PUBLIC POLICY PROJECTS

INSIGHTS

Carbon capture and storage in the UK: Infrastructure to unlock investment

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THIRD WAY

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PHILLIPS 66

Carbon Capture & Storage Association

VPI

Contents

ACRONYMS

BECCS	Bioenergy with CCS
CCC	Climate Change Committee
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDR	Carbon Dioxide Removal
CO_2	Carbon Dioxide
COP	Conference of the Parties
CTBO	Carbon Takeback Obligation
DAC	Direct Air Capture
DACCS	Direct Air Capture with Carbon Storage
DOE	US Department of Energy
GHG	Greenhouse Gas
Gt	Gigatonne
IEA	International Energy Agency
IEA-SDS	IEA's Sustainable Development Scenario
IPCC	Intergovernmental Panel on Climate Change
Mtpa	Million tonnes per annum
NDC	Nationally Determined Contribution

Acknowledgements

ABOUT PUBLIC POLICY PROJECTS

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Third Way's Climate & Energy Program designs and advocates for policies that will drive innovation and deployment of clean energy technologies and deliver the emissions cuts we need to win the fight against climate change. The more low-carbon options we have to work with, the better our chances of success. That is why we are proud to be part of a large and growing community promoting evidence-based solutions to the climate challenge that include advanced nuclear and carbon capture technology, as well as renewables, hydropower, existing nuclear, energy storage, and efficiency. For more information, please visit thirdway.org/issue/climate-and-energy

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This report is authored by PPP Senior Policy Analyst Francesco Tamilia, who has also project-managed the interviews, roundtables and webinars that informed this report.

Foreword

FOREWORD BY JON GIBBINS & NIALL MAC DOWELL

The appreciation of what has to be done, globally, to avoid dangerous climate change has changed dramatically over the last two decades; from the expectations in the UK in the early 2000s that a 60 per cent reduction in net carbon emissions might be sufficient, to a legally mandated 80 per cent reduction in 2008 and a 100 per cent reduction in 2019. Currently, there is a growing realisation, thanks to Intergovernmental Panel on Climate Change (IPCC) climate modelling and current emission levels that an extended period of negative emissions will be required, likely extending well into the 22nd century.

Unsurprisingly, the scope and ambitions of carbon capture and storage (CCS) technology development and deployment have also changed over the same period. CCS emerged on the world stage at the Gleneagles G7 Conference in 2005 but was then principally envisaged as a way of reducing emissions from coal, thereby enabling its retention in the electricity generation mix. Its scope was extended to cutting emissions from all fuel sources, after opposition amendments to the 2010 Energy Bill, and CCS projects developed under subsequent governments included both gas and coal power plants, although none of these went beyond the study stage.

Subsequently the UK was the first major economy to commit to a legally binding, economy-wide, net zero target in 2019, 11 years after passing the Climate Change Act.[1] From 2016, all sources of CO_2 emissions that could be captured at the point of production started to be considered, with reduction targets of 80 per cent soon moving towards net zero. Increasingly, carbon dioxide removal (CDR) is also expected to be used to recapture CO_2 emissions that are hard, or more expensive, to capture directly.

To enable the widespread deployment of CCS, shared CO_2 transport and storage infrastructure, including ships, rail and road, as well as pipelines, are now being planned, supporting the emergence first of discrete CCS clusters and subsequently the county-wide coverage that net zero requires.

Installed global CCS capacity is currently at 44 million tonnes per annum (Mtpa), which is required to increase to 5,600Mtpa by 2050 to limit global warming below two degrees Celsius.[2] But despite the definite progress that has occurred in our understanding of the role for CCS in mitigating the risk of dangerous climate change and how it might be delivered in principle, the essential first step of actual CCS deployment has not yet occurred in the UK. Neither has extensive progress been made overseas, where similar stories of many CCS projects not making it beyond the design study stage abound. This means that time has gone by without the learning-by-doing that can lead to serious reductions in cost and the establishment of successful reference projects to give confidence to future investors.

The UK now stands at a point where, as described in this report, there exists a broad portfolio of CCS projects being developed, based on two initial CO_2 transport and storage clusters, with a number of further clusters and plans for CO_2 shipping close behind. The UK is also facing a period of challenges in its energy supply that may prove to be as serious as the winter of 1946/47 or the oil crises of the 1970s, and with equally long-lasting subsequent impacts. There is one constant in this dynamic geopolitical landscape – the inexorably increasing concentration of CO_2 in the atmosphere, and the associated impacts of climate change.

The UK cannot avoid dangerous climate change alone by cutting its emissions to net zero, or even negative output. However, by taking the opportunity now available to actually 'put steel in the ground' for CCS projects, we can not only enhance current and future UK employment prospects and underpin future energy diversity, and hence energy security, but we can also make very material contributions to leading the future global market in CCS, and CDR with permanent storage, that is essential to underpin successful global action.

Recommendations

1. DELIVER ON IMMEDIATE PLANS FOR CCS, ESPECIALLY INFRASTRUCTURE

The government must deliver on its plans to support CO_2 pipeline transport and offshore geological storage infrastructure development for the Track 1 CCS clusters, HyNet, East Coast and follow on infrastructure such as the Scottish Cluster (which is also the Track 1 reserve cluster) and Humber Zero. This infrastructure is the key physical enabler for industry to progress the initial deployment of CO_2 capture projects and limited time is available to take UK CCS from nothing to something in the order of 100 $MtCO_2$/yr capacity by 2050.

The government must also see through, to a successful conclusion, the undertakings made on funding support for CCS infrastructure and the extensive work on business models for the different types of CO_2 capture. Unless a reasonable return can be expected on investments, industry cannot be expected to commit to the construction and long-term operation of these facilities. These support measures are essential for the 'first-of-a-kind' projects now being contemplated; in the longer-term other mechanisms, such a 'carbon takeback obligation' on fossil producers, may come into play.

To justify government support, CCS projects should be rigorously tested against credible counterfactuals to ensure technical viability, value for money, affordability, contribution to security of supply and compliance with UK carbon budgets and nationally determined contributions. Investment should be targeted to support the preservation and creation of jobs, and to enhance productivity nationwide.

2. DEVELOP ENGINEERED CARBON DIOXIDE REMOVALS TO PUT THE 'NET' INTO NET ZERO

The government must ensure that carbon dioxide removal from the air and permanent storage is also developed, taking advantage of the shared cluster infrastructure. While this will have higher costs than direct CO_2 capture and storage from point sources it is an essential technology for putting the 'net' into 'net zero'. In particular, because of the shared infrastructure and technologies, engineered CDR technologies such as bioenergy with carbon capture and storage (BECCS) and direct air capture with carbon storage (DACCS) should be treated as an integral part of CCS activities in government administration and policy-making rather than being grouped with nature-based offsets and removals.

3. BUILD A WORLD-CLASS UK SUPPLY CHAIN WITH SUSTAINED FUTURE DEPLOYMENT

If the UK is to develop a successful domestic CCS supply chain that can subsequently compete globally, clear government policy and signalling is required on support for future CCS deployment on transport and storage, including shipping, and further CO_2 capture projects. This will ensure that indigenous manufacturing capacity is developed, and that design and construction teams can be retained intact between projects. Finally, recent threats to the UK's energy security have made domestic fossil fuel production a much higher priority. However, without full CCS with all the CO_2 permanently stored, including carbon dioxide removal from the air as necessary, to give net zero GHG emissions, continued fossil fuel use, or methane production and conversion to hydrogen, cannot be consistent with the UK's 2050 net zero target.

Introduction

The impacts of the climate crisis are ever more evident and widespread across the world. It has become increasingly clear that there is no one-size-fits-all solution to tackling the climate crisis and that a multifaceted approach is needed.[3] Decades of little to no action in significantly reducing CO_2 emissions have left the world with limited mitigation pathways to limit global warming to 1.5 or 2 degrees Celsius. This reality has contributed to a renewed focus on carbon capture and removals technologies.

There are natural and technology-based solutions to remove or capture carbon from the atmosphere. This report focuses on technological solutions around the permanent sequestration of the captured CO_2. Carbon capture and storage (CCS) are an important group of technologies to help achieve the world's climate targets. Experts do not see them as the approach that will solve the climate crisis alone, but as part of a portfolio of technologies that are needed to get to net zero. Leading climate and energy bodies such as the International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC) and the UK's Climate Change Committee (CCC) have all outlined the importance of these technologies in the net zero transition.[4, 5, 6] In addition to cutting CO_2 emissions in the energy supply sector, CCS is also needed to play unique roles in:

a) Achieving decarbonisation in hard-to-abate industries such as cement, steel and chemicals.

b) Delivering carbon dioxide removals from the atmosphere with permanent geological storage, both to offer a route for all current emitters to atmosphere to achieve net zero by recapturing their CO_2 and, very likely, in the longer term, to deliver an extended period of net-negative global emissions to reduce atmospheric CO_2 concentration to a sustainable level.

CO_2 EMISSIONS REDUCTIONS IN THE ENERGY SECTOR IN THE SUSTAINABLE DEVELOPMENT SCENARIO RELATIVE TO THE STATED POLICIES SCENARIO

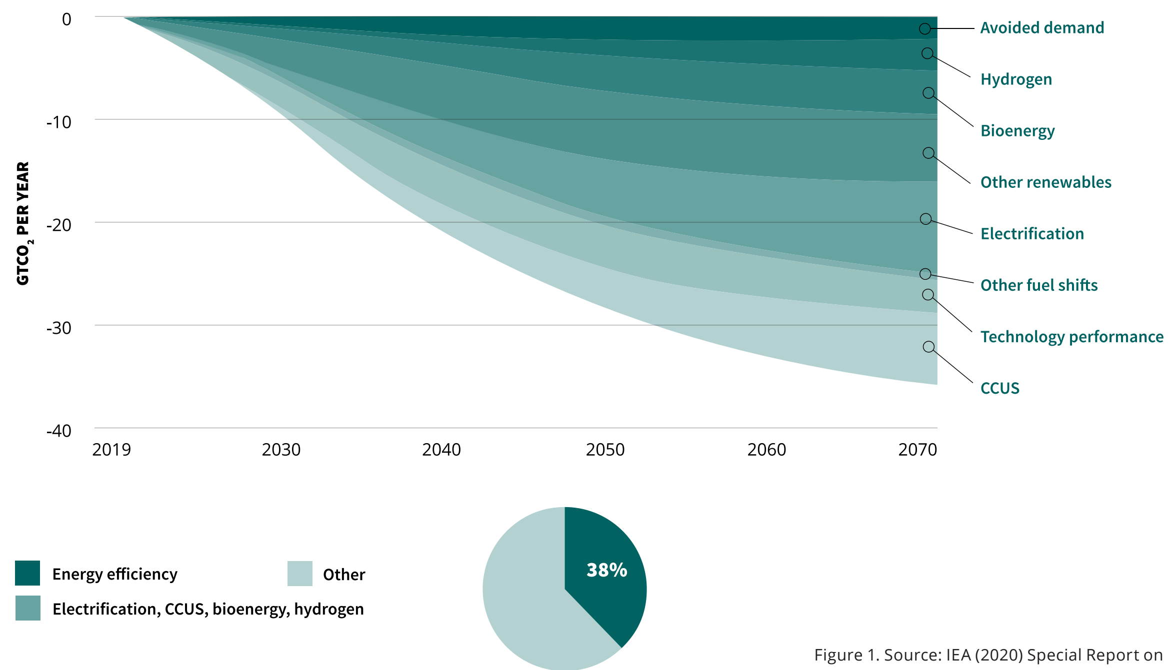


Figure 1. Source: IEA (2020) Special Report on Carbon Capture Utilisation and Storage

