THE ROYAL SOCIETY

CLIMATE CHANGE : SCIENCE AND SOLUTIONS | BRIEFING 5

Carbon dioxide capture and storage: A route to net zero for power and industry

In brief

Carbon capture and storage (CCS) is essential for net zero emissions to be achieved in any economy using fossil fuels or releasing carbon in any other ways. Improving efficiency and decreased emissions represent a first priority.

However, for hard-to-decarbonise areas such as heavy industry, CCS may represent the last line of defence against carbon emissions. CCS is proven worldwide at industrial scales and is a reliable, secure, and auditable method of storing carbon for at least 10,000-year durations[1, 2].

INSIGHTS

- Research indicates that CCS is required in most possible routes to achieve net zero emissions[3, 4].
- CCS is a proven technology option to decarbonise the power and industry sectors.
- With more experience of deployment needed for CCS to grow, clusters of multiple capture sites, feeding CO_2 through shared pipes, or shipping, to shared storage areas, provides a way to share and reduce unit costs. CCS projects of this type are being built and planned now.
- Research on novel capture technologies promises reduced costs in the future, but such new methods can take decades to become commercial.
- As well as CCS in industry, carbon dioxide removal, including negative emissions technologies such as direct air capture with carbon storage (DACCS), can help to achieve the widely agreed goal of net zero emissions by mid-century.
- Individual countries, or groups, can subsidise CCS or tax carbon to encourage capture and storage. However, to reliably store enough carbon to balance extraction, an obligation on carbon suppliers to undertake storage could be needed[5].

1. The need for CCS – what it achieves

CCS features in most of the projected pathways to a net zero world examined by the Intergovernmental Panel on Climate Change (IPCC).

CO_2 is the dominant anthropogenic, or human-sourced, greenhouse gas (GHG) – generated by use of fossil fuels, biomass combustion, agriculture, and diffuse industrial and domestic sources. CO_2 emissions can be reduced through energy efficiency and substitution of fossil fuels by renewable or nuclear energy. However to achieve net zero emissions, any surplus emissions need to be captured and securely stored.

CCS features in most of the projected pathways to a net zero world examined by the Intergovernmental Panel on Climate Change (IPCC) where the global average temperature rise is kept to 1.5°C from a pre-industrial baseline[3]. The only exceptions are those with extraordinarily rapid decarbonisation of energy supply. In the International Energy Agency (IEA) Sustainable Development Scenario, in which net global CO_2 emissions from the energy sector fall to zero by 2070, CCS accounts for mitigation of around 5.6 billion tonnes of carbon dioxide per year by 2050 ($GtCO_2$/yr), or around 140 times the present level of 40 million tonnes per year ($MtCO_2$/yr)[6].

Definitions

CCS is defined by the IPCC as "A process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere"[3].

Carbon Capture and Use (CCU) is defined by the IPCC as a process in which "CO_2 is captured and then used as a chemical feedstock reagent to produce a new product". However, this seldom stores CO_2 for long durations. CO_2 has for example been used to manufacture of fuels, chemicals and plastics.

CO2 to EOR describes a process where CO_2 is captured and used to help produce additional oil through enhanced oil recovery (EOR).

The IEA says reaching net zero will be "virtually impossible" without CCS and the UK's Climate Change Committee has said: "CCS is a necessity, not an option"[3, 4].

CCS is the leading technology option to store emissions from four major routes:

i. **Providing electricity**
CCS can be used to decrease CO_2 emissions from coal, gas, city waste or biomass-fired power stations and to supply low-carbon electricity.

ii. **Supplying 'blue' hydrogen**
CCS can be used to decarbonise the production of hydrogen from natural gas, biomass, or coal by capture before combustion. This creates so-called 'blue hydrogen', a versatile source of low-carbon energy for industry, transport, storage, and heat.

iii. **Decarbonising industry**
CCS can capture CO_2 from industries such as oil refining, cement, iron and steel, paper, glass, and agricultural fertiliser, which together account for almost 20% of global anthropogenic CO_2 emissions[6, 7]. The oil and gas industry, whose GHG emissions (UNFCCC Scope1 and Scope2) are around 10% of the global total, is well placed to lead in developing CCS as one of a series of measures that could significantly reduce its carbon footprint[8].

