine the environmental integrity of emission reduction-based policies by double-counting. Article 6 of the Paris Agreement provides flexibility, and its decentralized approach offers the possibility of establishing a dedicated international funding instrument for CCS that is based on the CSU approach. In the parlance of the Paris Agreement, CSUs could be generated as part of a country's 'Nationally Determined Contribution' (NDC) and they could be traded as Internationally transferred mitigation outcomes (ITMOs).

Another major limitation of existing carbon pricing policies is their tendency to focus on the emissions at the consumers' end without incentivizing supply-side policy to address the climate change challenge. This is sub-optimal since the subsurface competencies, skills, and assets required to enable CCS are all in the hands of oil and gas producers and could be used effectively for climate action. Unfortunately, current supply-side policy is not yet able to fulfil this purpose. The toolbox of supply-side instruments is so far rather limited, and some instruments do not recognize the political economy realities. This toolbox includes instruments such as leaving fossil fuel in the ground, and various forms of carbon storage obligations. Such supply-side policy instruments have been under-researched so far, with proposals tending to focus on the environmental effectiveness of an instrument but disregarding the important issues of economic efficiency and economic cost, as well as the need for a just and inclusive energy transition. Advocates of some supply-side approaches remain dismissive of CCS.

Burden sharing mechanisms and cooperative policies

Shifting the burden to producers alone will disincentivize them from pursuing large-scale CCS projects. Therefore, it is important to focus on mechanisms that allow these costs to be shared with importers/users. For instance, part of the CSUs generated could be sold to end consumers/importers using these fuels. This could be done through bilateral agreements or clubs. Country A exporting a certain volume of oil and gas to country B can generate enough CSUs to cover the volumes exported and sell all or part of these CSUs alongside the physical cargoes of oil and gas. This allows the cost to be shared between the two parties. Alternatively, a group of countries could agree to establish a fund to bid for CSUs which could be used to offset emissions associated with their fossil fuel imports. This could be implemented under the umbrella of the type of novel cooperative mechanisms envisaged by the Paris Agreement.

Recent work by Peszko et al.,[80] which uses macroeconomic simulations, explores some mutually beneficial policy options for cooperation between oil and gas exporters and importers on climate issues. This is achieved through a variety of scenarios that are embedded in terms of supply and demand, carbon tax, and trade policies. While the scenarios do not explicitly consider CCS, they provide a perspective for international cooperation that is relevant for CCS deployment. Based on the scenarios analysed, Peszko et al. argue for the establishment of a carbon wellhead tax agreement whereby oil that is taxed on its carbon content in an oil exporting country is exempt from CO_2 taxation in the importing countries. Details of the sharing of tax revenue would need to be negotiated bilaterally or internationally. This arrangement allows exporters to retain a share of the tax revenue that otherwise would be collected by the importer. A similar logic reciprocity could be applied to cooperation on CCS between exporters and importers, so that in exchange for decarbonizing oil 'upstream' through CCS, the 'decarbonized' oil would be exempt from climate regulations in oil-consuming countries. The arrangement could be implemented by allowing CSUs generated by the oil exporter to qualify as offsets under local policies (such as low-carbon fuel standards) applied in several oil importing countries.

Tax and trade policies

In a world where some countries/regions are considering applying carbon border adjustment measures (CBAM), supply-side

[79] Zakkour, P.D. and W. Heidug (2019), *A Mechanism for CCS in the Post-Paris Era: Piloting Results-Based Finance and Supply Side Policy Under Article 6*, King Abdullah Petroleum Studies and Research Center (KAPSARC) Discussion Paper, April 2019.
[80] Peszko, Grzegorz; van der Mensbrugghe, Dominique; Golub, Alexander (2020), 'Diversification and Cooperation Strategies in a Decarbonizing World', Policy Research Working Paper; No. 9315. World Bank, Washington, DC. © World Bank.

policies will increasingly become more important. The CBAM will initially apply to imports of cement, iron and steel, aluminium, fertilizers, and electricity, key sectors which oil and gas exporting countries are diversifying into and in which they have established competitive advantage. While oil, oil products, and gas imports have been excluded for now, the EU's direction of travel is clear, and it is seemingly a matter of time before these sectors are included under CBAM.

Applying carbon taxes to imports from oil and gas exporting countries has the effect of extracting part of the rents from these countries that could be used to diversify their economies and/or be invested in technologies that reduce CO_2 emissions. An extreme variant of CBAM is the application of what is referred to as Nordhaus taxes, where countries apply carbon taxes on imports from countries that are non-cooperative on climate change action, irrespective of the carbon content of their exports. This gives importing countries some leverage and could be used to induce a change in behaviour in countries not cooperating on climate change action. However, this will reduce the income of oil and gas producing countries, placing pressure on funds available for economic diversification. Such a tax will also be highly discriminatory, especially given that it is applied to exporting countries irrespective of their level of development and thus will be resisted and could be subject to legal challenges under the WTO. It also undermines key principles such as just and inclusive transition, the common but differentiated responsibility, and the current multilateral framework based on cooperation.

Under the different variants of CBAM, oil and gas producers may have the incentive themselves to introduce carbon pricing to counteract the carbon tax. Under certain conditions, such a tax enables producers to reduce the revenues leaking to importing countries imposing a carbon tax, and thus retain part of the revenues. For instance, an oil and gas exporter can introduce carbon taxes or new regulations that require a certain fraction of embodied carbon/CO_2 to be captured and stored in carbon sinks. This would result in the creation of CSUs that could be surrendered against oil and gas countries' exports to importing countries or sold to countries introducing CBAM. Cooperative schemes based on revenue sharing require the harmonization of regulations and taxes, and agreement to be reached on addressing the distribution issue. They also require putting in place a robust system of measurement, reporting, and verification. The Paris Agreement offers a flexible framework for such agreements.

Another advantage of introducing carbon pricing is that it allows oil and gas exporting countries to identify the most cost-efficient way to capture and store CO_2 and focus on the low-hanging sources of CO_2 emissions first, minimizing the revenue leakage to importers. It can also allow some time to leverage the high degree of integration in their energy sector. For instance, emissions from energy-intensive industries such as steel and aluminium could be captured and stored and/or used in EOR, and in the process generating CSUs which could be offset against the exports of steel and aluminium products. Given that the CBAM will not be applied equally across all products and may be applied in stages according to the export product (for instance, products such as aluminium and steel could be subject to CBAM earlier than exports of crude oil and natural gas), this gives oil and gas exporters more flexibility.