The outspoken support of these international organisations, particularly the IPCC in its *Special Report: Global Warming of 1.5 °C* in 2018, has been a turning point for CCS and engineered carbon dioxide removal (CDR)[7]. In all four of the IPCC pathways the world needs carbon dioxide removal, and three of the four pathways also require significant amounts of CCS. In its 2020 report, the IEA highlighted the importance of carbon capture, utilisation and storage (CCUS) in the transition to net zero, claiming that "reaching net zero will be virtually impossible without CCUS".[8] According to the IEA Sustainable Development Scenario (IEA-SDS), CCS accounts for around 15 per cent of the cumulative emissions reduction that is needed to achieve net zero targets by 2070 on a global scale, compared with the baseline Stated Policies Scenario.[9] In the report published in 2019, *Net Zero – The UK's contribution to stopping global warming*, the CCC argued that CCS "is a necessity and not an option".[10]

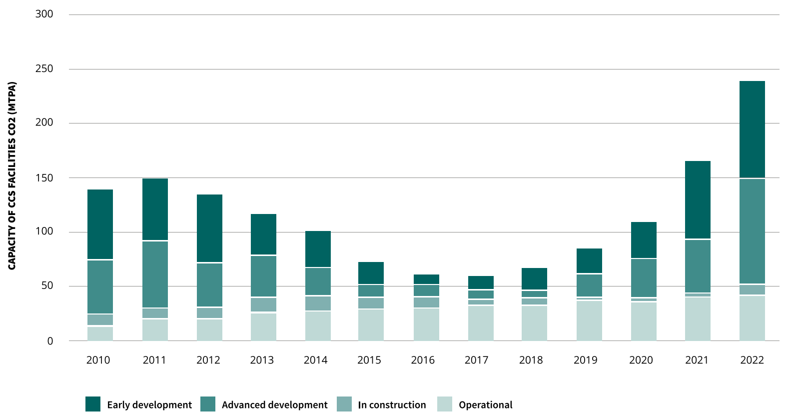


Figure 2. Pipeline of commercial facilities since 2010 by captura capacity (Mtpa)
Source: Global CCS Institute – 2022 status report

CCS is not new – all of the technologies required have existed for several decades (see Case Study 2). In recent years, however, it has received renewed global interest as the need to deliver net zero greenhouse gas (GHG) emissions, followed by a period of net negative emissions, in order to avoid dangerous climate change has emerged in studies such as the IPCC report noted above. For the fifth year in a row, the pipeline of CCS facilities being planned or proposed continues to grow exponentially. Confirming this trend, *The Global Status of CCS report* in 2022 revealed rapid development of CCS across North America, Asia Pacific, Europe and the UK, and the MENA region.[11]

This momentum, driven by greater scientific support from the world's leading organisations, and the increasing net zero commitments by thousands of companies and countries around the world, has strengthened policy support for CCS.[12] The innovative business models for CCS networks implemented as "clusters" are also contributing to this growing momentum. Today, there are significantly more plans for CCS hubs and clusters, where multiple point sources of CO_2 are connected to a shared CO_2 transport and storage network. These new systems, which have also been emerging in the UK in areas across the North West, Teesside, Humber and Scotland have various benefits including reduced risks, more efficient use of resources for storage, reduced CCS deployment timeframes and reduced unit costs.

Since 2017, there have been more than 30 new plans for integrated CCS facilities, mainly in the United States and Europe, and several projects are also planned in Asia and the Middle East. According to the IEA, "if all the announced projects were to proceed, the amount of global CO_2 capture capacity would more than triple, to around 130 Mt/year."[13]

Despite the significant progress made in recent years in terms of investment and the number of projects in the pipeline, more needs to be done to rapidly scale up these technologies to achieve the impact required to meet the IPCC targets. According to the IPCC, if global warming is to be limited to 1.5 degrees Celsius, between 100 and 1,000 Gt of CO_2 need to be removed from the atmosphere over the course of the 21st century, as well as the requirement for a rapid transition to net zero carbon emissions.[14]

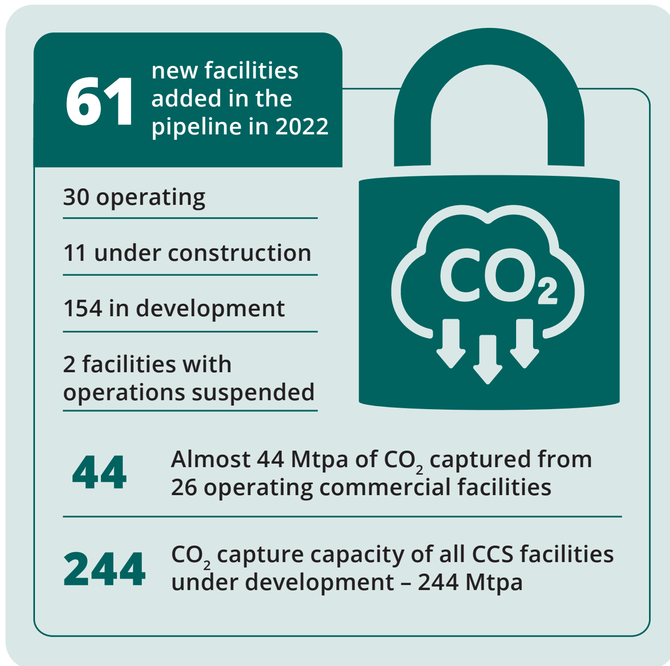
A coordinated international approach between private sector and international governments is required to overcome the most challenging barriers to the wider deployment of CCS and CDR technologies globally. Some obstacles facing the industry relate to costs and financial incentives, infrastructure, pace of the deployment and public acceptance, as well as a lack of investable and viable business models.

CDR is needed to put the 'net' into net zero, by recapturing residual CO_2 emissions and compensating for other GHG emissions from all human activities (most renewable energy options still have some GHG emissions on a full lifecycle basis, although these are likely to decline as the broader economy decarbonises). In addition, decades of inaction in tackling climate change have resulted in a period of net negative global GGR emissions being essential to avoid dangerous climate change; this can only be achieved through extensive use of CDR technologies and the CCS infrastructure to support them.

This report draws on a series of features, case studies, webinars, interviews and roundtables carried out in 2022. Throughout its development, Public Policy Projects (PPP) has consulted with senior stakeholders in the UK and international communities, with representatives of four different countries.

In the UK, PPP is grateful for the support received by the Carbon Capture & Storage Association (CCSA) in facilitating contributions from the UK clusters, including Andy Lane from Net Zero Teesside and David Parkin from HyNet. International testimonies included Brad Crabtree, Assistant Secretary for the Office of Fossil Energy and Carbon Management at the United States Department of Energy (DOE) and Iceland Ambassador to the UK H.E. Sturla Sigurjónsson. PPP is also pleased to have had contributions from frontline organisations in the private sector such as Carbon Engineering, Carbfix and Carbon Direct. The roundtable discussions were held under the Chatham House rule.

The scope of the report, which PPP carried out in partnership with Third Way, is to address barriers to wider deployment of CCS projects and issues surrounding their finance, regulation and policy.



Source: Global CCS Institute 2022 report

Chapter One

UK APPROACH TO CARBON CAPTURE

Since 2005, the UK has made numerous attempts to deploy CCS. For a variety of reasons, none of these attempts succeeded.[15] Yet, the UK is among those countries that have now seen a surge of CCS plans of deployment in recent years. Learning from previous CCS projects will prove crucial for the next wave of CCS deployment.

Progress in CCS development has been hampered by the limited disclosure of information from previous deployment studies and implemented projects, in the UK and abroad, including many of those which have received significant government support.

While some argue that, given enough time, sharing of useful information and the 'know-how' across the CCS industry is "bound to happen" eventually, a more effective and formalised approach to knowledge sharing for early projects that receive government support would substantially accelerate the rate of information exchange, reducing the possibility of cost overrun or project failure, thus enabling the CCS industry to grow faster.[16] Active learning from past successes and failures will substantially contribute to de-risking future projects, enabling the industry to scale more rapidly.

The UK's strategy on CCS is based on the 2018 Action Plan *The carbon capture usage and storage deployment pathway*. This report outlined how the government's ambition was, and still is, to drive down the costs and deploy CCS at scale during the 2030s.[17] In its *Plan for Growth*, the government then pledged to capture and store 10 million tonnes of CO_2 per year by 2030, an ambition that was then increased to between 20 and 30 million tons in the *Net Zero Strategy*.[18]

In recent years the UK government has made clear that it sees CCS as a key component of its decarbonisation plan, hoping in the long-term to capture something in the order of 50-100 million tonnes of CO_2 by 2050. Such ambition has been welcomed by the industry in the UK.