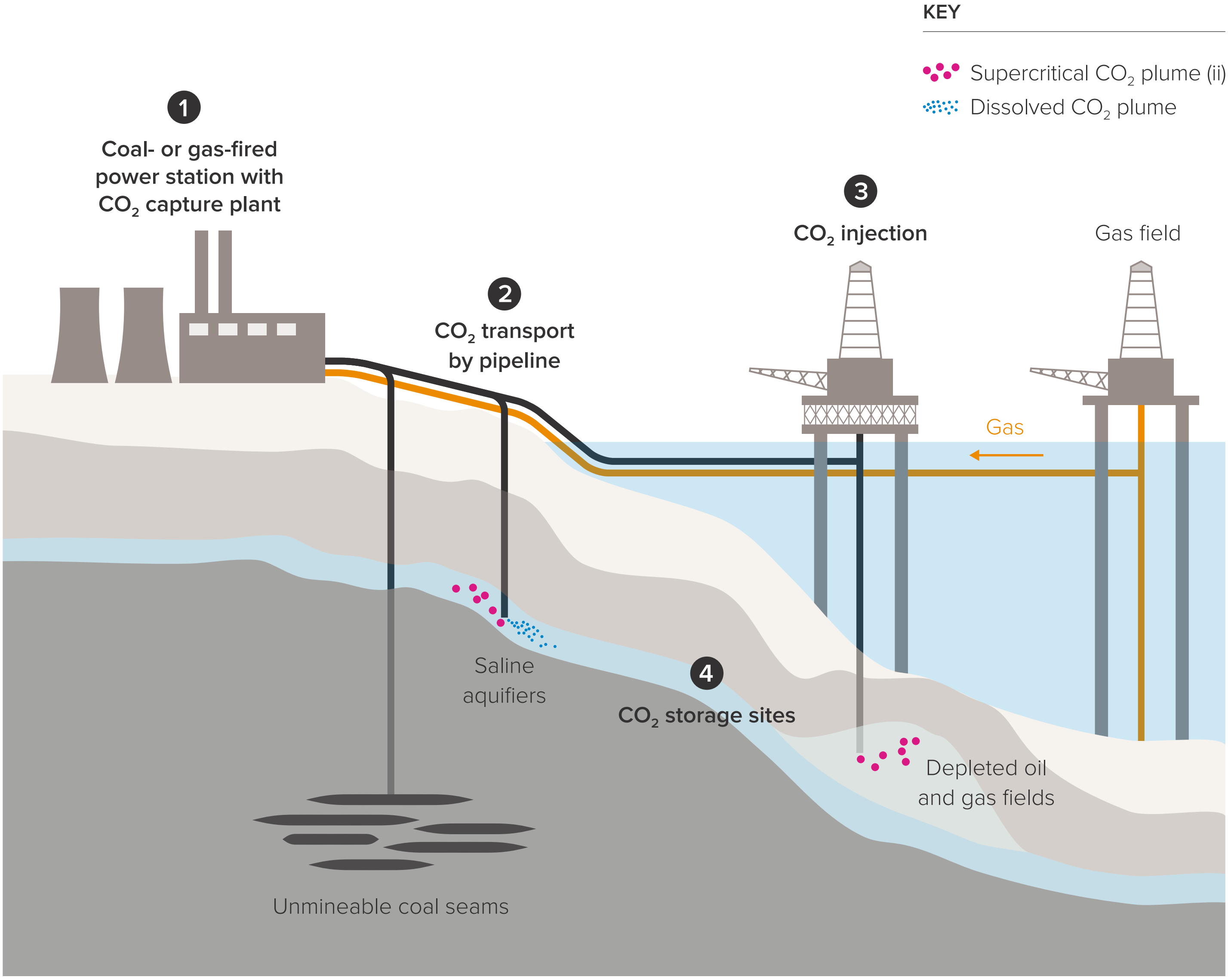
iv. **Negative emission technologies (NETs)**
NETs are technologies that remove CO_2 from the atmosphere. They include direct air carbon capture with carbon storage (DACCS), using chemical processes to capture CO_2 from the air, and bioenergy with carbon capture and storage (BECCS) which captures CO_2 from combustion or fermentation of biomass. NETs form part of a wider set of activities known as Carbon Dioxide Removal (CDR), defined by the IPCC as "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products." CDR and the even wider GGR (Greenhouse Gas Removal) also include nature-based solutions such as restoring forests and peatlands. (See briefing 9: *Climate change and land*).

