Carbon Capture, Utilisation and Storage in the 2020s: Four key challenges

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The UK's independent advisory group on climate change, the Climate Change Committee (CCC), has identified Carbon Capture, Utilisation and Storage (CCUS) as a critical technology in the UK's commitment to reach net-zero emissions by 2050[1]. Carbon dioxide (CO_2) is emitted by a wide array of sources, from power generation and heavy industry, to domestic heating and private vehicles. The UK is well placed to develop a CCUS industry, given its geographically clustered emission sources, extensive pipeline networks, proximity to potential storage sites, and wealth of offshore expertise. The potential of CCUS to realise deep decarbonisation across multiple sectors has prompted a UK government push for an established and growing CCUS industry by the end of the decade, through the development of industrial clusters with CCUS, and a network for CO_2 transport and storage (T&S).

This ambition will be an immense technical and commercial undertaking that will require cutting-edge engineering solutions and a marriage of public and private finance. In many cases, technical constraints underpin commercial barriers. In this piece, we explore four of the key challenges faced by the industry over the coming decade. We discuss how understanding the barriers to broad CCUS implementation from an engineer's perspective may help to inform well-designed commercial mechanisms, and how, in developing effective business models, the UK Government must cooperate with industries along the full CCUS chain and engage with industry-specific challenges.

1. Policy frameworks to support dispatchable power generation with CCUS

The UK's evolving electricity grid is increasingly reliant on renewable power generation. Indeed, the Government's net-zero scenarios forecast that by 2030, around two-thirds of the UK's grid demand will be met by renewable technologies[2]. However, the characteristic intermittency of a grid supplied predominantly through wind and solar energy raises concerns about security of supply – concerns that are compounded by the projected increase in peak electricity demand when we account for the forthcoming electrification of transport and heat. Recently, it has been proposed that power generation through traditional combined-cycle gas turbines (CCGT) with integrated CCUS may have a role to play as a source of flexible, dispatchable power that mitigates the risks associated with the intermittency of renewables[2].

From an engineering perspective, this proposition raises a number of questions and challenges. A CCGT power station with CCUS is less efficient than one without CCUS. The result is an increase in the levelised cost of electricity (LCOE) – that is, the average net cost of electricity production over the plant's lifetime. Efficiency drops further when CCGTs with CCUS are operating outside optimal baseload conditions or are in a transient state, such as start-up or shutdown. For example, a typical post-combustion capture unit follows two process stages:

1. **Adsorption.** An amine solution is used to adsorb CO_2 from combustion gases. The amine preferentially forms a temporary bond with CO_2 molecules, and the amine-CO_2 stream is then carried to a regeneration column.

2. **Regeneration.** In the regeneration column, superheated steam is used to strip the CO_2 away from the amine and carry a rich stream of CO_2 away to be compressed and stored. The amine is then recycled to the adsorption column to adsorb more incoming CO_2.

During startup, it takes time for the steam in the regeneration column to reach a temperature at which it can break the CO_2–amine bonds. During this time, the amine remains partially or completely saturated with CO_2 and is therefore unable to bond with as much of the CO_2 in the flue gas. The uncaptured CO_2 is released into the atmosphere. The CO_2 capture rate during startup is only about 40% – much less than the 90% of steady-state operations[3]. Engineering solutions to these problems may be found. A fresh feedstock of stored amine could be used during startup and shutdown, for example, increasing the costs of amine sorbent and storage capacity but bringing the capture rate up to 60%–90%.

Employing CCGT with CCUS as a flexible dispatchable power source would likely lead to a significant proportion of plant operation taking place in suboptimal or transient conditions. With this in mind, policy mechanisms must be designed to encourage power CCUS operators to react to market conditions rather than operate at steady state – with the risk of constant optimal operation leading to a displacement of lower-carbon sources of generation such as renewables. To incentivise flexible operation, the UK Government has recently proposed a dispatchable power agreement (DPA)[4], which seeks to mitigate the risk to investors of periods of low output through payments that are decoupled from output. These payments would be subsidised by consumers and would offer a degree of revenue certainty for generators. This framework, however, is novel, and it remains to be seen whether a DPA could ensure value for money for consumers and place power CCUS behind renewables but ahead of unabated CCGT in the merit order of generation technologies.

2. Building an effective and efficient transport and storage network

The design and implementation of a CO_2 transport and storage network is an immense technical and commercial undertaking. Many technologies are used in transporting CO_2 to storage sites, including maritime and rail systems, with the most typical mode of transport being a pipeline. One of the key opportunities in developing a transport and storage network is in the leveraging of existing infrastructure, such as natural gas pipelines and offshore platforms. An extensive technical assessment would be required to establish a change-of-use case for natural gas pipelines because of the risk of failure associated with operating under different conditions. Existing oil-and-gas production platforms may well be screened for suitable reuse as CO_2 injection wells. Much of the “topside” infrastructure of older platforms could also be recommissioned, leading to significant capital expenditure savings. The reuse-of-platforms opportunity is somewhat limited, however, by the need to optimise the injection well position according to suitable geological storage sites and by the aging infrastructure of many North Sea platforms.