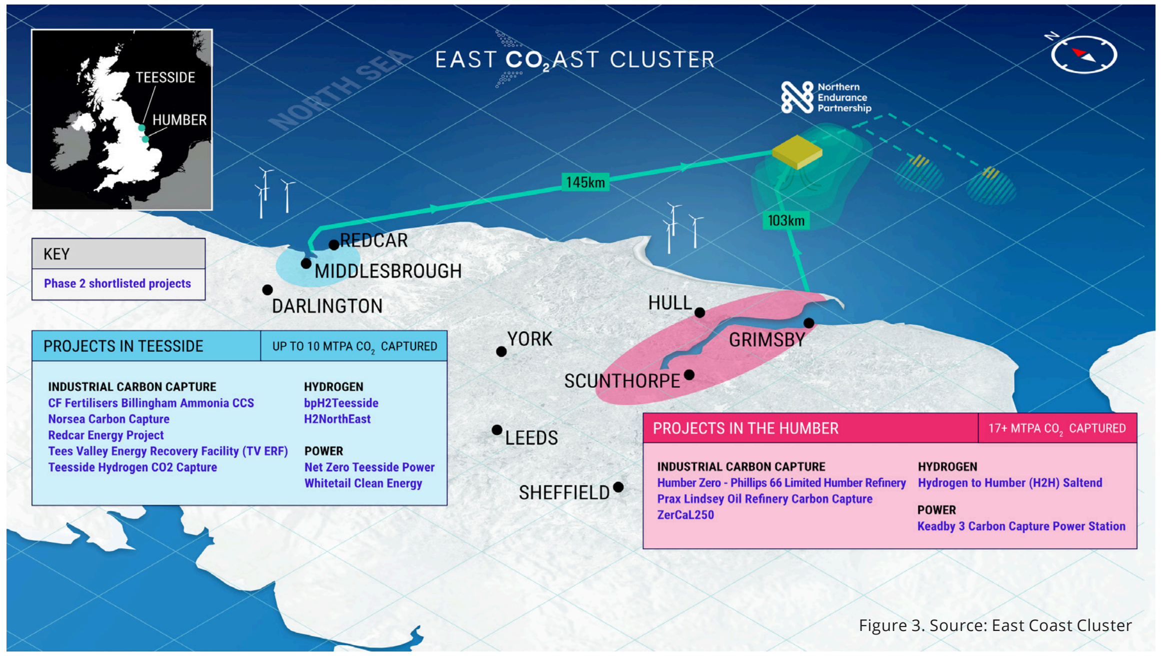


Figure 3. Source: East Coast Cluster

The first evidence session of PPP's report on carbon management explored the development and implementation of CCS in the UK. Speakers David Parkin, Project Director for HyNet and Andy Lane, Managing Director of the Net Zero Teesside and Northern Endurance Partnership (NEP), discussed the UK government's approach to decarbonising the UK's industrial heartland through integrating multiple emitters around common CO_2 transport and storage networks, as well as the challenges present and anticipated to arise with this approach.

There are currently half a dozen major industrial clusters around the UK, a number of which are located on the east coast, with two of these grouped to form the East Coast Cluster. As part of its *Net Zero Strategy*, the government fast-tracked two CCS clusters in October 2021, known as 'Track-1' clusters – the East Coast Cluster and HyNet North West.[19] The government has also selected a CCS cluster on the east coast of Scotland, The Scottish Cluster, also known as the Acorn Project, which will function as a "reserve cluster".

Andy Lane, Vice President of Carbon Capture at BP and Managing Director of NEP, commented on the UK's clusters approach, saying: "I think the UK is taking a significant lead, particularly in the concept of clustering and integrating multiple emitters around common systems of common stores". He also added that, in his role covering CCS globally, he has not seen this business model at the same level of maturity elsewhere in the world, other than in the United States, where the concept of industrial clusters is emerging using the UK as a model.[20]

However, only around 50 per cent of UK industrial emissions are located within these clusters and attendees at the PPP webinar stressed the importance for the government to mitigate the industrial emissions from dispersed sites as well.

David Parkin, who described the HyNet project as an 'ecosystem', gave an overview of the current status of the project. He argued that many organisations see HyNet as their roadmap to decarbonisation, allowing them not only to compete but to flourish in a low-carbon environment. "We do that in two ways. We do it through the production, distribution and use of low carbon hydrogen to displace natural gas and through direct emissions capture from major process emitting industries," he said.

Although the core of the project is clearly about emissions reductions, with HyNet's objective to take 10 million tonnes of carbon dioxide out of the north west, Parkin highlighted how the project will also have social and economic benefits. The benefits will relate mostly to job creation, associated with the construction and operation of the system, and job retention in high-value manufacturing jobs: "There are over 350,000 people working manufacturing in the north west, and without a route to

THE UK'S LARGEST CLUSTERS BY INDUSTRIAL EMISSIONS ONLY

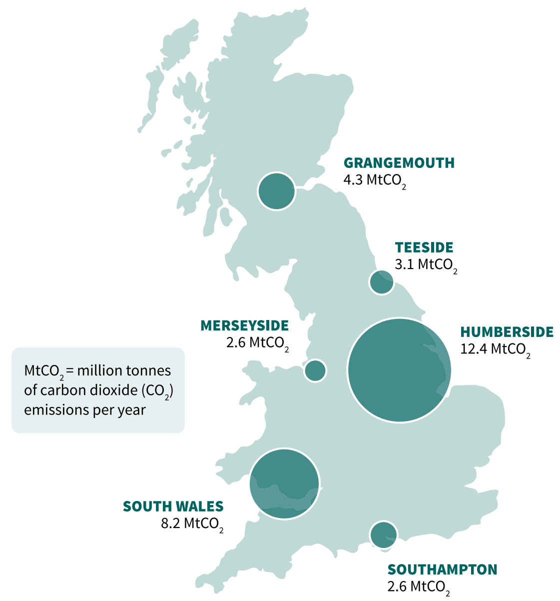


Figure 4. Source: Global CCS Institute

decarbonisation, those jobs will not exist by 2050. Net zero legislates them out of employment." Investments directed at the north west are also likely to generate spillover effects into other regions of the country. Therefore, astute deployment of CCS will contribute to overall productivity gains in the UK.[21]

CASE STUDY 1: HUMBER ZERO

Humber Zero is a world-scale project to reduce the carbon emissions of critical industry in the Immingham industrial area using carbon capture. The first phase of the project is a consortium between Phillips 66 Limited and VPI Immingham LLP and aims to remove up to 3.8 million tonnes every year by around 2027. The project intends to see an initial investment of more than £1 billion in carbon capture, with further investment intended in additional stages of the project to exceed £2 billion.

Humber Zero is supported by Innovate UK through the UK government's Industrial Strategy Challenge Fund (ISCF) including matches funding of a £12.5 million investment by the industrial partners for the current pre-construction engineering and design phase (also referred to as the 'define' phase) of the project. Each of the project's next phases are subject to obtaining certain necessary approvals and consents at certain milestones which have yet to be reached.

The Humber region is home to many industries, which are vital to support tens of thousands of local jobs, plus many more in the extended supply chain. These industries are a major contributor to both the local and national economy, supplying everyday goods from petrol to construction materials, metals and plastics, chemicals and food. The Humber region employs large numbers of people in those sectors, with around 60,000 people employed in manufacturing alone.

It is the largest industrial hub in the UK and emits more CO_2 than any other UK industrial cluster – up to 50 per cent more than the next largest cluster. By decarbonising, Humber industry would be able to remain competitive with other similar industries around the world that have also embraced decarbonisation. As a result, it would continue to thrive and support tens of thousands of jobs in the region. Humber Zero is premised on retrofitting carbon capture technology to heat and power generation and existing industrial processes. The captured carbon dioxide would be transported by pipeline to secure storage, deep under the bed of the North Sea.

At the Phillips 66 Limited Humber Refinery, carbon capture would be fitted to the Fluid Catalytic Cracker, while at the 1.2GW capacity VPI Immingham power station, two of the three gas turbines used to generate electricity would have their emissions captured.

The project is currently at the define phase and subject to certain necessary approvals and consents, will proceed to the next phase. The project intends to safeguard around 20,000 direct and indirect jobs, up to 2,500 jobs during the construction phase, and around 200 permanent roles.

Beyond the core CCS operations, there are opportunities which arise in new industrial ecosystems through the creation of supply chain businesses. Additionally, CCS deployment presents a strong business case for industry investment in the UK, due to the readily accessible option to decarbonise

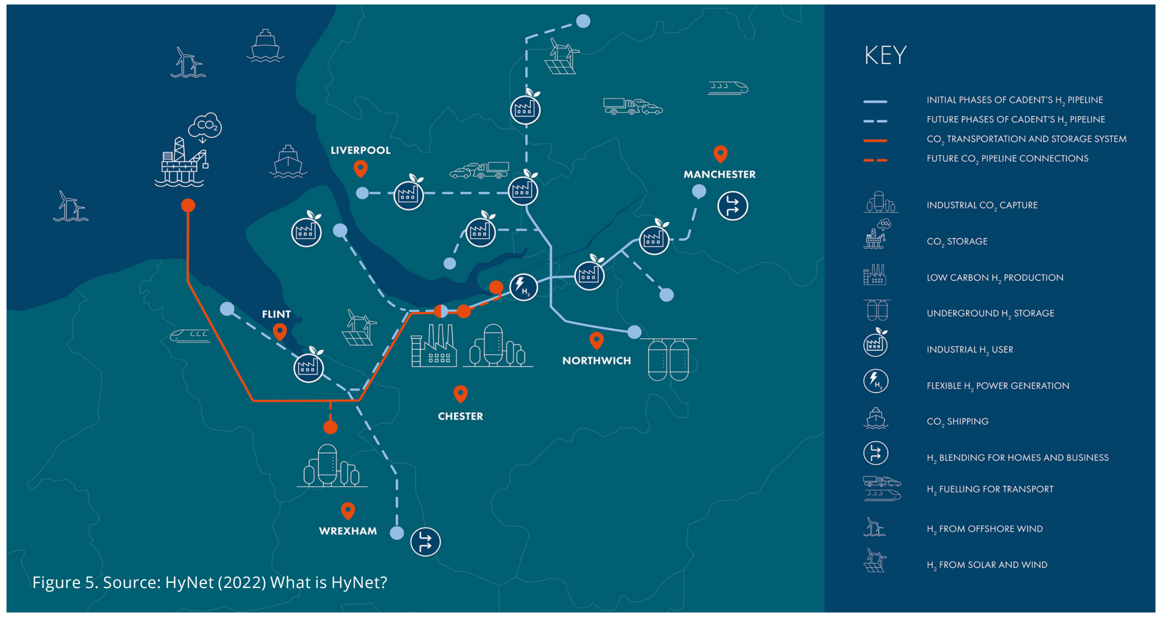


Figure 5. Source: HyNet (2022) What is HyNet?

operations. The utilisation of existing infrastructure, subsequently reducing deployment costs and environmental impacts, further bolsters these opportunities.

On the deployment, Parkin argued that if we are going to get implementation completed by 2030, processes must speed up significantly: "These projects have a long gestation period, not just from the engineering perspective, but the consenting regime which needs to go around them on the commercial frameworks."

Andy Lane spoke about the other UK industrial cluster – the East Coast Cluster. Its aim, Lane outlined, is to reduce CO_2 emissions by 50 per cent of the overall industrial cluster emissions in the UK. The Northern Endurance Partnership represents the infrastructure side of the East Coast Cluster. It is a carbon transportation and storage system that enables captured CO_2 to be safely transported and stored offshore in the Endurance reservoir. The other elements of the Cluster are all the various carbon capture projects scattered around the Teesside and Humber region.