CCS from the perspective of oil and gas exporters

CCS has mostly been approached from the perspective of project developers working in, for example, an international oil or gas company, putting in place frameworks that spread risks and costs, and enabling the deployment of CCS in specific geographical contexts. For oil and gas producing countries, the perspective is much wider and technology-based energy modelling has only limited relevance for the deployment of CCS in fossil-dependent economies. In oil and gas exporting countries, CCS relates to the future of oil and gas and the key role these sectors play in shaping their economies and the welfare of their people. It relates to maintaining and establishing key sources of competitive advantage in key sectors.

This implies that oil and gas exporters must take a leading role in scaling up CCS and geological storage. Also, to enable investments in CCS and minimize the adverse impact on their economies and public finances, oil and gas exporters should take a leading role in developing burden sharing mechanisms that generate new sources of revenues for CCS projects and/or allow for the costs to be shared both across the supply chain and between fossil fuel exporters and importers. Herein lies the importance of developing frameworks and mechanisms that give value to permanently storing CO_2 away in enhanced sinks located in oil and gas exporting countries, and to integrate these into climate finance. This requires the introduction of innovative mechanisms and harmonization of policies, and strong cooperation either through multilateral or bilateral agreements or clubs of like-minded countries. Such cooperative frameworks are key to deploying large-scale CCS, to enabling oil and gas exporters in progressing on their path towards low-emissions strategies, and to ensuring a cost effective, inclusive, and just transition.

TECH-BASED CARBON REMOVAL CREDITS: WHAT'S THE FUSS ALL ABOUT?

Hasan Muslemani

It is not enough to just reduce emissions: we need to actively remove carbon from the atmosphere. This is the conclusion of the UK's top climate advisers and the Climate Change Committee who forecast that as much as one sixth of carbon abatement by 2050 needs to come from carbon removals. The UN's Intergovernmental Panel on Climate Change (IPCC) also agrees, with their recent report stating that, by 2050, the US alone may need to remove the equivalent of one third of its current annual emissions every year.[81]

Some of the long-established carbon removal solutions available are nature-based, such as removing carbon through forestation. However, the planting of trees will not be enough on its own. First, trees – in time – die, meaning that they would not permanently sequester carbon from the atmosphere. Second, some trees die earlier than expected, especially in a changing climate. This was illuminated during the California wildfires this year, where thousands of Microsoft's carbon offsets were burnt to the ground. Third, trees need lots of land. For perspective, removing a million tonnes of carbon dioxide through forestation requires around 500–2150 times as much land as that needed by a single Carbon Engineering direct air capture plant.[82]

In short, we need engineered greenhouse gas removals to remove the millions of tonnes of carbon from the atmosphere which are required each year.

What is carbon removal?

Carbon dioxide removal (CDR) is the act of physically removing CO_2 from the atmosphere using natural processes, engineered technologies, or a hybrid of both. Recently, CDR solutions have become a vital part in our fight against the climate crisis, and action to support their deployment is now considered all but necessary.

Technically, we have been engaging in carbon removal, both directly and indirectly, for as long as we've been around. From planting trees to purposefully switching between agricultural practices that enhance the carbon content stored in soil, the concept of carbon capture and removal and how its different types compare to one another – and how carbon removals stack up against carbon avoidance techniques – have become a subject of heated debate.

In comparison to carbon avoidance, carbon removal enjoys an advantage as it exhibits higher additionality, more tangible effects, and direct and immediate impact on our climate. To top it off, removals can be easily measured in absolute terms, as opposed to carbon avoidance which relies on a multitude of assumptions regarding existing and future scenarios.

Here, we investigate the important factors that differentiate various types of carbon removals.

The choice between natural and man-made

As noted, carbon removals can come in all sorts and forms. CDR techniques have been widely categorized into either nature-based solutions (NbS) such as forestation and soil carbon sequestration, tech-based solutions such as direct air capture and storing CO_2 in building materials, or a hybrid of both, such as enhanced weathering or producing energy from biomass where the production facilities are retrofitted with carbon capture and storage technology (BECCS).

As there is no one silver bullet to meeting the Paris Agreement climate targets, a portfolio of these different solutions will be needed. This is because different solutions bring about varied advantages in terms of cost, potential for scalability, existing policy support, ease of replicability in other regions, permanence or durability of carbon removal, and transparency of role in climate mitigation – the latter of which may significantly influence the public acceptance of those solutions.

For these reasons, not all carbon removal credits generated using these solutions are made equal, which partly explains the myriad of credit prices existing in the market today. What's more, the uncertainty and nascency of the carbon removal credits market is expected to see its landscape change drastically over the next few years.

This article sheds light on key issues pertaining to the most common forms of carbon removal solutions, with focus on tech-

[81] IPCC (2021), 'Climate Change 2021 – The Physical Science Basis', Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

[82] The National Academies of Science, Engineering and Medicine (2019), *Negative Emissions Technologies and Reliable Sequestration – A Research Agenda*.

based solutions specifically, as nature-based ones have been extensively explored before. These issues should determine the quality of any given type of CDR credits and, in a utopian world, should correlate to their eventual price in the market, which is far from the case for existing carbon avoidance credits today.

What determines removal quality?

As far as tech-based CDR solutions go, their quality (and in turn that of their associated credits) has been appraised mainly in terms of two factors: permanence; that is how long the carbon is guaranteed to be removed for and the risk of reversal, and cost. Another important factor – albeit one which has been more prone to debate – is additionality, or more simply, how critical the role of carbon finance is in bringing these solutions to market.

For example, for a certain carbon removal project, credits could either be issued *ex ante* (before the project has taken place) or *ex post* (after the project has taken place). From an additionality perspective, whether credits are issued *ex ante* or *ex post*, project developers must demonstrate that the project in question would not have taken place without contribution from carbon finance, or for any specific reason other than climate mitigation – such as for generating revenue (for example in the case of already-subsidized wind or solar projects).

In a world with limited financial resources and a pressing need to allocate funds to the most promising climate solutions, credits are best issued *ex ante* (where the project is financed by the sale of future removal credits themselves), especially to guarantee the commercialization of new solutions which may exhibit the highest potential for carbon removal.