2. The science and technology of CCS – how it works

CCS is not a single technology or activity, but a series of steps – capture, transport, and storage – which can be assembled in many different ways (Figure 1). Most CO_2 capture systems have been designed to capture around 85 – 95% of the CO_2 from a point source. Reaching 99 – 100% typically requires larger equipment and multiple process steps that increase costs, for example by an estimated 10% for gas-fired power stations[6].

FIGURE 1

Overview of carbon capture, transport, and storage (i)[9].



i. Diagram is not to scale. The burial of CO_2 is typically at 1 – 5km, and 50 – 300km from the coastline.

ii. Supercritical CO_2 is the natural fluid state of CO_2 at pressures deep underground.

2.1 Capture

CCS for power, industry and hydrogen can be implemented using four main technology routes:

i. **Post-combustion** – CO_2 is separated from a flue gas or exhaust stream using chemical solvents, solid adsorbents, or membranes which allow exhaust gases to pass, but capture CO_2 from the stream.

ii. **Pre-combustion** – a fuel such as natural gas or coal is converted into syngas (hydrogen, carbon monoxide and CO_2), and then via a water-gas shift reaction to a mixture of hydrogen and CO_2. The CO_2 is separated from the hydrogen by solvents, microporous solids, membranes, or other methods. The 'blue' hydrogen thus produced can be used in other processes including ammonia production, heating, and power generation.

iii. **Oxy-fuel combustion** – fuel is burned in pure oxygen (and recycled CO_2 to make flame temperatures manageable), making CO_2 easy to split from the fuel gas while water is cooled, condensed, and removed.

iv. **Separation of industrial process emissions** – emissions arise from the feedstock or process chemistry, as in natural gas processing or ethanol production, and are captured using one or more of the processes described above, or industry-specific technologies. As the capture of CO_2 is part of the core process, it is typically more economical than other methods.

2.2 Transport

Transport of CO_2 from a capture site to a store is often most economically undertaken by dedicated pipeline, transporting CO_2 as a dense fluid at pressures greater than 1000psi. Thousands of kilometres (km) of CO_2 pipeline have been operated on land in North America since 1972, and hundreds of kilometres operated subsea since 1996 for offshore gas production operations using CCS in the North Sea and Barents Sea[3, 10]. Where industries are located on coastlines or rivers, shipping tankers may be used to connect CO_2 sources to shared hubs of storage[11, 12].