Lane believes that the challenge now is the implementation phase, saying, "we're getting close to implementation now and business models are becoming the critical path item to executing the project."

Shipping CO_2 could also play an important role in achieving the UK government's ambition to deploy CCS projects at scale in the 2030s. It could enable the UK to decarbonise many more industrial clusters, particularly those that are not close to CO_2 storage sites. A study commissioned by the Department for Business, Energy and Industrial Strategy (BEIS) re-affirmed that CO_2 shipping costs may be lower than the equivalent CO_2 pipeline costs for lower CO_2 flow rates, longer distances and shorter project lifetimes.[22] The report also found that the main barrier to CO_2 shipping relates to regulations, port constraints and the lack of business models.

Commenting on the potential for shipping in the UK, Lane argued that, because there are many areas of the UK that are not close to available storage capacity, the next rational step forward would be for the UK to develop the ability to ship UK emissions. Although he recognises that the UK now has different priorities, he asserts that some captured European carbon will eventually be stored in the UK. However, such speculation should not take away government attention from the implementation of CCUS projects currently underway.

If the UK is to succeed in its ambition to deploy CCUS at scale in the 2030s, it's important to improve the public's acceptance and understanding of carbon management technologies and the role they play in achieving the UK's climate targets. A study carried out by the University of Manchester on public awareness of CCUS found that 61 per cent of the respondents had "never heard" of CCS, while nine per cent had "heard of it and know what it is".[23] Participants in 'Public Dialogue' research on CCS, commissioned by the BEIS, highlighted how safety, costs, feasibility and environmental impacts are the greatest areas of concern for them.[24]

The findings of HyNet's public consultations and webinars seem to confirm this trend. Although participants fully understood the need for these technologies and broadly support CCS, it is still a complex landscape for the public to understand. Parkin explained that some of the pushback came from local construction issues and infrastructure development but by engaging in those conversations, HyNet was able to not only clarify some of the issues but also to improve the engineering design.

Lane also recognised the importance of improving the public's perception and understanding: "As an industry, outreach is something we must do more of, that's because we're representing an industry that's not well understood. I think that's a duty of all members of the CCUS community."

Speaking at the roundtable, one participant stressed not only the importance of public acceptance but argued the need to go beyond that and seek public support and enthusiasm for carbon capture and removal. A key element to engendering that support will be to carefully consider environmental justice issues and to engage with frontline communities. The participant also suggested that local governments play an important role and should work with industries to help facilitate the conversations.

Another participant reflected that his experience with focus groups and public outreach suggested that the most important factor was the positive impact on local communities in terms of job creation. He also argued that we should be moving away from the narrative of CCS being safe or unsafe but frame CCS as a new employer, saying, "we need to send the message that it's a sunrise industry rather than a sunset industry".

In the private discussion, attendees of the roundtable outlined several areas of priority for the UK government, as well as barriers that will need to be overcome if the 2030 deployment target is to be reached.

One attendee expressed concern about the government's ambition, arguing that there is currently a significant gulf between the UK's long-term policy ambition and what is currently being enabled through the spending mechanism. The attendee said: "The ambition is not significant enough to accelerate the industry to where it needs to go, where it could go. And I think without that growth of short-term ambition, you will not see the economic benefits flow back into the UK."

Another attendee with first-hand knowledge of operations on the frontline emphasised the importance for the government to focus on the deployment strategy, arguing that "it's a very difficult sell to industry boards; if the supply chain can't see that regular drumbeat of new projects coming through the pipeline then they can't invest either in skills or capabilities to meet that need. We need to see the deployment strategy." The current business model is reliant on the public sector, but the private markets will be required to support CCS, with government bolstering its deployment through appropriate regulation.

It was strongly agreed by the majority of the roundtables' participants that the best way of moving the industry forward is for the government to get the initial infrastructure going. They are confident that once this first hump is passed, everything else will follow. One participant said: "Once the initial infrastructure is in place, it will make it much easier for people to come in afterwards. This will lead to a virtuous circle where the more people that connect the greater the utilisation, the lower the unit cost [and] the more attractive it is for the next people."

There was also a widespread agreement among participants of the roundtable around the need for the government to be transparent and map out the short-, medium- and long-term steps to support the supply chain. One participant said: "We're building new infrastructure at scale, which is relatively expensive, and if it's underutilised for a significant period, it's going to get very expensive. And that's not going to be the right answer for anybody."

For the UK to reach its CO_2 capturing targets, two clusters are clearly not enough, and many more projects are needed. Yet, first-of-a-kind developers face some of the greatest challenges. These can be grouped into three main areas:

- Ending up with a project concept that the Treasury will agree meets value-for-money and affordability criteria when the final decisions on government support are being made.
- Building the project on time and on budget, especially with the ongoing risk of supply chain disruptions and inflation.
- Achieving successful operation for the 15–20 year economic lifespan of the projects (and longer if possible), bearing in mind that the technologies employed have usually not been operated for anywhere near that long in previous trials, nor at such large scale.

Failures in any of the three areas for these first projects will make it much harder to obtain support for the subsequent expansion of CCS in the UK.

Overall, moving into the deployment phase and getting the infrastructure into operation were the key insights that came out of the discussions. While many welcomed the government's ever-growing targets to capture CO_2, attendees also made clear that there needs to be more transparency concerning short- and medium-term objectives to allow the supply chain to better prepare.

Private investment is pivotal in scaling up CCS infrastructure, but government's role should not be diminished. It must optimally use its policy toolbox to build strong revenue support frameworks for CCS projects and the utilisation of debt markets, thereby de-risking the costs entailed in developing CCS technology. For example, governments can mandate specialist financiers to support investors through instruments such as project finance. Strong private market support allows for approaches which are sustainable beyond political cycles, an important factor in attracting future investment.

Chapter Two

INTERNATIONAL CASE STUDIES ON CARBON CAPTURE

An increasing number of countries have committed to net zero by, or around, the middle of the 21st century. Representatives of governments have been tasked with analysing the most efficient ways to reach those targets. Carbon management technologies are often identified as an crucial part of those plans, essential in mitigating emissions from emission-intense industries. CCS features in several long-term low emissions development strategies. According to the Global CCS Institute the number of countries that are highlighting the role of CCS technologies in their national decarbonisation plans is increasing rapidly.[25]

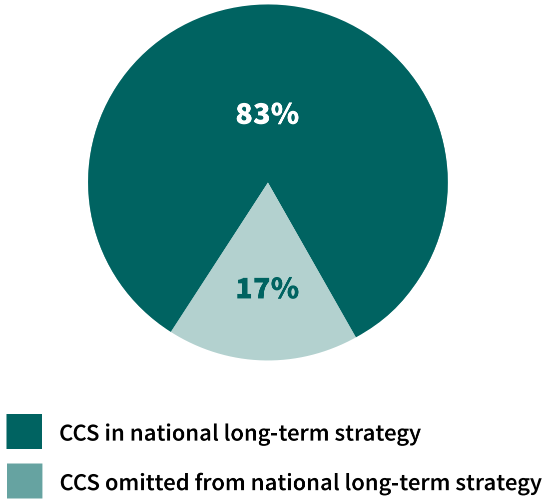


Figure 6. Source : Global CCS Institute – Global Status of CCS Report

At a global level, the history of CCS resembles, to some extent, the UK's experiences of unmet expectations and cancelled projects. However, as for the UK, recent years have witnessed a new momentum, principally driven by new business models, increasing investments and the introduction of net zero goals that see CCS as a "must have", rather than an optional extra. This boost for carbon management projects has not been limited to government policies. Companies in the private sector, such as Microsoft and United Airlines, are also investing in these technologies (in particular, engineered CDR), to meet their corporate climate targets.[26]

In 2021, there were around 40 million tonnes of CO_2 captured and stored by existing CCS projects.[27] If the world is to achieve the IEA's 'Net Zero by 2050' scenario, that number would need to rise to 1.7 billion tonnes of CO_2 by around 2030, approximately a forty-fold increase in the next eight years.[28] Despite the good progress, it's evident that a lot more needs to be done globally if the sector is to make a meaningful contribution to net zero.

In July 2022, PPP convened a webinar and roundtable with representatives of the United States, South Korea and the European Union, alongside senior stakeholders in the industry, to discuss how CCS and engineered CDR infrastructure and technologies are progressing in their respective countries, while also looking at barriers around deployment and policy.

CASE STUDY 2: SLEIPNER PROJECT

Equinor (then Statoil), an international energy company based in Norway, implemented the first industrial-scale carbon capture and storage (CCUS) project in 1996, 26 years ago. The project was developed as a solution to reduce the CO_2 contained in the natural gas extracted from the Sleipner West gas and condensate field in the North Sea. The maximum level for commercial specifications of 2.5 per cent was far exceeded, with the natural gas in the reservoir containing nine per cent CO_2. Without the Sleipner CCUS Project, the CO_2 produced would have been allowed to escape into the atmosphere. As a result, the licensees of the Sleipner West field would have been obliged to pay around $150,000 (in 1996, USD) per day in Norwegian oil and gas sector CO_2 taxes implemented in 1991.[29]

Geological storage of CO_2

On the 15th of September 1996, geological storage of CO_2 from the reservoir began. This is a process in which the CO_2 removed is reinjected 800 metres under the seabed into the saline, highly porous Utsira Sandstone Formation and trapped under a layer of sealing rock. The investments needed for compression and re-injection amounted to approximately $100 million (in 1996, USD).[30]

The Utsira Formation is estimated to be able to store up to 600 billion tonnes of CO_2, which will remain there for thousands of years.[31] As of 2022, approximately 21 million tonnes of CO_2 have been stored. As aquifer CO_2 injection was a novel process at the time of deployment, the Sleipner CO_2 monitoring programme was carried out to prove the efficacy of long-term storage. It included time-lapse seismic surveys, gravity field monitoring and marine and seabed surveys.[32]

Continued success in carbon capture and storage

After 26 years of operation, the Sleipner project has begun processing and storing CO_2 from neighbouring gas fields. It has also served as an example for numerous research networks and institutions and has provided the data used in technical articles exploring the modelling and monitoring of CO_2 monitoring.

Additionally, the successes of the Sleipner project have been adopted as industry best practice, for example, as a guide in the EU directive on geological storage of CO_2 and as a benchmark in the London Protocol and OSPAR Convention. Most notably, the IPCC reports of 2007 and 2014 have used the Sleipner CCS project as a landmark to inspire and inform action on climate change mitigation.[33]

Challenges to replicating the Sleipner Project

Since the Sleipner project's inception, a number of other CCS projects have been instigated. However, when considering replicating the project in different contexts, business models must be tailored to idiosyncratic challenges and opportunities presented along the specific value chain, especially when attempting to attract industrial companies and investors.