Tech-based CDR options

1. Direct Air Capture (DAC)

One such high-potential solution is DAC technology. Credits associated with DAC exhibit high additionality in the market due to the lack of financial incentives to support the technology's deployment and because its impact, once deployed, is immediate. What's more, if stored geologically or in certain materials (see below), the carbon captured is guaranteed to be locked out of the system indefinitely. However, if used for enhanced oil recovery (EOR), there is basis for claiming that the practice isn't as additional, considering the financial benefits accruing from the sale of the extracted oil, not to mention the counterproductive fact that carbon will re-enter the atmosphere once that oil is burned anyway.

Despite its high energy demands, DAC technology has both the flexibility to be deployed in areas with abundant renewable energy resources and near geological storage sites, and the modularity to be adapted and scaled up as needed. In terms of water usage, DAC plants require 1–7 tonnes of water to remove 1 tonne of CO_2 (comparable to the amount of water needed to produce 1 tonne of steel or cement).[83] It also requires minimal land space: for perspective, capturing 1 billion tonnes of CO_2 using DAC would require between 400 km^2 and up to 24,700 km^2 (around the size of Sicily) depending on the choice of technology, while through forestation an area of some 860,000 km^2 is needed – half the size of Alaska – to remove the same amount of CO_2![84]

DAC credits, however promising, come at a heavy price tag: around $600–1000/t$CO_2$ removed, although this is expected to decrease to as low as $100/t$CO_2$ with increased deployment. In ensuring high certainty in carbon removals, DAC credits would need to be added to a diversified portfolio of high-quality nature-based solutions.

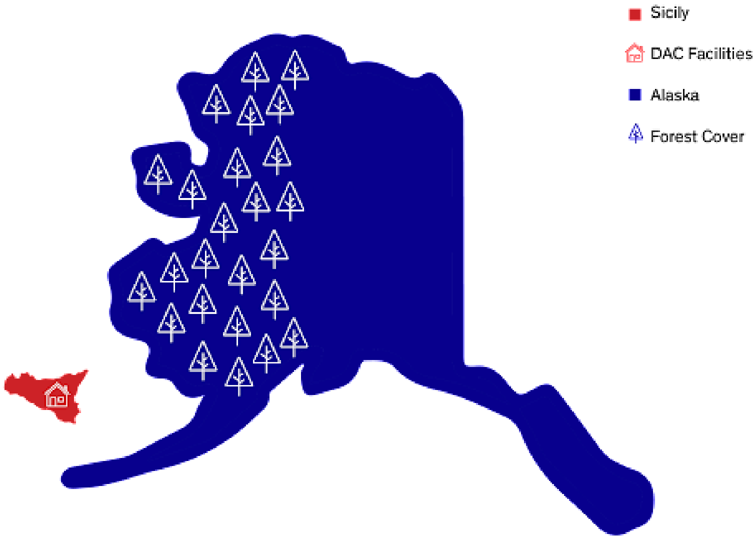
Additionality: high

Permanence: high

Cost: high

[83] Gerbens-Leenes, P. W., Hoekstra, A. Y., & Bosman, R. (2018), 'The blue and grey water footprint of construction materials: Steel, cement and glass', *Water resources and industry*, *19*, 1–12.
[84] World Resources Institute (2021). *Direct air capture: Resource considerations and costs for carbon removal.*

Scale of DAC deployment vs forestation needed to capture 1 billion tonnes of CO_2.



Real ratio of Alaska's land size to Sicily's is around 67:1.

2. CO_2 utilization in production processes

Whether captured through DAC or through other means, CO_2 can be utilized in the making of certain products, including building materials, fertilizers, textiles, biofuels, ink, or even man-made diamonds – yes, what was once believed to be a catalyst of climate change through mining could become an environmental contributor!

The additionality, permanence, and cost of removing CO_2 through these means, however, can vary. For instance, while diamonds are meant to last 'forever' and can trap CO_2 effectively indefinitely, CO_2 can re-enter the atmosphere after biofuels are burned or fertilizers used (although, admittedly, this may occur at slower rates or with lesser concentrations).

Similarly, CO_2 can be used in the production of building materials – say concrete – which can lead to carbon removal in two ways: a) the injected CO_2 is mineralized within the building material itself and may not be able to escape it unless heated to unnaturally occurring temperatures (such as 750–800°C) and b) CO_2 can displace traditional, more carbon-intensive raw materials such as cement in the production of those materials, leading to a double decarbonization effect. Moreover, using CO_2 to displace cement in concrete production represents an economic incentive, as CO_2 is far less costly than cement which, while appealing to producers, may impact how additional the practice is – depending on how additionality is defined.

One common feature of CO_2 utilization in any of these processes is the ease of measurability of the CO_2 removed and mineralized which, if applied as means to issue carbon removal credits, entails higher certainty in the amounts of credits issued against those removals. The cost of those removals will also depend on the type of application.

However, the use of CO_2 in these applications may lead to emissions displacement – or leakage – due to changes in production processes, such as emissions produced in capturing the CO_2 that is being utilized in the first place. Here, defining clear and transparent carbon accounting boundaries which take into consideration emissions displaced elsewhere is key.

Perhaps more worryingly, established and mature supply chains in these industries may hinder market penetration of CO_2 as a new raw material, with its utilization remaining all but a niche practice in the long term. Despite this, mobile solutions are emerging in the market to physically bring CO_2 into production facilities without requiring significant changes to the industrial processes themselves.

Additionality: relatively high

Permanence: moderate to relatively high (depending on application)

Cost: moderate to high

3. Biochar production

Biochar is biomass that has been chemically transformed using pyrolysis; that is biomass decomposition under high temperatures (300–600°C) and in the absence of oxygen. This reaction creates a stable carbon-rich product which resists decay, effectively locking carbon from the atmosphere for hundreds of years.

While biochar application improves soil carbon, several concerns exist regarding its application. First, there is only so much carbon that soils can absorb before reaching saturation; second, the carbon captured through biochar can be released if soils are not properly managed; and third, measuring the carbon which is truly sequestrated through biochar production can be difficult and its costs are uncertain, in the range of \$30–120/tCO_2.

Additionality: moderate

Permanence: relatively high

Cost: moderate to relatively high

4. Enhanced weathering

Weathering is the natural process of rock decomposition through chemical and physical processes, which occurs over geological timescales and removes CO_2 from the air in the process. *Enhanced* weathering is the act of purposefully pulverizing and distributing large amounts of crushed rock onto agricultural soils to accelerate this process into climate-relevant timescales. One co-benefit of doing so is enriching the soil with bicarbonates, which also ultimately helps avert ocean acidification once those bicarbonates are washed off to the ocean (bicarbonates enhance the ocean's buffer capacity to absorb more CO_2 from the air).

