

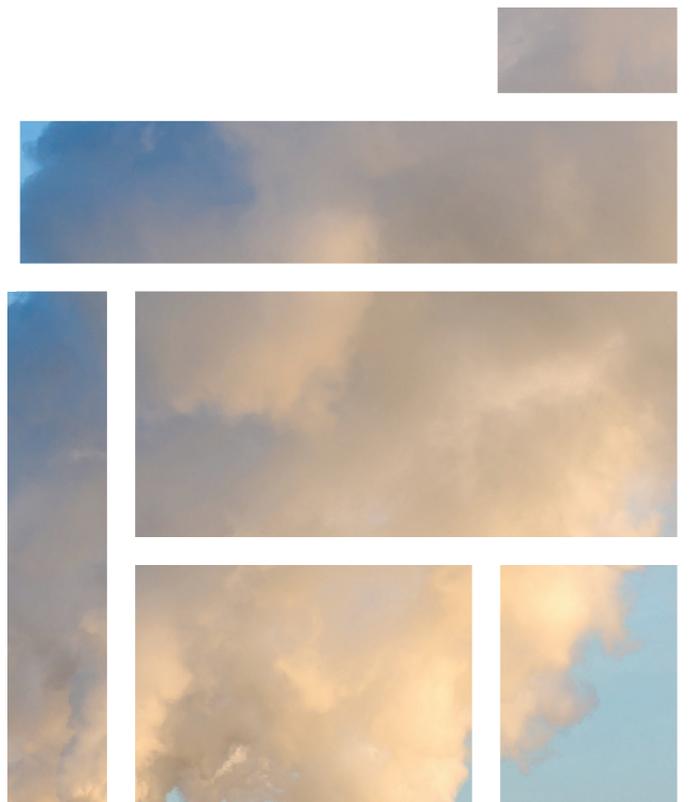
A Chemical Engineering Perspective on the Challenges and Opportunities of Delivering Carbon Capture and Storage at Commercial Scale

The development of this report was led by the **IChemE Energy Centre Carbon Capture, Utilisation and Storage Task Group.**

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Executive summary

1. In the context of the 2015 United Nations Climate Change Conference Paris Agreement to limit global warming to well below 2°C relative to pre-industrial levels, most environmental models and forecasts agree that carbon capture and storage (CCS) is an essential technology for lowering greenhouse gas emissions to the level needed to meet this commitment. In many models the early inclusion of CCS in the global energy system also provides the lowest-cost routes to a low-carbon economy. Despite this the deployment of CCS is currently limited to 37 projects worldwide, with 18 operational and the remainder in earlier stages of development. Collectively these facilities store 31 Mt of carbon dioxide (CO₂) pa, only a fraction of the rate estimated to be necessary to stay within this 2°C scenario (2DS), ~10 Gt pa by 2050. This report presents a chemical engineering perspective on how to implement CCS at the scale and rate required to meet global decarbonisation targets, considering the commercial approaches required to support its effective deployment.
2. CCS technologies are ready for widespread global deployment at scale, whose safety and environmental risks can be reliably managed to low, acceptable levels. CCS has been field-tested by large-scale demonstrators and some commercial projects for over 20 years. This report also explores the application of CCS across sectors and regions, highlighting areas where it can play a significant role in decarbonising the global economy.
3. CCS has a crucial role to play in mitigating CO₂ emissions in many global industries. For the industrial manufacturing sector whose emissions represent over 20% of total anthropogenic CO₂ emissions globally CCS offers a readily-deployable cost-effective decarbonisation solution, where cost-competitive alternatives are not currently available in many cases. Energy-intensive industries in which the emission of CO₂ is an inherent part of the production process, such as cement or iron and steel, dominate industrial emissions; here CCS presently represents the only realistic option. CCS, combined with process efficiency optimisation, should be a priority for industrial plants, and chemical engineers in collaboration with industry and government should develop the required policies, regulation, incentives and technologies to decarbonise this sector by 2050.
4. Hydrogen gas, alongside ground-source heat pumps, is now seen as a leading contender to decarbonise domestic and commercial heating sectors that, in many regions are currently fuelled by carbon-intensive natural gas. CCS enables the large-scale production of low-carbon hydrogen from fossil fuels through mechanisms such as steam methane reforming of natural gas. The viability of this approach should be investigated at large scale and would be a strong driver for the commercialisation of CCS.
5. Meeting the Paris Agreement targets will likely depend on a significant contribution from negative emissions technologies which remove CO₂ from the atmosphere. One of the few candidates deployable at the level required to make this contribution is bioenergy with CCS (BECCS). It is anticipated that demand for BECCS will increase rapidly through the 2030s which in turn necessitates significant growth in CCS infrastructure in the 2020s. It will be important that the negative emissions delivered by BECCS are properly valued and incentivised to ensure the use of biomass is sustainable.
6. Where there is a mechanism to monetise the storage of CO₂, through its use in enhanced oil recovery (EOR) or where realistic carbon pricing exists (through emissions taxes or an effective carbon trading system) the deployment of CCS can be market driven, and the application of CCS for EOR has been widely adapted commercially. EOR can result in the net storage of up to 80% of the CO₂ injected if it is operated to maximise CO₂ storage rather than oil/gas recovery and the avoidance of emissions from recovery of more carbon-intensive new reserves is accounted for. However, EOR is not a panacea as it is not effective for all depleted oil and gas reservoirs.
7. Carbon dioxide utilisation (CDU) is clearly of interest in repurposing CO₂ as a relatively low-cost potential feedstock. Several studies indicate that CDU is unlikely to make a major contribution to decreases in anthropogenic CO₂ emissions at the rate required to stay within the 2DS, which for carbon-capture related technologies is estimated to be around 10 Gt of CO₂ per annum by 2050. The global CDU industry currently utilises in the region of 0.2 Gt CO₂ per annum, of which only 25% of the products can be considered to sequester CO₂ long-term. Whilst it will have an important role in promoting wider principles of resource efficiency and developing the circular economy, it should be considered separately from CCS regarding its potential contribution to meeting the Paris Agreement targets.
8. Widespread commercial deployment of CCS is contingent on a range of political, economic and technical conditions being met, which vary across regions and industries. This report identifies these conditions, analyses the current blocks to commercialisation of CCS and makes recommendations for policymakers, investors and industry on how these might be overcome. It is written from a chemical engineering perspective and identifies the key contributions and insights that chemical engineers can bring to creating a global CCS industry. Whilst there is a focus on the UK, EU and to some extent the US, particularly regarding policy and commercial issues, the report attempts to reach beyond these to give a global perspective on the key issues and how they can be addressed.