Exploring a site for safe storage can be potentially costly and lengthy, especially as sites must have the necessary integrity, equating to zero leakage.[34]

Informing the future of CCS projects

In June 2019, Equinor announced it would disclose datasets from the Sleipner field to advance innovation and development in the field of CO_2 storage. All data was published via the SINTEF-led CO_2 Data Share Consortium.[35] Using the experience of Sleipner, future large-scale CCS projects will focus on capturing CO_2 from onshore industrial activities and transporting and storing it in offshore saline aquifers.[36]

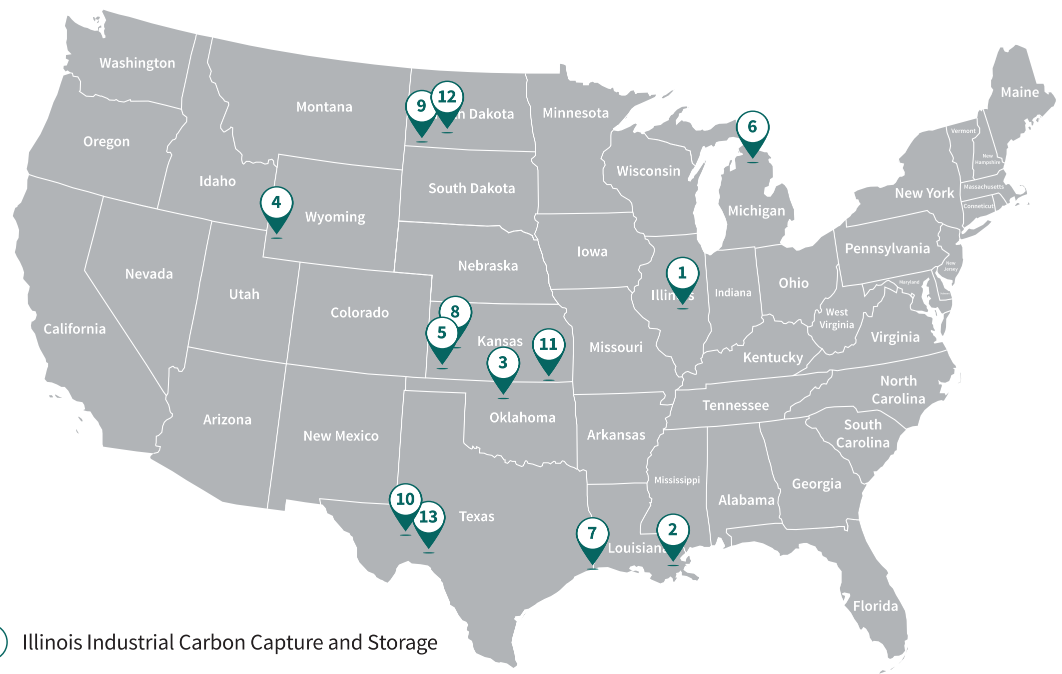
Carbon capture and removal in the United States

In the United States, the Department of Energy (DOE) has been funding research and development in several CCS-related aspects for more than two decades. The US has also been one of those countries that have helped revitalise CCS momentum globally and is currently making significant progress. In the last few years, the US Congress and the private sector have become particularly interested in carbon utilisation, "as a means to capturing CO_2 and converting it into potentially commercially viable products".[37] Such interest has led to billions of dollars in investments in carbon management.

Brad Crabtree, Assistant Secretary for the Office of Fossil Energy and Carbon Management at the DOE was representing the United States at PPP's webinar in July 2022. He defined the planned $12 billion USD investment in carbon management over five years in the Bipartisan Infrastructure Law as a "once-in-a-generation opportunity for carbon management in the US." This currently stands as the largest national investment in carbon management in the world, although the per-capita investments are lower than some European counterparts.

The $12 billion funding includes $100 million for the Carbon Capture Technology Program, up to $2.5 billion for Carbon Storage Validation and Testing, $310 million for the Carbon Utilisation Program, $3.5 billion for Regional Direct Air Capture Hubs and $115 million for the DAC Technology Prize Competition.

OVERVIEW OF CCS PROJECTS IN OPERATION IN THE US



1. Illinois Industrial Carbon Capture and Storage
2. PCS Nitrogen
3. Enid Fertilizer
4. Shute Creek
5. Core Energy CO_2-EOR
6. Arkalon
7. Air Products Port Arthur Facility
8. Bonanza BioEnergy
9. Red Trail
10. Century Plant
11. Coffeyville Plant
12. Great Plains Synfuls Plant
13. Terrell Gas Processing

Figure 7. Source: CATF

Crabtree argued that one of the most important aspects of the Infrastructure Law is that it formally places the large-scale commercial demonstration of technology under the auspices of the DOE's research and development programme. "One of the recurring themes over those 20 years, both in the United States and in Europe, was the need to expand research and development to support early commercial demonstration of technologies, and we finally broke through with the Infrastructure Law," he said.

In order to incentivise the development of CCS projects and unlock investments, Congress established the carbon dioxide sequestration credit – 45Q. This tax credit received bipartisan support and was well-received by the industry, with the Global CCS Institute claiming that 45Q is "the most progressive CCS-specific incentive globally".[38] A significant step forward in enhancing the 45Q tax credit was also made with the passing of the Inflation Reduction Act (IRA) in August 2022, which boosted support for carbon management technologies more generally.[39]

The IRA bill includes increasing government subsidies for capturing CO_2 from industry and power sources from $50 to $85 per metric tonne, where the CO_2 is stored in saline aquifers. It also increases the credit values for direct air capture (DAC) technologies to $180 per tonne for projects seeking to capture and store CO_2 in secure geologic formations, $130 per tonne for CO_2 utilisation and $130 per tonne for CO_2 stored in oil and gas fields. Commenting on the new legislation, Madelyn Morrison, External Affairs Manager at Carbon Capture Coalition said: "This legislation, coupled with the ground-breaking carbon management provisions included in the bipartisan infrastructure law, could deliver an estimated thirteen-fold increase in deployment of carbon management technologies and between 210 and 250 million metric tonnes of annual emissions reductions by 2035."[40]

There are 13 commercial-scale carbon capture projects operating in the United States today (see Figure 7), most of those in sectors that produce highly concentrated streams of CO_2 and using existing, well-proven, technologies. These new investments will help bring commercial deployment into areas such as power generation and heavy industry, where lower concentration streams of CO_2 are produced. These are typically more challenging and costly to capture and manage and require the implementation of new, or scaled up, technologies.

The Clean Air Task Force (CATF), a US-based international NGO, commissioned the Rhodium Group to look at which provisions in the infrastructure bill on carbon management were already enshrined in law, as well as those already being implemented together with this tax credit package. This was to establish what those investments would result in from a deployment standpoint. They estimated that, if the full investment potential of the bill is realised and enhanced tax incentives and federal investment into projects and technology are maximised, the US could see between 210-250 million tonnes of CO_2 captured annually by 2035.

Speaking at the PPP webinar, Crabtree also highlighted that, alongside the country's commitment to meeting the climate goals of net zero by 2050, the Biden administration is ensuring that a significant portion of the investments, up to 40 per cent, goes to disadvantaged communities. These investments will particularly focus on those communities that are proximate to the major facilities that are set to be retrofitted.

"We are taking real, measurable action to reduce traditional pollutants in communities," Crabtree added. "At the same time, we want to make sure that they have access to workforce development, job training and other opportunities so that they have the skill sets to take advantage of some of the high-wage jobs that will be created by these many projects funded under the Infrastructure Bill."

Carbon capture and removal in South Korea

Speaking at the National Assembly in October 2020, South Korean former President Moon Jae-in announced South Korea's ambition to achieve carbon neutrality by 2050. In September 2021, the country enacted the "Carbon Neutrality Act", enshrining the minimum level of mid-term national greenhouse gas emissions reduction target in law to ensure the implementation of its Nationally Determined Contribution (NDC). The legislation set into law two climate targets, to cut greenhouse gas emissions in 2030 by 35 per cent or more from the 2018 levels and to reach carbon neutrality by 2050.[41]

South Korea considers CCS technologies essential to achieve both the country's 2030 NDC and 2050 carbon neutrality goals. It aims to reduce emissions by 10.3 million tonnes through CCS by 2030. Bong-Yong Jeong, Director of South Korea's leading organisation for CCUS promotion and commercialisation, K-CCUS Association, said during a PPP webinar that most scenarios used by South Korea to determine net zero pathways contain an important role for CCUS, helping the country avoid emitting between 55 – 85 Mtpa of CO_2. Because of the important role that this technology plays in its decarbonisation plan, the country is committed to accelerating the development and demonstration of CCUS technologies.

Another important feature of South Korea's path to decarbonise is the *Green Growth Plan*, which is renewed every five years. The Plan features some key policy initiatives in relation to CCUS, such as the continued demonstration of CCUS technology, strengthening efforts to secure offshore CO_2 storage and promoting the development of CO_2 utilisation. In terms of commercialisation of CCUS and technical development, Bong-Yong set out South Korea's 2050 Carbon Neutral Strategy which relies on technological advancement and subsequent cost reduction, large-capacity storage facilities and their social acceptance and market-based incentives balanced with a regulatory approach.

Bong-Yong also stressed the importance of South Korea's CCS Demonstration Program, arguing that these projects are "critical to learning and improving the large-scale deployment of CCUS".