One reported issue with enhanced weathering, however, is that the practice may be an incentive for increased mining.[85] Moreover, while highly additional and permanent, the cost of enhanced weathering depends largely on the rock source, the technology chosen for rock grinding, and the transport of material; costs can thus range from \$60/tCO_2 for dunite to \$200/tCO_2 for basalt.[86]

Additionality: high

Permanence: high

Costs: moderate to high

Concluding remark

Despite the myriad of tech-based CDR solutions and their respective advantages and disadvantages, it is without doubt that a portfolio of all of the above, combined with nature-based solutions and with BECCS (which remains much less explored in the carbon offsets market) is needed: the more shots on target the more likely it is that we will achieve the goal of successful and sustainable climate mitigation.

THE PERTINENT ROLE OF CARBON DIOXIDE REMOVAL AND DIRECT AIR CAPTURE IN ACHIEVING THE GOALS OF THE PARIS AGREEMENT

Peter Freudenstein, Louis Uzor, and Christoph Beuttler

Direct air capture (DAC) as a form of carbon dioxide removal – the practice of removing CO_2 directly from the atmosphere and storing it permanently – has in recent years started to receive the attention it deserves. Policymakers now must pave the way for the industry to scale up in the race against time to reach net-zero by 2050 as stipulated in the Paris Agreement.

Climate science has been explicit for a while now, and since the release of the IPCC Special Report on Global Warming of 1.5°C it has become clear that removing gigatons of CO_2 from the atmosphere annually, in addition to more ambitious

[85] Chow (2020), 'Enhanced weathering for carbon capture', Earth.org.
[86] Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018), 'Potential and costs of carbon dioxide removal by enhanced weathering of rocks', *Environmental Research Letters*, *13*(3), 034010.

emissions reductions, is the only way to achieve the goals of the Paris Agreement. This means reaching net-zero around 2050 and net-negative greenhouse gas emissions thereafter. As a result, policymakers and companies have begun to step up to the challenge: We are finally seeing increasing financial commitments by corporate leaders as well as governments, such as the USA, the EU, and the UK, to scale permanent carbon dioxide removal (CDR) solutions, and in particular DAC. But we still have a lot of ground to cover.

DAC captures CO_2 from the air and combined with permanent storage (DAC+S), it provides an efficient way of removing CO_2 from the atmosphere for good. For clarity, it is important to note that DAC+S is different from carbon capture and storage (CCS). CCS usually refers to capturing CO_2 at industrial sources, thus preventing additional (fossil) CO_2 from entering the atmosphere. Consequentially, it does not constitute a removal as in DAC+S, but an emissions reduction.

DAC+S showcases key characteristics that make it a CDR solution with high potential for delivering an essential part of achieving the gigaton scales of annual CDR capacity needed by 2050. Benefits of DAC include its flexibility in location, its immense cost reduction potential, its unparalleled efficiency in terms of land use, and its political appeal. It also provides certainty that the CO_2 is indefinitely removed and stored. Last but not least, it is an incredible opportunity to turn one of the most challenging aspects of addressing climate change into a large driver for a green economy and job opportunities.

To unlock this potential, however, we need a more concerted effort by all stakeholders to scale up DAC.

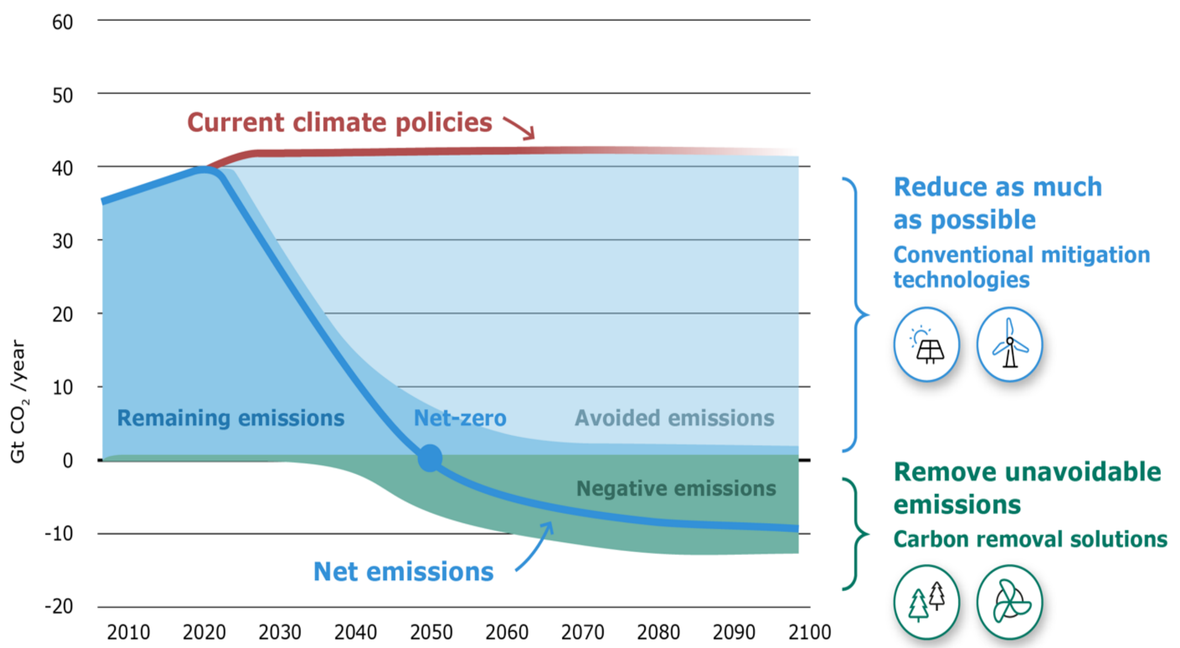
Most importantly, given the current required growth rates for carbon dioxide removal (60 per cent per year) swift and firm policy interventions are urgently required. Delaying action on CDR would result in having to double CDR capacity every year, making an already complex challenge even harder. Policymakers must now focus on developing and advocating for pragmatic policy options that can be implemented in the short term to aid CDR scale up and accelerate the buy-down of costs. This includes incentives such as the improved 45Q tax credit in the US for DAC+S or advanced proposals in the EU to incentivize large-scale DAC operations via a carbon contract for differences that would bridge the gap between costs of first-of-a-kind projects and current market prices.