Chemical engineers can expect to play a significant role to play in the development of a CCS industry in many areas:

9. Systems analyses for each country/region are required to determine the potential role and impact of CCS on their current and future energy systems. Energy roadmaps for each region must employ a whole-systems approach to consider how CCS can integrate with different power sources, industrial plants and existing carbon capture, transport and storage infrastructure. In this context the role of CCS is not to defer or slow down the rate of development and introduction of renewable energy sources. It can be deployed alongside energy efficiency, demand reduction, and other low-carbon energy sources to provide the fastest and least-cost approaches for mitigation of dangerous climate change. Fossil fuel power plants fitted with CCS can provide the low-carbon base-load supply or load-balancing capability needed to cope with the intermittency of renewables, providing flexibility and facilitating the optimum use of renewables across daily and seasonal fluctuations. They are not mutually exclusive competitors but complementary companions within an integrated energy system.

10. An integrated process systems engineering approach is also needed to optimise the design of CCS networks on regional, national and international levels. Considering the entire CCS chain (encompassing capture, transport, storage and measurement, monitoring and verification of storage sites) can help to identify both optimal technical solutions and appropriate commercial models.

11. In the short-term, the costs of CCS can be reduced to competitive levels through multi-plant large-scale (>1 Mt CO₂ pa) deployment of CCS plants; by exploiting the economies of scale, the efficiency learnings from the delivery of successive installations and the consequent reductions in the cost of capital. There is evidence that electricity prices associated with CCS-enabled power plants can be driven down by around a third after several have been built. In the medium- to long-term, continuing innovation and development of future CCS technology (especially for capture which currently represents up to 80% of the total CCS cost) and alternative storage mechanisms are required to continue to drive down costs and improve process efficiency.

12. The capacity and integrity of CO₂ storage infrastructure must also be clearly established by exploration and characterisation of suitable geological structures and the installation of long-term monitoring. Chemical engineers should also encourage broader thinking on high-capacity CO₂ sequestration such as accelerated carbonation to solid materials by, for example, injection into deep, hot basalt formations.

The establishment of a global CCS industry will also require a partnership between policy makers, industry, finance sectors and a range of other stakeholders throughout the economy. To develop the CCS sector, the following key recommendations and observations need to be built into future policy and commercial processes:

13. Establish effective carbon pricing, through a carbon tax or an effective carbon permit trading system. Given the key role that almost all integrated climate assessment models now demonstrate for CCS in meeting the challenging COP21 targets, we strongly recommend that governments seek regional and international agreements to introduce financial mechanisms to make it cheaper to avoid CO₂ emissions than release it to the atmosphere. As the cost of implementing CCS varies across industries, carbon prices should be sector specific as they are in Norway. Such carbon pricing systems should also look to minimise the potential for 'carbon leakage'. This leakage occurs when carbon-intensive producers shift activities to regions with lower carbon costs, moving the location of the emissions source without reducing their magnitude.

14. Develop new commercial approaches for CCS to reduce costs and risks faced by participants at all stages of the CCS cycle. This can be achieved by a combination of several essential elements:

- a. *Stable enabling policy frameworks*, which identify and implement policy drivers for CCS in terms of incentives and regulation, in particular mechanisms to make investments in CCS financially feasible.
- b. *New business models* based on sharing of risks and costs between public and private sector stakeholders. For example, consideration might be given to decoupling CO₂ capture investments from the CO₂ transport and storage elements which could be provided by a publicly backed and funded infrastructure provider. By transferring the risks of CO₂ transport and storage to the public sector, including long-term storage risks, investments in CO₂ capture would become more attractive and feasible and lower the cost of capital. The commercial arrangements between the infrastructure provider and the users should include the ability of the users to transfer CCS costs to its consumers and the availability of value-for-money market support mechanisms.
- c. *Shared transport and storage infrastructure development*, into which a wide range of diverse CO₂ generators can feed, is a high priority. Optimising the connectivity between CO₂ sources and sinks and clear specifications (eg impurity intolerance) for transport and storage of CO₂ streams are key aspects of increasing CCS process efficiency and reducing costs.

15. There is an urgent need for those involved in CCS development and implementation to engage in a meaningful, evidence-based dialogue with policy-makers, the public and other stakeholders such as NGOs. The sector needs to listen to concerns (for example around excess capital costs, health, safety and environment, and the impact of CCS on the deployment of alternative decarbonisation technologies), understand and respond with solutions and present clearly information on the risks and opportunities to ensure that decisions on the role of CCS in local communities are reached objectively.

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