Designing a safe and efficient CO_2 pipeline network at the required scale presents pressing challenges. For example, major pipelines must accommodate streams of CO_2

from a wide variety of processes. Rich streams of CO_2 from different processes are likely to vary significantly in their composition, pressure, mass flow rate and fluid phase. Inconsistencies in the CO_2 stream may influence transport and storage efficiency and safety[5]. For example, non-condensable gases present in CO_2, such as hydrogen and methane, may have several adverse effects, such as the following:

- **Higher costs from reduced transport efficiency.** Non-condensables reduce stream density and generally broaden the temperature and pressure region in which both liquid and gaseous phases are present in the stream. It is far more efficient to transport CO_2 in the liquid phase than in the gaseous phase due to the increased work done in compressing much larger volumes of gas.

- **Increased risk of pipeline blockage.** Hydrates formation and corrosion from acid gas streams could lead to significant pressure drops or, in extreme cases, pipeline failure and leakage.

- **Reduced storage efficiency.** If the CO_2 plume contains high levels of impurity, much of the available pore space in the rock may be occupied by impurities rather than CO_2, lowering the trapping efficiency. This effect is compounded by the presence of any non-condensables acting to lower the density of the injectate CO_2 stream.

Therefore, to set appropriate operating envelopes of temperature and pressure, the influence of impurities on the phase behaviour of the CO_2 stream must be well understood. At present, our understanding of complex phase properties is limited, and imposing conservative constraints on CO_2 stream composition from various sources may not be feasible, particularly in a cluster where there is interaction between multiple process streams. Further understanding of the multiphase behaviour of CO_2 transport is therefore critical to the development of practicable CO_2 quality requirements for transport.

Given the risks to private T&S investors, the UK Government have proposed a CO_2 Transport and Storage Regulatory Investment Model (TRI) to support the development and operation of a UK T&S network[4]. Early developers of the network may receive a capital and operational expenditure allowance to mitigate costs in the early operational phase. Utilisation incentives, either through reward or penalty, may also be used to encourage use of the network. Also proposed, is a change-of-use relief that would remove some of the operators’ liability as they decommission oil-and-gas infrastructure for reuse in the T&S network, and a government support package for low-risk, high-impact events such as CO_2 leakage and stranded assets.

3. Fostering CCUS clusters and capturing emissions from dispersed sites

Industrial emissions account for around two percent of the UK's terrestrial carbon emissions[6] and represent one of the most difficult technical challenges in decarbonisation. For example, industries such as steel and cement production require consistent high-temperature heat, which at present can be practicably produced only through the burning of fossil fuels. CCUS can be used as a method of capturing carbon emissions from these processes. However, the dispersal of emission sources, variability in operations, and irregularity of output make designing effective business models to support industrial CCUS complex.

The challenges of dispersed sites can be overcome to some extent by fostering industrial clusters; that is, a collection of emission sources that share the same CCUS infrastructure. Clustering has been a feature of UK industry since the Industrial Revolution and the boom of textile industries across the North of England. Successful contemporary examples exist, such as Tech City UK in East London, a technology cluster, and the North East of England Process Industry Cluster, which comprises a series of co-located industrial processes in the northeast. The UK has committed to developing a series of industrial clusters, where CCUS is used to capture emissions from various emission sources within the same geographical region[7]. Development of these clusters is ongoing in areas with existing process industry infrastructure, such as the Zero Carbon Humber project in Humberside, and the South Wales Industrial Cluster in South Wales.

This strategy could lead to a more rapid uptake of CCUS in the UK, as the prospect of creating co-dependent CCUS industries lessens risk for infrastructure owners. Clusters also promote carbon abatement in industries that otherwise do not emit enough CO_2 to justify dedicated CCUS infrastructure. Inevitably, however, some emission sites will be located outside the catchment of proposed clusters. The commercial risks of CO_2 transport from these dispersed sites are much greater than for clustered sites, with higher capital costs to develop transport infrastructure, operational costs for different modes of transport across greater distances and limited opportunity to benefit from economies of scale.

Ultimately, the key barrier to uptake of CCUS in the industry is a lack of incentive to implement costly and complex CCUS solutions that are so far unproven across most carbon-intensive industries. A commercial mechanism such as a contract for difference (CFD) could help in this regard, by providing more certainty in the cost savings available from reducing emissions: a CFD sets a strike price and the emitter is paid the difference between the market price of CO_2 and the strike price, if the strike price exceeds the market price. Such measures might run in parallel with a carbon tax on imports via a carbon border adjustment. This would help ensure that the UK's low-carbon industry is not displaced by cheaper, carbon-intensive imports from abroad.

Designing any support scheme, across multiple industries is non-trivial, given the heterogeneous nature of industrial emissions and the non-uniform way in which the cost to emitters is likely to be distributed. One possible strategy may be to develop fully integrated clusters, with each industry cluster owned and operated by only one group of stakeholders. This, however, presents challenges in aligning industries that have no, or only a limited, heritage of cooperation and that may operate under different models of costing, process safety and commercial ethos. Successful coordination of these industries may be critical to the development of CCUS clusters.