CCS DEMONSTRATION PROJECTS FORM THE BASIS OF TECHNOLOGICAL ADVANCEMENT AND COMMERCIALISATION

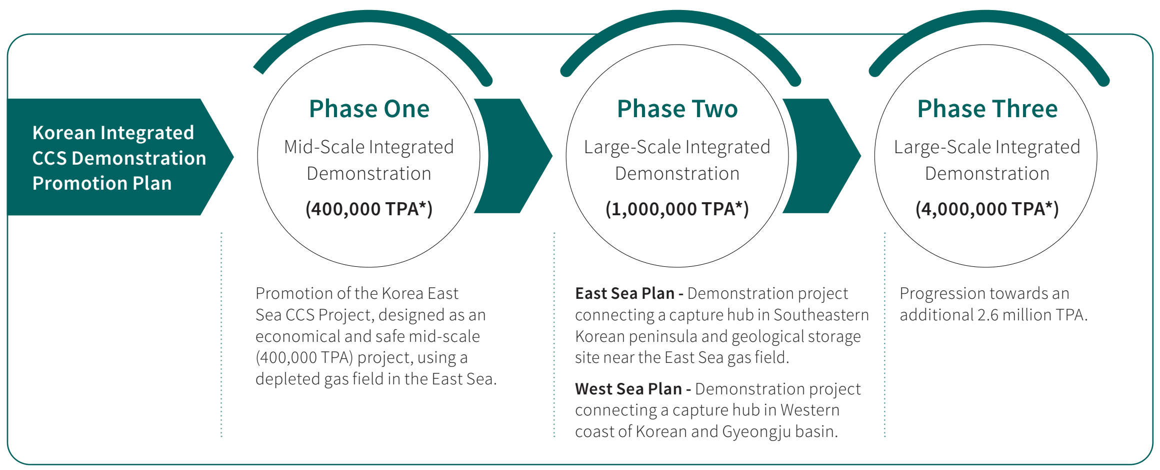


Figure 8. Source: PPP Webinar, July 2022

Bong-Yong further argued that the country is committed to creating a competitive market for the utilisation of CO_2. The objective of the CCU Roadmap is to achieve technological competitiveness through technical improvements and innovation for CCU-based products. "By 2030, it aims to form an initiative to see a product market and achieve the commercialisation of CCU technologies. The Roadmap also sets a goal of cost competitiveness by 2040," he concluded.

A key demonstration project currently underway in South Korea is the East Sea CCS Project, which is expected to inject and store 400,000 tonnes of CO_2 per year. The project aims to demonstrate the feasibility, safety and efficiency of middle-scale CCS in South Korea.

Finally, Bong-Yong touched upon the importance of having the right partnerships so that "the unnecessary barriers to CCUS are removed and the deployment can be accelerated". Earlier in 2022, South Korea and Australia launched a joint carbon capture project worth $4.7 million.[42]

The South Korean government is also working to reform various complex pieces of legislation that can apply to CCUS projects, with the objective to enact a single, integrated CCUS policy. The policy, Bong-Yong argued, will be comprehensive and aim to streamline all aspects of the CCUS value chain.

CASE STUDY 3: EAST SEA'S CCS DEMONSTRATION PROJECT

As many core technologies in CCS have similarities with exploration and production technologies in the gas and oil industry, companies in this field are at the forefront of CCS businesses. The decommissioned Donghae Gas Field in the East Sea is scheduled to end production in 2022, with the East Sea CCS Demonstration Project aiming to repurpose this offshore gas field for the storage of captured CO_2. The Korea National Oil Corporation (KNOC) is leading the mid-sized project, involving eight South Korean companies, which is supervised by the Ministry of Trade, Industry and Energy.[43]

Carbon capture and storage in South Korea's roadmap to carbon neutrality

South Korea is the ninth-biggest greenhouse gas emitter globally, producing 1.7 per cent of global CO_2 emissions.[44] As the costs of CO_2 storage often renders the concept impractical, the viability of this project is important to prove that it can significantly reduce South Korea's carbon footprint.

The South Korean government has shown its determination to develop CCS technologies as a method of coping with climate change. As such, this project is part of the government-led "multi-department large-scale CCS demonstration project and the commercialisation for CCU", of which KNOC is aiming to inject 0.4 million tonnes of CO_2 per annum into the Donghae-1 gas reservoir. The construction phase is expected to take place from 2023-2024, with operation beginning in 2025. Operation is expected to cease in 2055, with the depleted gas field eventually storing 12 million tonnes of CO_2.[45, 46]

The location for the nation's first CCS project is advantageous, as storing CO_2 will help stabilise the pressure to balance the loss of the extracted gas. Primarily, the project will collect CO_2 from industrial plants, including from the petrochemical and oil refining industries located at the other end of the pipeline in Ulsan. Upon operation, it would be South Korea's first major CCS project and could potentially become one of the biggest in the world.[47]

Overcoming concerns over cost and technology

As well as establishing the infrastructure for an all-stage CCS demonstration to capture, transport, store and monitor CO_2, the project will also support the development of practical research and development technology on how to inject, store and monitor CO_2. This is an important element for showcasing the feasibility, safety and efficiency of CCS at a mid-scale.

Carbon capture costs between $60 and $70 per tonne are expected, significantly over the $30 mark that the Korean government currently states is required to allow the technology to become more widely adopted.[48] As governments increase the penalties for companies that fail to offset pollution, storage will become more attractive. Repurposing an offshore gas platform reuses existing underwater pipelines and cuts out the expensive process of finding and developing an alternative site in the country.

Local government involvement

The Ministry of Trade, Industry and Energy has invited local governments to collectively carry out this project. However, in order to participate, local governments must secure a site for building temporary storage for the captured carbon dioxide, a facility for transportation and ancillary facilities. This may obstruct the ability for local governments to apply which could delay the project.[49]

Carbon capture and carbon removal in the EU

The EU has a clear target of reducing GHG emissions to at least 55 per cent by 2030 and eventually reaching climate neutrality by 2050.

In developing this report, PPP spoke to Emilien Gasc, Climate Attaché of the EU Delegation to the UK, about the EU's approach to carbon management. The European Union has been interested in carbon capture and carbon removal for quite some time. Yet, Gasc argued that the real watershed moment was the passing of the Climate Law in early 2020. The law introduced the concept of negative emissions, making it a mandatory objective for the EU. Following the Climate Law, the EU explained in subsequent texts its plan to promote CCS and carbon removal and reinforced its commitment to CCS deployment.

"Whatever we do in this sector must not distract from the mitigation efforts at source, and it must also do no harm to biodiversity," argued Gasc. "We will sponsor and support projects that yield the most social co-benefits, but also biodiversity," he added.

Gasc continued by setting out the EU's priorities, stating that the first one remains to reduce fossil carbon use by 95 per cent by 2050, followed by a focus on the residual five per cent by favouring recycling carbon from waste, sustainable biomass, or air. "Following those steps, we can then go full into active carbon removals, which we acknowledge will become the main focus of action after climate neutrality is achieved," he concluded.

A timeframe for EU priorities on CCUS:

- **Short-term solutions:** identify solutions for carbon farming, foster new industrial value chain for sustainable CCUS, fund demonstrators.
- **Mid-term enablers:** learn from demonstrators, create an EU framework for the certification of carbon removals based on robust accounting rules.
- **Longer-term:** further integration of carbon removals into the EU regulatory and compliance frameworks (post-2030).

In terms of storage of carbon, Gasc argued that the EU's approach is similar to other countries that are developing clusters on transportation and storage. However, CO_2 storage also represents a challenge for the EU. Europe has 300 Gt of theoretical CO_2 storage potential but it is not evenly distributed. "Another challenge relates to the level of acceptance; not every EU member state is on the same wavelength on this. Some of them are opposed to storage, others not necessarily so," he said. Gasc recognised that when creating an open market, the EU will need to acknowledge these difficulties and enable those with domestic issues around carbon storage to participate in the EU's CCUS market.

OVERVIEW OF EXISTING AND PLANNED CCUS FACILITIES

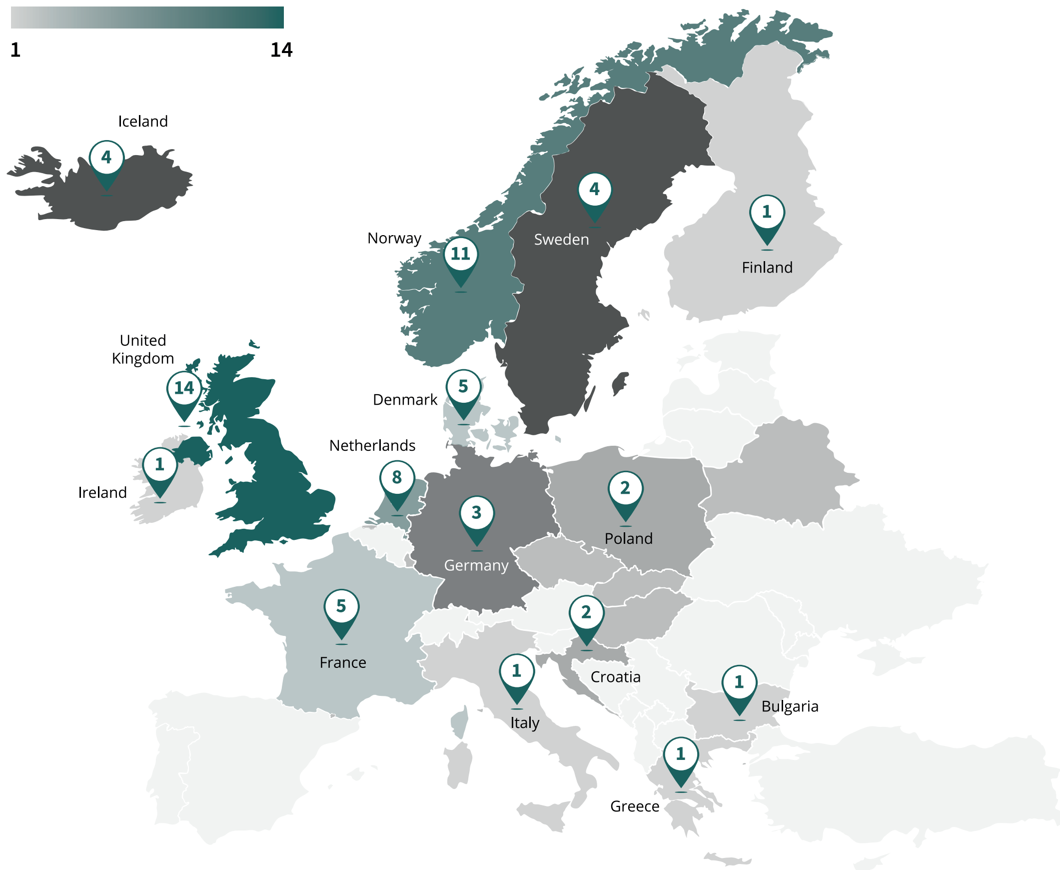


Figure 9. Source: CATF

Perhaps the biggest announcement in the EU's December 2021 paper was the notion of a regulatory framework for the certification of CO_2 removals. The EU acknowledges that "any future climate policy will need to be credible, and for this, we need reliable definitions and guarantees in terms of environmental integrity," Gasc said.

He concluded by saying that although the EU acknowledges the substantial technical challenges, it will propose an EU regulatory framework for certification of carbon removal by the end of 2022. At the same time, the EU believes that a number of viable, scalable solutions for carbon removals already exist, particularly in the agricultural sector.

Regarding supporting other countries, Gasc explained that currently, the EU's top priority is to develop its own regulatory framework, which can then be used as a benchmark for collaboration abroad. This is a similar approach that the EU has also employed with the Carbon Border Adjustment Mechanism (CBAM).