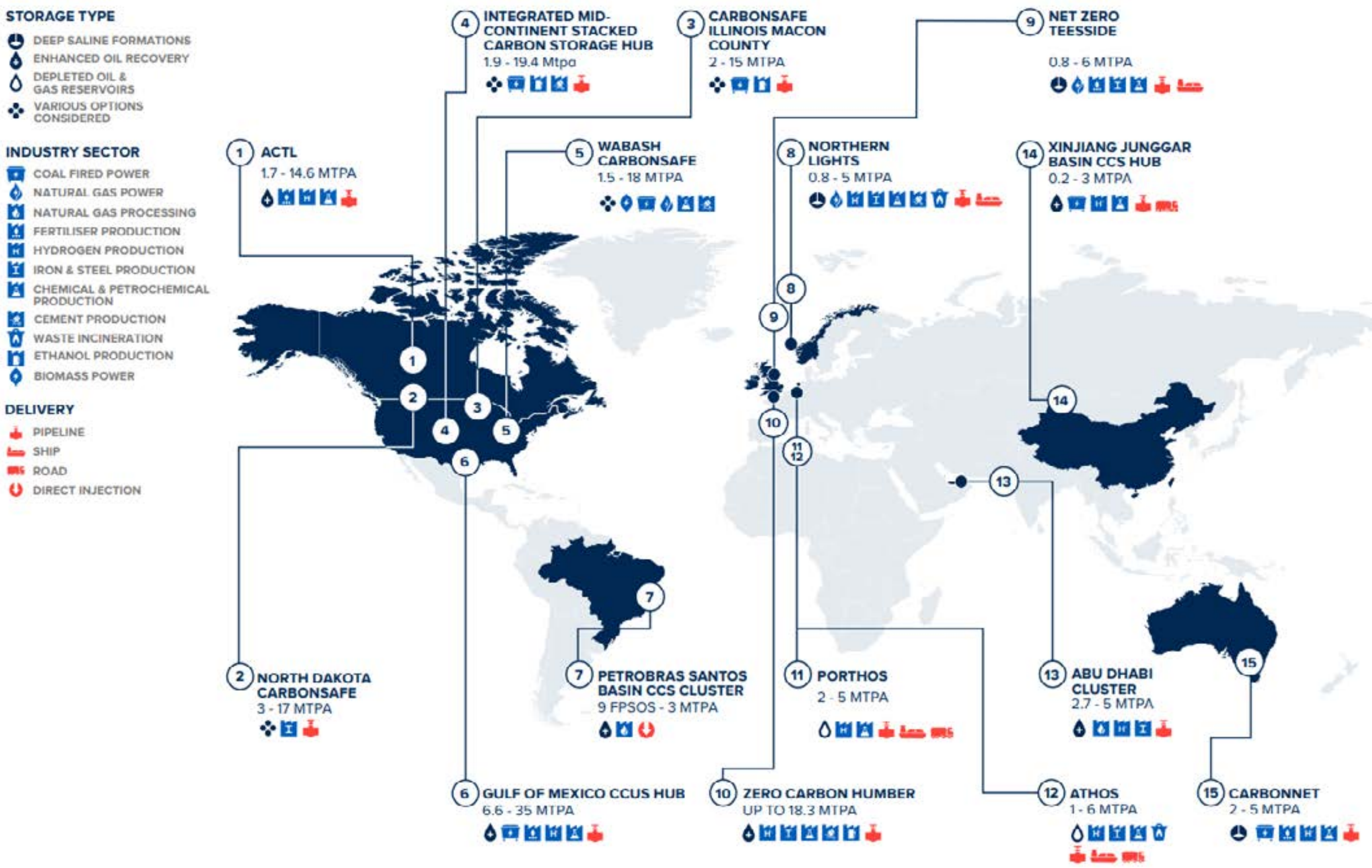
2.3 Storage

CO_2 needs to be permanently stored in carefully selected underground porous rock formations with adequate porosity, permeability, and security. Primary targets are depleted gas fields and oilfields, or saline aquifers – porous sandstone formations containing undrinkable salt water. Storage depths typically range from 1 to 5 km[1]. Risks that CO_2 will leak once injected are very small, with research showing that 98% of the CO_2 can remain trapped for 10,000 years[1, 13]. Sites are typically monitored for around 20 years to provide evidence for permanent containment[14]. When CO_2 is used for commercial EOR, most CO_2 remains stored, but the process typically produces 'new' CO_2 by way of incremental fuel production. However, if enhanced storage of CO_2 is needed for climate mitigation, additional CO_2 can be injected and safely stored in some oil and gas reservoirs, offsetting the life-cycle emissions of the oil to result in secure net storage[15].