The rationale for carbon dioxide removal and direct air capture

CDR is required for three main reasons. First, inevitable residual emissions will likely continue even post-2050 in sectors such as heavy industry, agriculture, or aviation. These must be neutralized with CDR. Second, we cannot rule out the possibility of a temperature overshoot. Current commitments after COP26 in Glasgow are still insufficient to reduce emissions at the rate that is required to stay below 1.5°C. If we end up temporarily breaching the remaining carbon budget, CDR will be the fallback option to reduce atmospheric concentrations of CO_2 below the threshold of 1.5°C again. Third, to reach net-negative greenhouse gas (GHG) emissions, the absolute CO_2 concentration in the atmosphere needs to be reduced. Historic emissions have amassed in the atmosphere since the Industrial Revolution and additional warming is essentially already locked in. Permanent CDR approaches, such as DAC+S, are the only sustainable option to reverse this trend. The below figure illustrates these three reasons.

Within the suite of CDR approaches, DAC+S is one of the most promising solutions. In the case of the Climeworks' DAC technology that captures CO_2 from ambient air, the CO_2 is captured through a cyclic adsorption/desorption process using chemical sorbent material. The air-captured CO_2 is then permanently stored – via innovative underground mineralization (for example using the Carbfix technology), or in conventional storage sites such as saline aquifers or depleted gas fields.

It is this ability to be paired with permanent storage approaches that makes DAC+S such a promising candidate. In this budding industry bursting with innovative ideas, being able to provide certainty that every ton of CO_2 removed is a ton of CO_2 that will not further contribute to global warming, is an important asset. DAC+S also represents a transparent CDR approach because it can be precisely measured due to its engineered nature. This makes it particularly attractive, especially when designing policy, and we expect DAC+S to take up an ever-larger share of CDR capacity as we move towards 2050 and beyond.



CDR solutions like DAC+S are needed to neutralize unavoidable emissions, revert a possible temperature overshoot, and eventually achieve net-negative GHG emissions

Source: Adapted from IPCC (2018) & United Nations Environment Programme (2021)

Direct air capture must and can achieve gigaton scales by 2050

Achieving gigaton-scale of permanent CDR capacity will not be without its challenges, but it is crucial to addressing the climate crisis. What makes DAC a likely candidate to provide a large share of this future CDR capacity are its:

- large potential for cost reductions,
- modularity and economies of scale,
- flexibility of siting,
- political feasibility,
- potential for substantial economic and job opportunities.

First, DAC is still at an early stage of development, with Climeworks as the leading company in this space, having just launched the world's largest DAC+S plant 'Orca' in Iceland in autumn 2021 at a nominal capture capacity of 4000 metric tons of CO_2 per year. Although some opine that this equates to no more than a 'drop in the ocean', it represents a major milestone for the DAC industry – it is the first time that the whole process from capturing to storing the CO_2 permanently has been performed at large scale. Cynics cited that DAC at the current price point of \$600–\$1000/tCO_2 is cost-prohibitive, but we know it has the potential for immense cost reduction as we scale up. History and recent examples such as solar PV or batteries have repeatedly proved that technology costs typically fall dramatically with deployment. In terms of DAC, we foresee a long-term price of around \$100/t as realistic since many of the cost reduction features – ranging from more effective sorbent materials and improved energy efficiency to standardization and commercial mass production – have yet to be exploited. As DAC plants increase their capacity and are replicated, they will also benefit substantially from economies of scale and reduced capital costs, as capital markets learn to work with DAC. Estimated learning curves of at least 12–20 per cent for DAC can be achieved as the industry scales up.

The factor of siting flexibility remains underappreciated in current discussions but will increasingly become a decisive factor as we venture into the megaton realm and face increasing limited land availability. Since CO_2 concentration is dispersed evenly across the globe, a DAC plant can technically be built anywhere. As a result, DAC plants can be situated where renewable energy and storage sites are most accessible and affordable, but it also means that the plant can be built on non-arable land, avoiding any use conflicts such as food security or biodiversity. At scale, the land efficiency of DAC will be a major upside, given that land will only increase in value and decrease in availability.

Finally, DAC as a climate solution is politically appealing, thus increasing the likelihood that the relevant regulatory and political frameworks needed for scale up will be implemented. This is because DAC addresses a clear scientific call to action, but it can also be integrated into the existing political economy by offering obvious opportunities to both current and new interest groups. This is clearly illustrated in the recent passing of the infrastructure bill in the US, and the introduction of a possible clean energy standard as part of a larger social and climate spending bill. Both bills included substantial DAC provisions, but while DAC even received a substantial boost during the actual negotiations (with the introduction of a large-scale deployment programme), the standard was cut due to its perceived stringency and political baggage. DAC was able to offer a positive forward-looking narrative that appealed to the majority of policymakers. This positive narrative refers to the simple fact that investing in direct air capture means kickstarting a sustainable and long-term trillion-dollar industry to address climate change.

In contrast, we anticipate that there will be an end-date for CCS, and certainly of carbon capture and utilization (CCU) applications in a net-zero world, because the only fossil CO_2 emissions by then should come from unavoidable sources and will be covered by CDR. In contrast, the need for DAC will likely only increase post-2050, especially as the world should enter a net-negative status and draw down more CO_2 than it emits. In other words, what the trillion-dollar fossil fuel industry has emitted over the past 150 years will be removed by a similar-sized new industry, while also cleaning up new emissions in the meantime. Additionally, initial estimations show that a scaled-up DAC ecosystem can deliver millions of jobs in the construction and operation of DAC plants, as well as in complementary areas such as in the steel, chemical, or renewable energy industries. Local economies stand to benefit too, especially the ones that are slated to be impacted by the ongoing energy transition such as those that host large fossil fuel complexes.