Although there is a significant gap between how much CO_2 the world is currently capturing and storing and what is required to meet the IPCC's climate targets, senior stakeholders speaking with PPP have clearly demonstrated that there is tangible and significant progress underway. Deployment of CCS and engineered CDR with permanent storage at a scale in accordance with IPCC targets can only be achieved if countries work together to share best practices and seek collaborative solutions for meeting this common goal.

CASE STUDY 4: ENI'S RAVENNA CCS HUB

Integrated energy company, Eni, is leading the development of an upstream operations and CO_2 storage hub off the coast of Ravenna, Northern Italy. Although in early development, carbon capture and storage technologies are being leveraged as an opportunity for Eni and the Italian industry to create one of the world's largest CO_2 storage centres and a leading hub in Southern Europe.

The hub is capitalising on the ideal environment provided by the Ravenna District, particularly the natural gas production assets which are characterised by the depleting fields offshore in the Adriatic Sea. However, the fundamental objective is to reduce emissions deriving from the Italian industrial sector, which was responsible for emitting 158 million tonnes of CO_2 in 2019. In particular, the project will target the hard-to-abate sectors for which there are no current efficient or cost-effective decarbonisation technologies, which currently account for 20 per cent of Italy's CO_2 emissions.[50]

A major CO_2 storage site for Ravenna

As part of the CCS Ravenna Hub, the depleted natural gas fields in the Adriatic Sea will be converted into exclusive permanent CO_2 storage sites. Eni is also developing CO_2 capture systems that use ionic liquids that are potentially more efficient than the currently used amine-based liquids. Elements of the existing infrastructure will be reused to increase the speed at which a solution can be provided for reducing emissions in the Italian industrial sector at competitive prices. Additionally, all stages of the storage process are being optimised in order to make the technology more efficient for large-scale application.[51]

More than €1.1 billion will be invested in the Ravenna Hub as part of a major regional investment plan. The development of the Ravenna Hub is expected to begin by 2023, first with an experimental program focusing on national regulatory enabling. The industrial deployment phase will be launched by 2027, with an initial captured CO_2 storage capacity of four million tonnes per year, a quarter of which will stem from Eni's activities and the remainder from third parties. The storage potential of the Adriatic offshore fields is estimated to be up to 500 million tonnes of CO_2. This allows for flexibility and further industrial expansions in alignment with increasing decarbonisation needs of both national and international industrial third-party sites.[52]

Carbon capture and storage in the energy transition

The Ravenna district provides an ideal environment for the CCS model, with existing land and sea infrastructures reducing the cost and time needed for implementation, as well as negating the need to commit new land resources. The favourable location includes transport links, connecting infrastructures such as the large industrial port and the national gas network. These features, combined with a developed industrial system and culture in the area, provide a strong foundation for a CCS project. Therefore, such a model cannot be perceived as directly translatable in all contexts. However, it demonstrates how existing oil and gas infrastructure can be repurposed to help nearby industrial sectors offset their emissions.[53]

Future carbon capture and storage development

The Ravenna CCS project is one of the international hubs that are part of the Oil and Gas Climate Initiative's CCUS KickStarter initiative to help lower costs of CCS and attract widespread commercial investment in the field.[54] The CCS technology implemented in the Ravenna area will offer substantial opportunities for the local area and surrounding companies, with the potential to create a zero-carbon industrial cluster.[55]

CASE STUDY 5: CARBFIX

Carbfix has mineralised CO_2 underground at Hellisheiði in Iceland continuously since 2012 and on a commercial scale since 2014. The CO_2 is primarily captured from a nearby geothermal power plant, since 2021 Climework's Direct Air Capture Plant, Orca, has been located at the same site. The company started out in 2006 and was formalised by four founding partners in 2007; Reykjavík Energy, the University of Iceland, CNRS in Toulouse, and the Earth Institute at Columbia University. The company's mission is to become a key instrument in tackling the climate crisis by reaching one billion tonnes of permanently stored CO_2 (1 Gt CO_2) as rapidly as possible.

Carbfix's process captures and permanently removes CO_2. It imitates and accelerates the natural processes of storing carbon in rocks as CO_2 is dissolved in water and injected into the subsurface where it interacts with reactive rock formations, such as basalts, to form stable minerals. The carbonates are stable for thousands of years, thus providing a permanent and safe carbon storage. Carbfix's carbonated water reacts with rocks underground and releases available cations such as calcium, magnesium and iron into the water stream. Over time, these elements combine with the dissolved CO_2 and form carbonates filling up the empty space (pores) within the rocks.

The timescale of this process initially surprised scientists. In the Carbfix pilot project, it was determined that at least 95 per cent of the injected CO_2 mineralises within two years, much faster than previously thought. Results from the pilot phase were published in Science in 2016, which confirmed the rapid mineralisation of the injected CO_2. The first pilot injections were carried out in 2012 at the Carbfix pilot injection site in collaboration with ON Power, located close to Hellisheidi power plant in SW-Iceland.

Following pilot operations, Carbfix upscaled the CCS operations at the Hellisheiði power plant to industrial scale, simultaneously capturing CO_2 and H_2S through a simple single-stage water scrubbing process. Since 2012, Carbfix has successfully, safely and permanently mineralised approximately 80 thousand tonnes of CO_2. The current rate of mineralisation is approximately 17 thousand tonnes annually.

For the Carbfix technology to work, three requirements must be met: favourable rocks, water, and a source of carbon dioxide. The global storage potential of CO_2, using the Carbfix technology is greater than the emissions that would result from burning all remaining fossil fuels on earth. It is estimated that Europe could theoretically store at least 4,000 billion tonnes of CO_2 in rocks, while the United States could store at least 7,500 billion tonnes.

The technology is highly cost efficient and thus, is scalable. The costs for capture, transport and storage combined have been shown to be as low as $25 USD/tonne. To be able to scale up rapidly, the legal environment needs to be favourable and evolve at the needed pace. Public awareness and acceptance are also a potential concern whenever injections into the subsurface are involved. The cost to emitters of either continuing to emit (business-as-usual) or use alternative mitigating solutions other than Carbfix determines the business case to a large degree.

Plans call for bringing emissions from the power plant down to near-zero in the coming years. Since 2017, Carbfix has worked in collaboration with Climeworks, a Swiss clean-tech company specialising in DAC technology. Climeworks developed a small DAC pilot plant (Arctic Fox) next to the Carbfix CO_2 mineral storage operations at the Hellisheiði geothermal power plant as a part of the EU funded Carbfix2 project.

Currently, Carbfix is working on the Coda Terminal project, in southwestern Iceland, a hub for CO_2 transport and mineral storage, and is the first of its kind in the world. The CO_2 will be transported to Iceland in specifically equipped ships that run on sustainable fuel and permanently stored underground as solid carbonate minerals via the Carbfix technology. At full scale, the Coda Terminal will have the capacity to annually inject about three million tonnes of CO_2 for permanent mineral storage.

Chapter Three

DELIVERING CARBON CAPTURE IN THE UK

Despite a growing pipeline since 2017, experts around the world agree that much more is required, and urgently. CCS capacity in operation today is around 44 Mt of captured carbon dioxide and, according to the IPCC, this needs to reach multiple gigatons by the middle of the century. As for the capital investment, Global CCS Institute General Manager Guloren Turan told PPP during a webinar that the Institute estimates that more than one trillion USD will be required over the next 30 years.

There was a widespread sentiment among participants that the UK government must now focus on delivery, understand the sense of urgency and meet its deadlines without causing further delays. "It's frustrating, we have set good targets with the *Net Zero Strategy*. But we are now falling down on delivery," said one participant. Previous cancellations of UK CCS projects mean that the industry will now need to reach targets at a pace that is incredibly challenging.

There are certainly legitimate concerns about delays. The UK government announced the Phase Two projects in August of 2022, several months after the decision was due. "The fact that these Phase Two projects are already delayed by six months is going to have an impact on the delivery dates. Coordination is going to get more difficult, particularly between about 2027 and 2030," said one participant of the roundtable.

Stuart Haszeldine, Professor of Carbon Capture and Storage at the University of Edinburgh told PPP that the UK also risks losing the CCS markets to Europe. He argues that while the UK "goes slow and makes it very complicated", its competitors around Europe are speeding up. There is already evidence of increased attention to CCS from several EU countries and companies. According to Haszeldine, following the Northern Lights Project in Norway, commercial developers are looking to sign 10- and 15-year-contracts with suppliers of CO_2 from around the North Sea and around the Baltic. Further evidence came in August 2022 when Denmark and Netherlands announced new cooperation on CCUS with the objective to advance CCUS development and deployment in both countries.[56]

"Every time we've done some analysis of the jobs and the financial gross domestic product value of CCS of the UK, the largest value always turns out to be the storage part," argued Haszeldine. "The UK is just not taking it seriously. BEIS knows this is something important to do, but because they're taking so long over Track 1 Projects, that's just being delayed resulting in the UK losing commercial value for CCS," he said.

Haszeldine believes that BEIS' objective to deliver CCS through competition is decreasing the competitiveness of the UK rather than increasing it, "I can understand from the very first projects, but the time for that is now disappearing rapidly. We need to get on with building because other countries will be building soon," he concluded.

The effective and timely deployment of CCS in the UK is an incredibly important growth opportunity for the government, but is a difficult problem to solve. It would place the UK as a leader and export its expertise aboard, notwithstanding the fact that the UK has intrinsic geological advantages to deploying CCS. CCS is also an important option for reconciling increased domestic fossil fuel production with future net zero targets. The UK has already approved several fossil fuels projects since COP26.[57, 58]

This seems to be consistent with a review commissioned by the government in March 2021 which found that "continued licensing for oil and gas is not inherently incompatible with the UK's climate objectives" (while also acknowledging that this "may not always be the case in future").[59] The review also recommended the introduction of a "checkpoint". The Climate Compatibility Checkpoint (CCP) was introduced as part of the North Sea Transition Deal in order "to ensure that oil and gas licences awarded are aligned with wider climate objectives, including net zero emissions by 2050, and the UK's diverse energy supply".[60]

Yet, the IEA has clearly pointed out previously that net zero will necessitate huge declines in the use of coal, oil and gas, saying "there is no need for investment in new fossil fuel supply".[61] However, the energy crisis and the current geopolitical tensions as a result of the Russia invasion of Ukraine have reopened the debate on whether or not such approach should be considered.

If the UK is to go ahead with the new oil and gas fields, Haszeldine believes that this can could create an "opportunity" for the UK. He explained that each one of these new oil and gas fields being developed could act as a global testbed for making those oil and gas fields CCS compatible through CCP placing several obligations on the construction and operation of these newly consented hydrocarbon developments (see Appendix one for details).