2.4 Examples operating worldwide in industry

FIGURE 2

Clusters of CCS plants operating or in development[16].



Global capture and storage capacity is now around $40MtCO_2$/yr.

Capture operations:

CCS has been proven to be effective in industrial scale facilities across key sectors (Figure 2)[17]. As of late 2020, 26 were operating; three were under construction; 13 in advanced development, reaching front end engineering design; and 21 in early development. Global capture and storage capacity is now around $40MtCO_2$/yr[17]. Around $30Mt/CO_2$/yr is sold for EOR while around $10MtCO_2$/yr is stored geologically to mitigate climate change. By 2030, capacity is expected to have grown to around $120MtCO_2$/yr[17].

The operations now running cover a wide range of applications.

Natural gas processing uses well-established CO_2 separation technologies. Operations include Shute Creek ($7MtCO_2$/yr) and Century Plant ($5MtCO_2$/yr) in the USA as well as Gorgon ($4MtCO_2$/yr) in Australia[17].

Coal-fired power with CCS using amine solvent for post-combustion capture of CO_2 used for EOR has performed safely and effectively at two power stations: the Boundary Dam plant in Saskatchewan, Canada, since 2014[17]; and Petra Nova in Texas, since 2017. Petra Nova's operations were suspended in 2020 due to the impact of the low oil price on the EOR aspect of the project[18].

Gas-fired power with CCS has not yet been undertaken at scale, although small-scale CO_2 capture without permanent storage has been used commercially at a natural gas combined cycle plant in the US. A 'clean gas' project at Teesside, North-East England, is now proposed by a consortium of six energy companies, while two similar gas-power-CCS projects are being planned in the Humber region[19, 20].

Industrial CCS has many applications including the following:

- 'Blue' hydrogen production in the QUEST project in Alberta, Canada, uses amine solvent to capture $1MtCO_2$/yr with 99.5% purity[21]. The Port Arthur refinery in Texas, uses pressure swing adsorption to separate CO_2, leaving 99% pure hydrogen[22].
- To decarbonise cement production, which accounts for 8% of the world's CO_2 emissions, the EU Low Emissions Intensity Lime and Cement industry-research collaboration (LEILAC) has run a demonstration plant at Lixhe, Belgium, and is designing a scaled-up plant at Hannover, Germany[23].
- Norway's Longship CCS programme includes capture of CO_2 from the Brevik cement plant and a waste-to-energy facility in the Oslo-fjord region, shipping it in liquid form to an onshore terminal on the coast, from where it will be piped to storage under the North Sea by the Northern Lights project[24, 25].
- Emirates Steel Industries in Abu Dhabi, has developed the first iron and steel plant with CCS, using methane reformed to a hydrogen / carbon monoxide syngas for direct reduction of iron ore[26, 27].

Storage operations:

While much captured CO_2 is currently stored by means of enhanced oil recovery (EOR), geological storage has also been carried out and monitored to meet high performance standards for climate purposes[28]. For example, $1.7MtCO_2$/yr is stored in saline aquifers at the North Sea Sleipner and Snøhvit operations and $1MtCO_2$/yr in an onshore aquifer from the Quest project[11]. More than 12,000Gt of potential CO_2 storage resources have been identified worldwide and 400Gt have been evaluated as investable.

Technology can provide detailed monitoring of a storage site to ensure safety and compliance with local regulations. For example, time-lapse seismic reflection surveys can confirm the security and behaviour of stored CO_2 to the point where at the Sleipner storage site containing $20MtCO_2$, one metre-plus thick layers of CO_2 one kilometre below the surface can be detected[29, 30].