Governments need to step up to the scale up challenge

Realizing the potential of DAC and the need to scale it up, private companies have charged ahead in funding the first set of CDR projects and bringing down costs. Governments, however, have an even greater responsibility to ensure a sustainable acceleration of CDR capacity to meet global climate goals. Some countries that are already spearheading these efforts include the UK, the European Union, and the US, as well as some smaller European countries. They are motivated by the increasing urgency to act on climate change and by the economic opportunities presented by CDR. They have done so by creating large cost-share programmes in the US for the construction of first-of-a-kind large-scale DAC plants and providing hefty tax credits to incentivize operations. The EU has just announced that it's developing an EU-wide CDR strategy, setting out a concrete 2030 capacity target for engineered CDR solutions and developing a stringent and comprehensive CDR certification mechanism. Switzerland, where Climeworks is headquartered, is pioneering Article 6 bilateral climate deals in the framework of the Paris Agreement that will eventually lead to an international carbon removal compliance market.

Still, large gaps persist. Most governments have yet to realize that CDR is an important part of the portfolio of solutions in their climate strategy, to claim credibly that they are pursuing a net-zero strategy. They must also come to grips with how to implement CDR policy in practice. That means we should already be well into the deployment and commercialization phase of CDR.

Policy instruments such as carbon contracts for difference or cost-share programmes must be structured in a way that encourages rapid commercialization of more CDR projects. Underpinning any CDR deployment strategy also requires the creation of a stringent accounting framework that goes beyond the current free-for-all in the voluntary carbon markets. CDR policy mechanisms will only be effective and justifiable for proven and measurable CDR approaches.

The design and development process of CDR markets via governments must also be based on a stringent differentiation from practices that reduce emissions, such as CCS, for the following reasons:

- As opposed to markets designed to incentivize emission reductions, CDR for removals will be needed beyond the point of reaching net-zero emissions. According to mitigation pathways modelled by the IPCC, global emissions need to become net-negative throughout the second half of the century and beyond. Thus, CDR will have to be delivered each year on gigaton scales and policy incentives must be introduced to achieve this scale. Contrarily, CCS will likely only play a minor role in some industrial processes that will eventually be replaced by sustainable alternatives.

- Prior to reaching a net-zero status, there are valid arguments for a conceptual split between CDR and emission-reduction technologies such as CCS. Most prominently, fears of a substitution effect between CDR and far-reaching emission reductions through CCS present a key barrier to the sustainable development of a thriving CDR industry. Acknowledging the need for CDR, scholars have therefore repeatedly advocated for a clear separation between removal and reduction targets and thus for separate incentive structures to minimize such ill-fated confusion.

To be clear, the overarching goal of addressing climate change will remain the same, and emissions reductions need to be prioritized alongside CDR to reach net-zero in 2050. Thereafter, however, CDR such as DAC will be the main tool to sustain a healthy planet and it is due time for governments to put in place frameworks that set the world on a path to achieving gigatons of CDR annually.

LINKING DIRECT AIR CAPTURE (DAC) TECHNOLOGY TO THE VOLUNTARY CARBON CREDITS MARKET

Hasan Muslemani

Direct Air Capture (DAC), arguably the most robust form of carbon removal in the world, has recently gained traction amongst the environmentally conscious, not to mention within climate investment communities. Simply put, DAC is an engineered solution that sucks CO_2 straight out of thin air, to be subsequently buried in safe underground geological storage sites, or alternatively re-used in carbon-based industries, for example in agriculture, food and beverage, and biofuel production. The indispensability of DAC developments towards meeting international, sectoral, and corporate climate targets has recently been reflected by global public policy support, including the US's dedication of $3.5 billion in funds for DAC infrastructure hubs and the UK's pledge of £100 million to develop DAC and other removal technologies. The technology, as an artificial means of carbon removal, is intended to complement the wide array of existing nature-based solutions (NbS), such as forestry, soil carbon sequestration, biochar production, and wetland restoration.

Deploying DAC along with NbS is considered key in achieving *carbon neutrality* or meeting corporate *net-zero* targets. Before exploring DAC's role within the offsets market, it is important to note the difference between these concepts.

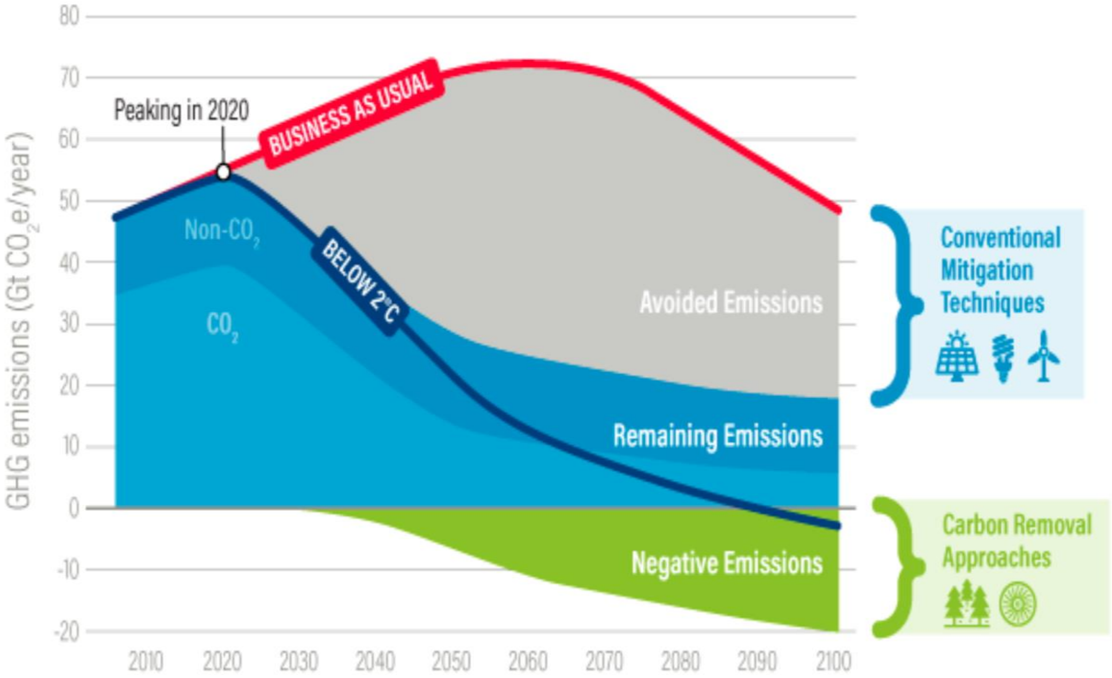
DAC: key to a credible climate mitigation strategy

Misleadingly, the terms 'carbon neutrality' and 'net-zero carbon' have been often used interchangeably – even amongst world leaders. The term 'carbon-neutral' was voted New Oxford American Dictionary's word of the year in 2006, to highlight the rise of green movements at the time. The IPCC defines carbon (or climate) neutrality as a concept of state where human activities result in no net effect on the climate system: put differently, it involves a balancing of the *flow* of emissions over time, by avoiding emitting CO_2 amounts equivalent to the ones that would have been emitted under a business-as-usual scenario.