It is also difficult to predict how demand for CCUS within a cluster may evolve with time. For example, hydrogen can be produced by reforming natural gas into hydrogen and CO_2. The CO_2 can then be sequestered. Given that hydrogen has the potential to be a major source of energy in the coming decades, hydrogen production is a prime candidate for CCUS clustering. However, hydrogen can also be produced by electrolysis of water, where water is separated into hydrogen and oxygen using electrical potential. At present, electrolysis is more expensive than natural gas reforming, but with electrolyser technology rapidly developing, this may not always be the case. The risk of displacement or redundancy of a critical process in the CCUS chain, leading to low utilisation, may well be a further barrier to investment.

It has been proposed that the T&S infrastructure could be operated using a service-based business model: one company would manage the handling of CO_2 and charge emitters a fee for the service[4]. The handling company would assume the costs and risks of CO_2 transport and could be supported by government in the early stages of operation. This model could also support the development of a pan-European market for T&S services in which UK-based companies would be key providers, lowering the risk of poor infrastructure utilisation.

4. Realising negative-emissions technologies

One of cornerstones of the UK's net-zero commitment is the direct removal of greenhouse gases from the atmosphere using negative-emissions technologies (NETs)[1]. Even with deep decarbonisation throughout the UK, there will be residual greenhouse gas emissions from hard-to-decarbonise sectors, such as steel and cement production and some chemical production, as well as from smaller emitters from distributed sources. These emissions must then be offset by direct removal of greenhouse gases from the atmosphere. The CCC projects that these technologies may offset around 50 $MtCO_2$/yr by 2050, primarily through Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC)[1].

BECCS is the process of utilising energy from biomass with integrated CCUS. Given that bioenergy is theoretically carbon neutral without CCUS, capturing and storing CO_2 from bioenergy production has the net effect of removing carbon emissions from the atmosphere. BECCS will primarily be applied to power generation through combustion of biomass and biofuel production through the conversion of biomass to ethanol. The technology has the potential to remove up to 50 $MtCO_2$/yr by 2050 but at present is in the pre-commercial stage[1].

One of the biggest challenges in scaling BECCS is the development of supply chains for biomass feedstock. If we are to meet targeted emissions removal through BECCS, the production and import of biomass feedstock will likely double by 2040[8]. The carbon intensity of the process should also account for the carbon intensity in the production and distribution of biomass feedstock. A full lifecycle analysis of BECCS, which would include carbon emissions from land clearance, biomass production, and distribution, would be necessary to establish the full carbon negativity of BECCS. This will require further work to understand the potentially carbon-positive effect of harvesting different forms of biomass, and accounting for these effects in an accurate and a consistent way. Other technical issues can arise due to the quality of biomass as a combustion feedstock. Combustion of biomass leads to a lower-quality flue gas versus conventional power generation and a subsequent energy penalty at the capture stage, leading to a higher LCOE compared to conventional power CCUS. Further government support may well be required to ensure commercial viability while the technology matures.

DAC is the process of removing CO_2 directly from ambient air. This is done by passing air through a unit where CO_2 is absorbed or adsorbed by a sorbent material, which can be a solid or liquid. The concentration of CO_2 in air is very low, which makes the separation difficult; therefore, strongly binding sorbent agents are necessary. This process is generally associated with high regeneration temperatures because it takes a lot of energy to break CO_2-sorbent bonds when the sorbent is strongly binding. This leads to a large energy demand and associated cost in CO_2 removal: current estimates place the cost of DAC at around 150–300 £/tCO_2[9]. Currently the carbon price is around 45 £/tnCO_2, deriving little economic incentive for DAC. However, the carbon price is set to rise, and the technology is developing. With new sorbent materials that can regenerate at lower temperatures and economies of scale in the future, the price of DAC may fall significantly. Innovation in this space is being supported by the Department of Business, Energy and Industrial Strategy, which has recently announced the Direct Air Capture and Greenhouse Gas Removal Innovation Program. This program will aim to support NETs that have the potential to remove CO_2 from the atmosphere at less than 200 £/tCO_2[10]. The Government should continue to support this innovation and could look to subsidise target industries by bridging the gap between the cost of DAC and the carbon price, in order to stimulate the development and early uptake of DAC.

Conclusions

The UK, with offshore expertise and close proximity to an array of potential storage sites, is well placed to develop a CCUS industry as a centre for capture technology innovation. The challenges in scaling the industry, as with most industries, lie primarily in the cost of developing and operating the necessary infrastructure. Technical innovation through improved capture technologies and modelling of transport and storage will be important in mitigating these costs. The UK Government can support the industry through practicable business models that incentivise investment and by continuing to support innovation. The proposed CCUS clusters around the UK suggest that by the end of the decade, CCUS could be an established and growing industry. Although the detailed picture is not yet clear and technical challenges will persist, the role of CCUS in the UK's road to net zero is becoming increasingly well defined.

Contacts

We recently teamed up with Patrick Mortimer, PhD student at the University of Cambridge, to understand some of the most pertinent challenges in the CCUS space from a technical perspective. For more information about the topics discussed in this paper, contact:

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