3. Research, development, and deployment priorities

As with many technologies, the overarching barrier to deployment is cost. The IPCC has estimated the costs of avoiding emissions through CCS (in 2015 prices) as ranging from \$20/tCO_2 for the most economical usage in gas processing and bioethanol production to \$60–140/tCO_2 for fossil fuel-fired power generation and up to nearly \$190/tCO_2 for the costliest cement application[3]. These estimates compare with an average CO_2 price of only \$2/tCO_2 across the 22% of global emissions covered by pricing in 2020[31], although prices have reached \$50/tCO_2 in the EU Emissions Trading System[32]. Industry estimates suggest that 450MtCO_2 could be captured, used, and stored with a commercial incentive as low as \$40/tCO_2 by deploying CCS on low-cost opportunities[17].

The economic challenges explain why the majority of current projects are gas processing and bioethanol operations that sell CO_2 to oil companies for EOR. For geological capture, transport, and storage to be viable, capital, and operational costs need to fall, while the carbon price needs to rise in many markets, or storage obligations need to be applied.

Many CCS technologies are proven, and studies indicate that further deployment is the main key to accelerating progress[5].

3.1 Deployment priorities

Several aspects of deployment are expected to reduce costs and facilitate new operations.

Sharing learning is a proven method of increasing learning rates and decreasing costs across an industry. For example, Shell has estimated that the QUEST project could now be built for 30% less than it was originally[33]. The Global CCS Institute (GCCSI) reports that the cost of capture fell from over \$100/tCO_2 at the Boundary Dam facility in Canada to below \$65/tCO_2 for the Petra Nova facility in the US, some three years later[17]. The GCCSI estimates that with a learning rate – the fall in costs per doubling of capacity – of 8%, CCS costs can be expected to halve by mid-century[17].

Sharing infrastructure in an industrial cluster reduces costs by common usage of pipelines or ships gathering CO_2 from several capture sites. In the UK, for example, the government has committed more than £1billion (around \$1.35billion) to help establish a series of clusters using CCS[34]. This is part of a projected 170MtCO_2/yr of storage needed to reach net zero by 2050. Such growth is comparable to, but less than the North Sea's oil and gas development, where 15,000 boreholes were drilled, and 45,000km of pipelines laid[35, 36].

Global knowledge sharing is also essential to enable rapid progress. Since many projects are supported by government, developers can be required to publish as much design and performance data as possible.

Accelerated and repeated construction is required to reduce capture costs and to improve system design. All components of the CCS chain, and several capture technologies, are already ready to deploy as pilots or at demonstrator scale, as they are at high technology readiness levels (7 – 9)[37].

Many CCS technologies are proven, and studies indicate that further deployment is the main key to accelerating progress.

3.2 Novel capture technologies

Beyond the evolution of technologies that are already being deployed, there are some novel developments which could enable step changes in cost-effectiveness over the medium to long term, such as by increasing capture efficiencies towards 99%, decreasing the energy demand of CCS equipment, or reducing installation costs.

Molten carbonate fuel cells (MCFC) use hydrogen from a fuel source such as natural gas along with CO_2 from flue gas to produce electricity, heat, and water. The captured CO_2 exits the fuel cell at a high concentration and can easily be separated.

Advanced cycles for combustion: Techniques such as calcium and chemical looping – where an oxygen carrying substance is circulated through two reactors – work to improve the basic efficiency of the CO_2 capture process through better integration with the power supply process.

Novel supercritical CO_2 (sCO_2) techniques use CO_2 at or above its critical temperature and pressure, offering potential benefits such as higher efficiency, lower capital costs and higher CO_2 capture rates. One emerging sCO_2 process attracting significant interest is the Allam-Fetvedt Cycle which creates a new type of power station. Rather than fitting a CCS unit onto a current combined cycle gas turbine (CCGT) plant, the turbine burns gas in a single operation with oxygen, with pure CO_2 becoming the working internal fluid, before capture or recycling. An Allam-Fetvedt Cycle demonstrator in Texas has reported a net efficiency of 59%, similar to a conventional gas-fired plant[38].