'Net zero carbon', on the other hand, involves the overall *stock* of CO_2 in the system, which goes beyond balancing emissions which we emit today, to actively removing them from the system. The removed emissions include residual emissions which cannot be avoided using conventional mitigation techniques, in addition to emissions which we had previously put into the atmosphere since the industrial revolution, until the overall balance of what we emit and what we remove is zero. Going beyond that, if the removed amount of CO_2 from the atmosphere ultimately exceeds what we emit, a state of 'negative emissions' is reached.

On a corporate level, being carbon neutral simply means offsetting a corporation's own emissions by investing in carbon-reducing projects elsewhere in order to 'neutralize' those emissions. The concept of carbon neutrality has been both hailed *and* criticized – perhaps understandably – as a tag for companies who offset their emissions in a much cheaper way than opting to make drastic changes to their own operational processes. In practice, the concept argues that a company maintains, or can in theory even *increase*, its emissions while claiming to be carbon-neutral, which is not especially helpful in the fight against climate change and may raise claims of greenwashing.

Role of carbon avoidance and removal approaches in achieving carbon neutrality and net zero carbon targets.



In contrast, a corporate net-zero climate strategy entails that a company's operations would result in no *net* carbon emissions released – something that can be achieved by first reducing the company's own emissions if and where possible, and, second, by investing in carbon removal solutions that will counter the residual emissions that it *does* emit.

Here, it is also worth noting that carbon neutrality can be achieved by investing in projects that *avoid* or *mitigate* the release of carbon into the atmosphere, such as those enhancing conservation or producing energy from renewables rather than from fossil fuels, where the alternative (namely continuing with a business-as-usual approach) would have released more CO_2 into the air. While encouraged, this means that the existing CO_2 balance in the atmosphere is maintained.

Why does this matter for DAC?

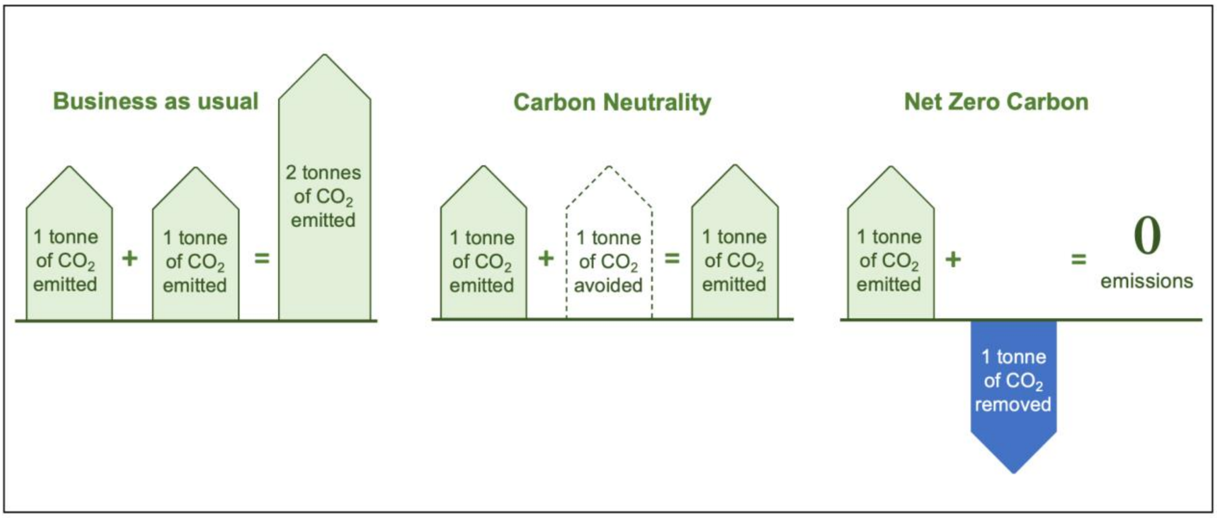
DAC is a solution that ***physically removes*** CO_2 from the air, and it does so ***now***, effectively reducing the total atmospheric CO_2 balance and eliminating global warming effects which that uncaptured CO_2 would have otherwise caused over many years. DAC also allows for storage of CO_2 for thousands of years, as opposed to other forms of carbon removal such as forestation which may only lock CO_2 out of the atmosphere for the lifetime of trees – tens to hundreds of years, or even less in the case of wildfires, for instance. As such, DAC's role has recently become especially prevalent in helping corporations in their quest to go 'net-zero'.

To avoid or to remove? That is the question

Whether corporations seek carbon neutrality or net-zero strategies has significant implications on the type of carbon offset credits they (should) seek in the market. Until recently, the carbon offsets market has been dominated by 'avoidance' rather than 'removal' credits: we here further highlight the difference between the two.

Carbon *avoidance* projects mitigate carbon emissions which would have otherwise entered the atmosphere in their absence. In contrast, carbon dioxide removal (CDR) technologies – one main technology of which is DAC – generate carbon *removal* credits which, as already highlighted, go beyond merely avoiding emissions to physically removing CO_2 from the system, where one removal credit is equivalent to 1 tonne of CO_2 removed.

Difference between carbon avoidance and carbon removal.



London-based climate solutions company, BeZero Carbon, has developed a carbon credits ratings framework which assesses all credit types in the market – avoidance and removals – based on the same risk factors. Yet, we find that removals tend to achieve higher scores than avoidance due to their higher additionality. The concept of additionality addresses whether an avoidance/removal project would have been commissioned without the need for carbon finance or for other purposes or co-benefits than climate mitigation.

Additionality, however, is not binary.

For example, while renewable energy projects – prime examples of avoidance projects – contribute largely to environmental protection, they may be largely supported by the revenue generated through the sales of electricity. For DAC, the only accrued benefit is climate mitigation, and the business model supporting the technology's deployment is the sale of the associated removal credits themselves – rendering DAC a highly additional solution.

Other differences between both types of credits lie in the quality, permanence, immediacy (or lack thereof) of climate impact, and credibility of their role in climate mitigation.