The industry would likely push back against such plans, Haszeldine cautioned, citing the increased costs. However, the government could make clear that this also represents an opportunity for the UK oil and gas industry to be able to sell low-carbon oilfield development around the world.

While CCS projects that are being deployed for the foreseeable future must rely almost exclusively on the support regimes that are already in place, as described in the previous chapters, in the longer-term new markets may emerge. Several stakeholders who have spoken to PPP suggested that carbon markets have the potential to significantly contribute to the global deployment of CCS. One participant of the roundtable claimed that "ever since people started talking about CCS, there's never been any financial reward for injecting CO_2 into permanent storage – that's the biggest policy gap worldwide. Finding a way through this is a critically important part of the jigsaw puzzle." This again points to the need for viable business models for sustained interest and investment in CCS.

There are two core elements of carbon markets. Firstly, it's important to design the carbon markets to make sure that the CO_2 goes to permanent disposal. Secondly, it's important to evaluate all different proposals, including subsidy, taxation and obligation.

The subsidy route, which is one currently undertaken by the UK and EU, sees governments cost-sharing and co-developing the risk and financial input into new, first-of-a-kind projects. Although this route is inevitably going to be slower and more expensive because of the need for detailed government inspections, it is seen as necessary because it gives the industry the confidence that something is being built that is likely to work. However, "if you rely on the subsidy route, it's going to be very risky meeting the net zero project target by 2050," argued one roundtable participant.

Another option is the tax route, where companies are charged to emit CO_2 and they are allowed to buy emissions trading scheme certificates to avoid the tax. However, there are significant doubts about this route, particularly in terms of environmental credibility.

According to another participant of the roundtable, as businesses work toward their ESG commitments and see where the world is heading, they are buying carbon credits that offset or reduce their emissions. However, those schemes are doing nothing at all to decrease carbon in the atmosphere, "the pace of climate change is driven exactly by the concentration of carbon dioxide in the atmosphere. So, saying that you are emitting a bit more slowly or you're emitting five per cent less doesn't do anything for climate change mitigation at all."

Meera Atreya, Senior Science Advisor at Carbon Direct, discussed during a PPP webinar in July 2022 a research that suggests that many projects in the voluntary carbon markets are of low quality and lack environmental robustness. In her presentation, Atreya spoke about voluntary carbon markets and compliance markets. She argued that, in order to scale the markets in a high-quality way, there are a few challenges that need to be overcome.

The first challenge relates to the poor quality of the credits and the lack of consensus about what is really a rigorous accounting method. The second is about certification schemes, which are currently not robust, and governance, which is currently not aligned with the science. The final challenge is the lack of assurances for scaling a high-quality supply of these credits. Overall, Atreya argued that any money spent on carbon projects should amount to a real climate benefit.

Guloren Turan, General Manager at Global CCS Institute, also spoke to PPP about carbon markets. She said that this is not just a market issue, but explained that as scaling up takes place, there need to be policies in place that will create the business case, arguing that without the policies in place, private sector finance is unlikely to come. Existing CCS projects have been predominantly financed based on either a balance sheet or the provision of government grants. As we go forward, she said, we need to come to a place where these projects will be able to stand on their own, where they would be able to attract investment from commercial banks or through various different instruments, such as bonds.

CCS credits are likely to be more expensive compared to natural-based solutions. However, according to Turan, there might be a role for them in sectoral decarbonisation, such as in the cement sector. "Companies that are not implementing CCS themselves, maybe because they're too small, could buy credits from their own industries. This could further facilitate the development and implementation of CCS in a particular industry," she said.

The quality of the carbon credits surfaced several times in the discussions as a crucial element. According to Meera Atreya, the credits that are delivering high-quality carbon removal now are those at higher costs. In her mind, the goal is to have the market represent projects that are all scientifically valid and then scale those technologies that are doing scientifically valid carbon removal and get them to a place where they become affordable.

Finally, Atreya suggested that forward purchasing and advanced market commitment is an effective means of scaling these technologies. The demand for CDR is growing very quickly, but the voluntary carbon market consists of projects with questionable quality and there are currently few carbon removal options available. She argued that carbon markets must have integrity if they are going to be driving real climate impact: "We need to build consensus on what constitutes a high-quality carbon credit in order to improve our ability to actually measure and verify this."

Helen Bray, European Policy Director at Carbon Engineering also agreed that robust certification is important for the commercial scale of these technologies. "Without robust monitoring, reporting and verification, we can't prove what we are delivering, that we are permanently removing carbon dioxide from the atmosphere," she said. Given the need to scale these technologies in a way that will costs, Helen argued that governments need to support first-of-a-kind facilities through several policy initiatives such as tax incentives. Ultimately, once robust certification is in place and the costs begin to decrease, Bray argued for an examination of how to incorporate permanent, high-integrity, carbon removal into compliance markets.

Of all the proposals mentioned in the discussions, one was mentioned repeatedly as a valid policy option: carbon takeback obligation (CTBO). CTBO is not a tax, but "an obligation put on the fossil fuels extractors and importers to dispose, safely and permanently, of a progressively rising fraction of the CO_2 generated by their activities and, crucially, the products they sell. That fraction would rise to 100 per cent by the year of net zero, 2050." [62]

Haszeldine, who supports such an obligation, acknowledged that many companies are hesitant to do that because are no carbon capture and storage projects which are operating to provide a framework of action. As a result, Haszeldine advocated a two-step process: "We first need this grant-funded set of projects which we're going through now, such as the UK clusters, to show that this can be done. But once those first-generation projects are operating by 2027, we should be transitioning out of grant funding into obligation."

A study published in 2021 by the University of Oxford and the University of Edinburgh explored the economic implications of imposing a carbon takeback obligation on the global fossil fuel industry. The study shows that "it provides an affordable and low-risk route to net zero emissions, particularly if complemented by conventional measures to reduce near-term fossil fuel demand." Commenting on that study, Haszeldine said: "Carbon takeback provides the fossil fuel industry with the strongest possible incentive to make amends: survival by becoming part of the solution, not the problem."[63]

Several roundtable participants also endorsed the CTBO, suggesting it has great potential. "The carbon takeback is hard to implement, but a very good idea. And I think starting from something small and ramping up can help build that pipeline and really get things going," one attendee said.

Another attendee of the roundtable, however, suggested it would be wiser to amend existing policy frameworks rather than create a new one: "I fear that if we put a lot of time behind the carbon takeback obligation and it's difficult to implement, we would have wasted that time. Whereas why don't we take existing policy frameworks, highlight where we can improve them and why we need to fulfil those gaps." Regarding policy frameworks, one roundtable participant argued that they can be useful to start this off, but they will not be enough to continue to their full development. Overall, although it was not indicated as the only solution, several participants of the PPP discussions spoke positively of CTBO as a tool that can play a significant role in scaling up countries' efforts to reach net zero.

Conclusion

Amid the concurrent and interlinked energy and cost of living crises, advocates for net zero targets may find themselves on the periphery of government attention. However, governments must persist in their efforts to deploy CCS as a crucial component of the net zero pathway. Further delay in starting implementation will lose irretrievable time to develop the UK's capacity for subsequent roll-outs of CCS and CDR at the scale that is essential to meet UK, and international, net zero targets.

As experts and stakeholders debate and discuss the details of deploying carbon management technologies, one thing is certain: the world needs carbon capture and removal to reach net zero and cannot fail this time around, as little time is left to restart and deploy at scale by 2050. It's important to move past debates on whether the world needs these technologies, and focus predominantly on delivering them.

The biggest risk for the timely, large-scale implementation of CCS to tackle climate change is that significant numbers of projects do not go ahead in the current wave and we fail to deliver on the scale that is necessary to make a meaningful impact. How we go about mitigating that risk is something that governments and industry leaders alike are working to understand.

Nonetheless, there are clear signs of optimism in the industry that this time CCS, and newer technologies like engineered CDR, will be deployed at scale and be able to contribute towards tackling climate change. The recent passing of the US Inflation Reduction Act (IRA) is a clear example of this. As the momentum of carbon management technologies continues to grow, so should governments' ambition. Representatives of the private sector involved in the development of this report have recognised the UK's commitment to carbon management technologies. At the same time, they have also made clear that a lot more support is necessary, particularly with first-of-kind projects.

The Climate Change Committee's 2022 Progress Report highlights that, while the UK government has a solid net zero strategy in place, there are still important policy gaps and reiterates that focus must be placed on delivery.[64] Throughout the discussions, participants of the report also urged the government to begin building the infrastructure that is needed for the wider deployment of CCUS.

The successful deployment of carbon management technologies in the UK would mean more green jobs for local communities, more private sector investment and an opportunity to become an international leader in the sector by exporting the skills and the technologies. Most importantly, it would mean that significant progress has been made in the pursuit of net zero in the UK and also demonstrated CCS to the rest of the world to help them to follow suit.

Appendix

Writing for UKCCS Research Centre, Stuart Haszeldine suggested 'CCS-Ready' obligations on the construction and operation of newly consented hydrocarbon developments.[65]

A. Installing subsea pipelines compatible with CO_2, to enable instant reuse of gas fields for CO_2 storage.

B. Planning and engineering borehole cements and tubings to be compatible with CO2 injection and Joule-Thompson cold temperatures during CO_2 refilling of depressurised gas fields.

C. Electrify operations on new offshore platforms to minimise operational emissions from gas-powered generators during hydrocarbon production and, later, CO_2 refilling.

D. Plan and build the onshore facilities of pipeline landfall from production platforms, so that conversion is easy for CO_2 tanker shipping to bring CO_2 to storage from all around the North Sea and Baltic states.

E. Mandate that the carbon embedded in the new hydrocarbons being produced is increasingly offset by storage of CO_2 at secure geological sites already being developed elsewhere in the UK. That can start at five per cent carbon per year and rise to 50 per cent embedded* carbon per year during the life (and profits) of the new fields.

*Embedded emissions are emissions in the hydrocarbons produced (Scope 3 emissions). Making that a rule for every new project makes a level field for all.

Stuart Haszeldine also argued that emissions by flaring methane and venting CO_2 from offshore platforms should stop completely as soon as possible and well before 2030, "it's a lethargic date considering the increasing climate damage caused by emissions of these gases." Despite COP26's promising targets of methane cuts, 60 per cent methane decrease from a 2015 baseline, and the good progress has been achieved in 2020 and 2021, it's still not enough, Stuart argued.

CASE STUDY LIST

CHAPTER ONE

Case study 1: Humber Zero

CHAPTER TWO

Case study 2: Sleipner Project
Case study 3: East Sea's CCS Demonstration Project
Case study 4: Eni's Ravenna CCS Hub
Case study 5: Carbfix

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