3.3 Storage research priorities

Injection of CO_2 into geological storage has been securely undertaken since 1972. The future challenge is to undertake storage at tonnages running into billions rather than millions of tonnes. This will require improved monitoring, including subsurface detection and use of borehole sensors. More powerful computer models have a role in tracking CO_2 movement and ensuring its retention underground.

BOX 1

The Acorn Project – demonstrating combined CCS, DACCS and hydrogen.

Scotland's planned Acorn hub has been awarded the UK's first offshore CO_2 storage licence and provides a demonstration of CCS, DACCS, and 'blue' hydrogen production. The first phase will capture around 340,000t/yr of CO_2 from the St Fergus gas terminal in Aberdeenshire. The captured CO_2 will be piped into a sandstone reservoir around 100km offshore[39]. For the second phase, a new plant will produce 'blue' hydrogen from natural gas at St Fergus, storing the CO_2, and feeding hydrogen into the national gas transmission system, initially at a level of 2% then rising to 20%, thereby reducing carbon levels. The offshore reservoir also has potential to receive additional CO_2 from other sources including industrial sites, shipped CO_2 via the port of Peterhead; DACCS from Carbon Engineering could store CO_2, share the same pipeline and undersea reservoir at a proposed facility near St Fergus developed by Pale Blue Dot Energy[40]. The project has been award £31 million by UKRI as part of the UK Industrial Decarbonisation Challenge[41].

3.4 Negative Emissions Technologies (NETs)

Negative Emissions Technologies that capture CO_2 from the atmosphere are being researched for potential future deployment as they may be required to offset hard-to-abate emissions, as well as some historical emissions. Direct air capture with carbon storage (DACCS) is being piloted in a number of small-scale operations in North America and Europe, typically using chemical processes. Costs have been estimated at between $200 and $600/tCO_2$[42]. Factors that could lower costs include improved processes resulting from rapid building and serial learning using small, modular plants directly above storage sites.

Other negative emissions technologies under study include carbon capture and use (CCU) creating building materials such as timber, straw, and cork, and also engineered products such as bricks, in ways that lock up some CO_2. Biochar is a stable, long-lived product that stores carbon in soil having been produced by pyrolysis, or burning biomass with little oxygen.

Bioenergy with CCS (BECCS) has featured prominently in climate models to achieve negative emissions as it involves crops or trees absorbing CO_2 as they grow and then being burned for power or fuel while capturing CO_2. However, its actual carbon footprint is heavily debated, given for example the carbon released in land clearance and harvesting[43]. Some experts argue BECCS could be applied sustainably, for example using sugar cane, arable grain straw or rice husks[44].

Disadvantages of conventional CCS include reliance on capturing pure CO_2 from large-scale industrial facilities. By contrast, many NET technologies can be undertaken with low purity CO_2 using small, modular equipment positioned close to storage sites. If the future cost of NETs can be kept below that of the most costly applications of CCS, then NETs may be used to offset hard-to-abate emissions. For example, if CCS at $120 t/$CO_2$ can remove 60% of emissions at a cement works but the remainder cost $300 t/$CO_2$, the operator may instead purchase CO_2 capture from air provided by a NET. This could lead to a global price cap on CO_2 capture.

BOX 2

Enhanced land weathering.