In terms of quality, for instance, deploying DAC technology would result in direct and instant CO_2 elimination which can also be very accurately measured and in absolute terms, meaning there is no need to make assumptions about a baseline scenario (as is the case for an avoidance or an NbS removal project). In other words, by buying a DAC removal credit, one literally pays for the carbon the technology captures, assuming the end destination of the captured CO_2 is permanent geological storage.

DAC also guarantees that the CO_2 captured and stored is locked out of our system for thousands of years (in other words, has high permanence), where some nature-based solutions such as soil carbon sequestration may not achieve the same scale of permanence because carbon in the biosphere sees continual dynamics of release and sequestration. Moreover, due to the lack of economic incentives, the concept of capturing CO_2 out of air may very well pass the public sentiment test and in turn be supported by the investment community.

Highest quality credits

The aforementioned BeZero Carbon Rating (BCR) framework includes six factors against which a project, whether avoidance- or removal-based, is appraised. These factors include additionality, over-crediting (rigour of crediting assumptions), permanence, leakage (emissions which may be produced elsewhere due to the project's implementation), policy environment, and perverse incentives (whether a project developer has other incentives to undertake the project). Against these factors, DAC naturally scores highly – even higher than other tech-based carbon removal solutions such as bioenergy with carbon capture and storage (BECCS) and CO_2 mineralization in construction materials (for example, concrete production).

In the case of the former, it may be argued that, considering the revenue accruing from the electricity generated, BECCS is not as additional as DAC. Furthermore, BECCS has had leakage concerns associated with large-scale land use and change. For context, BECCS requires around 400–2400 times more land space than DAC to achieve the same amount of carbon removals[87] (and did we mention the convenience of DAC being deployable *anywhere* in the world and achieving the same results?!). For the latter, substituting the use of cement for CO_2 in concrete production represents an economic incentive for the project developer, as sourcing CO_2 is much cheaper than cement, which would adversely affect the additionality of the project. As such, and due to their high additionality and minimal risk of leakage, DAC offsets have been prime candidates for inclusion in government and commercial net-zero strategies.

The price tag

However promising, DAC requires highly innovative and expensive installations that demand higher prices than typical offsets, and as a result the costs of DAC credits in the market have been in the range of $600–1000 per tonne of CO_2 removed. One of the factors driving up their price is the cost of the underlying technology, in addition to its high energy demands: if deployed at the scale required to remain within the 1.5–2°C scenarios of global warming, it is estimated that DAC combined with geological storage could require around 300 exajoules (that is one quintillion [10^{18}] joules) in energy input per year by 2100 – around half of the global energy consumption today, and a quarter of the projected energy demand in 2100.[88] For DAC to be feasible, costs would need to drop from current levels to around $100/t$CO_2$.

Indeed, significant cost reductions of deploying DAC are largely expected to occur with increased deployment and modularity of the technology. Similar cost reductions have already been seen in the development of other clean technologies (for example, solar photovoltaic projects witnessed cost reductions of around 300-fold between 1975 and 2018). While DAC admittedly needs to be commercialized in a much shorter timespan in order to achieve the decarbonization potential needed, its costs need only be reduced by a factor of 10 to become commercially competitive. In fact, if the global deployment of DAC technologies follows an annual growth rate of 25 per cent, its levelized cost is forecasted to reduce to below $100/t$CO_2$ in ten years.[89]

DAC removal credits are now being sold by Carbon Engineering, Climeworks, and Global Thermostat. For every pre-purchase of DAC credits, project developers guarantee that an equivalent tonnage of CO_2 is captured and safely stored underground within a certain timeframe.

[87] Fern (2018), *Six problems with BECCS*.
[88] Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019), 'An inter-model assessment of the role of direct air capture in deep mitigation pathways', *Nature communications*, *10*(1), 1–12.
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CONTRIBUTORS TO THIS ISSUE

Philip Andrews-Speed is a Senior Research Fellow, Oxford Institute for Energy Studies

Sanne Akerboom is assistant professor of Regulation and Governance of the Energy Transition at the Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University and Director of the Sustainable Industry Lab

Ashok Belani is Executive Vice President Schlumberger New Energy

Christoph Beuttler is Head of Climate Policy at Climeworks

Ida Egeland is a Senior Analyst at Equinor

Darrick Evensen is a Lecturer in Environmental Politics, School of Social and Political Science, the University of Edinburgh

Bassam Fattouh is Director, Oxford Institute for Energy Studies and Editor of the Oxford Energy Forum

Peter Freudenstein is Climate Policy Manager at Climeworks

Damien Gerard is Vice President Carbon Capture and Storage Schlumberger New Energy

Ashraf Ghazzawi is Saudi Aramco Executive Director of Strategy & Market Analysis

Wolfgang Heidug is a Visiting Senior Research Fellow, Oxford Institute for Energy Studies

Nnaziri Ihejirika is a Research Associate, Oxford Institute for Energy Studies

Malcolm Keay is a Senior Research Fellow, Oxford Institute for Energy Studies

Ahmad Khowaiter is Saudi Aramco Chief Technology Officer

Jon C. Knudsen is Chief Commercial Officer at Aker Carbon Capture

Gert Jan Kramer is Professor of Sustainable Energy Supply at the Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University and Chair of the Sustainable Industry Lab

Samantha McCulloch is Head of CCUS Unit, International Energy Agency

Hasan Muslemani is a Carbon Removals Scientist at BeZero Carbon

David Phillips is Head of UK and Investor Relations at Aker Carbon Capture

Ragni Rørtveit is Business Development Advisor at Northern Lights

Graeme Sweeney is Chairman of the Zero Emissions Platform (ZEP)

Louis Uzor is Climate Policy Manager at Climeworks

Hallvard Valen is an intern at Aker Carbon Capture

Eirik Wærness is Senior Vice President and Chief Economist, Head of Global External Analysis at Equinor

Adam Whitmore is Principal Advisor Climate Change Policy at Bellona

Emil Yde Aasen is a Business Analyst at Aker Carbon Capture

Paul Zakkour is Founding Director of Carbon Counts and Visiting Researcher at KAPSARC

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THE OXFORD INSTITUTE FOR ENERGY STUDIES

57 Woodstock Road | Oxford | OX2 6FA

Direct Line: +44 (0)1865 889136
Reception: +44 (0)1865 311377
Fax: +44 (0)1865 310527

www.oxfordenergy.org