One form of enhanced weathering involves intensifying a century-old farming technique of spreading fine-grained rock dust, such as basalt, over cropland. This process accelerates a chemical reaction which removes CO_2 from the atmosphere, converting it to carbonate and bicarbonate ions which are either washed into the ocean, to increase alkalinity, or precipitated as carbonate minerals, like limestone, on land. The approach can also improve crop production, increase protection from pests and support soil fertility[45]. Small-scale field trials of rock weathering estimated the CO_2 capture in a range of 110–220g/m_2, with capture efficiency of around 60%. Basalt is available at scale, for example, produced as a waste product in mining gold, diamonds or nickel in countries such as Australia, Brazil and the US. This could provide enough material for 0.7 – 1.2 $GtCO_2$/yr of sequestration, although mining can raise some social and political challenges. Costs for removing 0.5 – 2.0 $GtCO_2$/yr have been estimated at $80 – 180/tCO_2$[46]. Pre-crushed waste rock dust is important to speed the chemical reaction rates- as high carbon energy for crushing significantly reduces the net carbon captured. Enhanced weathering requires further research and demonstration to gauge its potential.

4. Actions needed to deliver CCS – how it can grow

Three fundamental and inter-related barriers to CCS persistently surface: costs; security of storage; and regulatory frameworks.

Three fundamental and inter-related barriers to CCS persistently surface: costs; security of storage; and regulatory frameworks. These can be addressed by a combination of scientific evidence, technological innovation, and policy development. Policy frameworks are needed to help reduce costs, stimulate deployment, and provide operators with the opportunity to demonstrate secure storage.

One policy option would be to focus on research to create new technologies that represent a step change in effectiveness and cost. However, while novel approaches outlined above merit support, the pace of technology innovation and transfer to date suggests that such transformational options cannot be expected to be viable at scale until at least 2040.

Evidence suggests the main priority for progression is to deploy the available technologies more widely, with costs falling through learning-by-doing. Widespread deployment of CCS can lead not only to deep reductions in GHG emissions, but also to many benefits likely to secure public support, including high value jobs, and cleaner air.

CCS can be applied in a variety of strategies to achieve net zero. It can reduce emissions significantly in industries where process emissions occur, or fossil fuel use continues in some form, such as in gas power plants or cement manufacture. It can decarbonise energy vectors such as hydrogen for use in multiple applications. It can create a 'circular carbon economy' by re-capturing emitted CO_2 from the air. It can also act as a transition to cleaner industrial processes, such as iron making using hydrogen instead of coal, where policy-makers want to avoid locking fossil fuels into the system for the long term.

Economic policy incentives are required for CCS, especially if the investment is to pay back before being replaced by zero-carbon energy options. Initially these can be provided by subsidies, technology-based performance standards and carbon pricing through emissions trading or taxes. But additional incentives are also needed to ensure CO_2 storage is initiated. In particular, market growth can be made reliable by Government mandates that ensure that any continued CO_2 production is balanced by its storage[47].

One method of addressing both capital and operating costs of CCS is a 'Carbon Take Back Obligation' which requires producers and importers of fossil fuels to store a progressively increasing fraction of the CO_2 generated by the production, refining, transport and use of the products they sell[47]. The proportion would increase to 100% or even more to ensure that any ongoing emissions are balanced by the same quantity of carbon stored underground, reliably and for long duration.

5. Conclusion

CCS is required, especially becoming operational in the short to medium term, to fully decarbonise power generation, hydrogen production, emission-intensive industry, and other hard-to-abate activities. The present rates of CCS project construction are much too slow to create the capacity needed to fully contribute to the goal of net zero by 2050[5]. Government actions to financially support and mandate CO_2 storage are essential. A deployment-led approach for CCS is now the optimum route to accelerate progress in reducing costs and scaling up the technologies. Policies are important, but delivery during this decade is essential. For as the IPCC's projections indicate, without CCS the Paris goals are likely to be out of reach.

This briefing is one of a series looking at how science and technology can support the global effort to achieve net zero emissions and adapt to climate change. The series aims to inform policymakers around the world on 12 issues where science can inform understanding and action as each country creates its own road map to net zero by 2050.

To view the whole series, visit **royalsociety.org/climate-science-solutions**
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