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 (CO_2) 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 CO_2 emissions in many global industries. For the industrial manufacturing sector whose emissions represent over 20% of total anthropogenic CO_2 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 CO_2 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* CO_2 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 CO_2, 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 CO_2 injected if it is operated to maximise CO_2 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 CO_2 as a relatively low-cost potential feedstock. Several studies indicate that CDU is unlikely to make a major contribution to decreases in anthropogenic CO_2 emissions at the rate required to stay within the 2DS, which for carbon-capture related technologies is estimated to be around 10 Gt of CO_2 per annum by 2050. The global CDU industry currently utilises in the region of 0.2 Gt CO_2 per annum, of which only 25% of the products can be considered to sequester CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 capture investments from the CO_2 transport and storage elements which could be provided by a publicly backed and funded infrastructure provider. By transferring the risks of CO_2 transport and storage to the public sector, including long-term storage risks, investments in CO_2 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 CO_2 generators can feed, is a high priority. Optimising the connectivity between CO_2 sources and sinks and clear specifications (eg impurity intolerance) for transport and storage of CO_2 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.

Contents

1. CCS – an essential carbon mitigation strategy

This a briefing paper is produced by the IChemE Energy Centre. It seeks to give a chemical engineering perspective on key issues concerning the changing energy landscape over the decades ahead. It addresses the issues surrounding the large-scale introduction of carbon capture and storage (CCS) to prevent the release of carbon dioxide (CO_2) into the atmosphere. The paper explores the technical, commercial and policy situation for CCS globally and identifies challenges and opportunities facing chemical engineers playing their part in making the large-scale deployment of CCS a commercial reality.

In 2015 the 21st session of the Conference of Parties (COP21) convened by the United Nations Framework Convention on Climate Change (UNFCCC) resulted in an agreement by 196 nations to limit global temperature rise to well below 2°C compared to pre-industrial levels. This is necessary to avoid unacceptable damage to the earth's natural environment and all its inhabitants. Many models and scenarios have assessed how best to achieve this aim whilst ensuring the energy needs of society are not compromised. After accounting for alternative decarbonisation strategies such as energy efficiency improvements and an increase in low-carbon energy sources, most integrated assessment models (IAMs) still envisage the need to use CCS to mitigate the remaining emissions by capturing CO_2 from burning of fossil fuels and industrial processes[1,2] (*Figure 1*). In fact, its early inclusion in energy portfolios provides the lowest cost routes to decarbonisation. Widespread deployment of large-scale CCS is therefore highly likely to be an essential component in achieving agreed carbon mitigation targets.

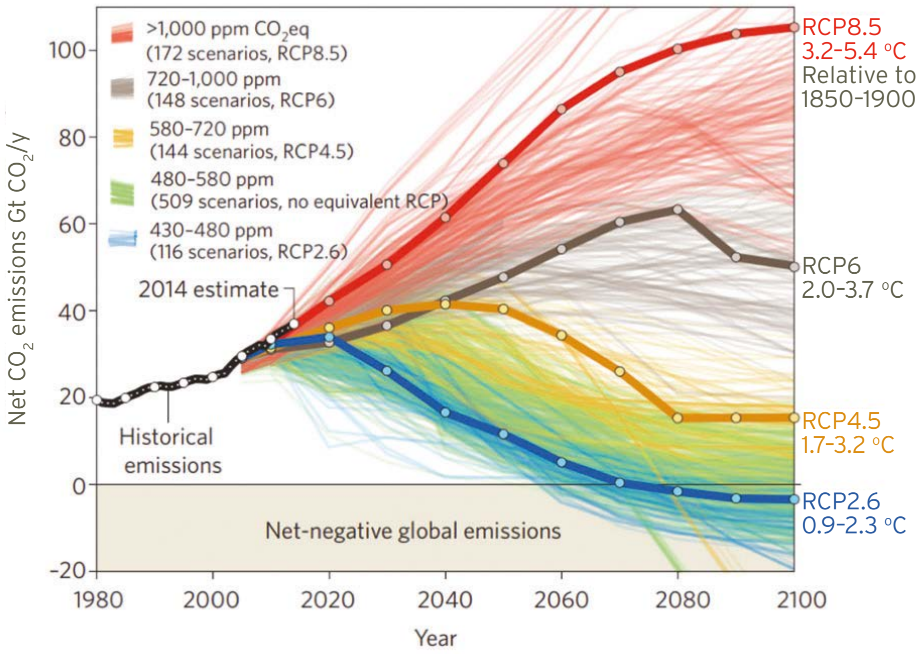

Figure 1[3]: Predictions of CCS integrated assessment models (IAMs) of future CO_2 emissions for a wide range of energy mix scenarios to achieve different mean global temperature rises relative to 1859–1900. Without CCS, less than 50% of the IAMs achieve the COP21 target of 1.5–2.0°C and these are on average 138% more expensive than those which incorporate CCS.

The deployment of CCS at large scale is currently limited to just under 40 projects worldwide at varying stages of development (from planning to operation), that cumulatively store a fraction of the 10 Gt CO_2 pa IAMs estimate will need to be captured by 2050. This report identifies the political, economic and technical conditions required for the widespread commercial deployment of CCS; it analyses the current blocks to CCS commercialisation and makes recommendations for policymakers and investors 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, this report attempts to reach beyond these to give a global perspective on the key issues and how they can be addressed.

2. CCS – a tried and tested technology

Chemical engineers play a fundamental role in the development and application of CCS technologies and the research that underpins them. The "technology readiness levels" (TRL) system qualitatively assesses the maturity of technologies through the different stages of the research and development (R&D) process. Of the different CCS technologies at varying stages of development (*Figure 2*) most are at the pilot plant stage (TRL 6) or above. It is important to recognise that although a technology has been demonstrated at lab or pilot scale, this does not necessarily imply that the technology has commercial relevance. Also, successfully reaching a TRL stage does not indicate that the technology is capable of moving to the next stage.

There are a number of technologies for capture, transport and storage that are readily deployable at commercial scale (TRL9), which in this context is defined as capturing over 0.4 Mt CO_2 pa. Several other technologies that can reduce costs and increase efficiency are at TRL7–8 and most should, in time, move to TRL9. Therefore, all the elements of the CCS chain are in place for commercial deployment and their safety and operability has been confirmed in a significant number of demonstrator and commercial operations. The range of examples given in this section aims to demonstrate that the barriers to widespread large-scale deployment of CCS are not technical and the potential for future cost reductions through alternative technologies with improving TRL stages is good.

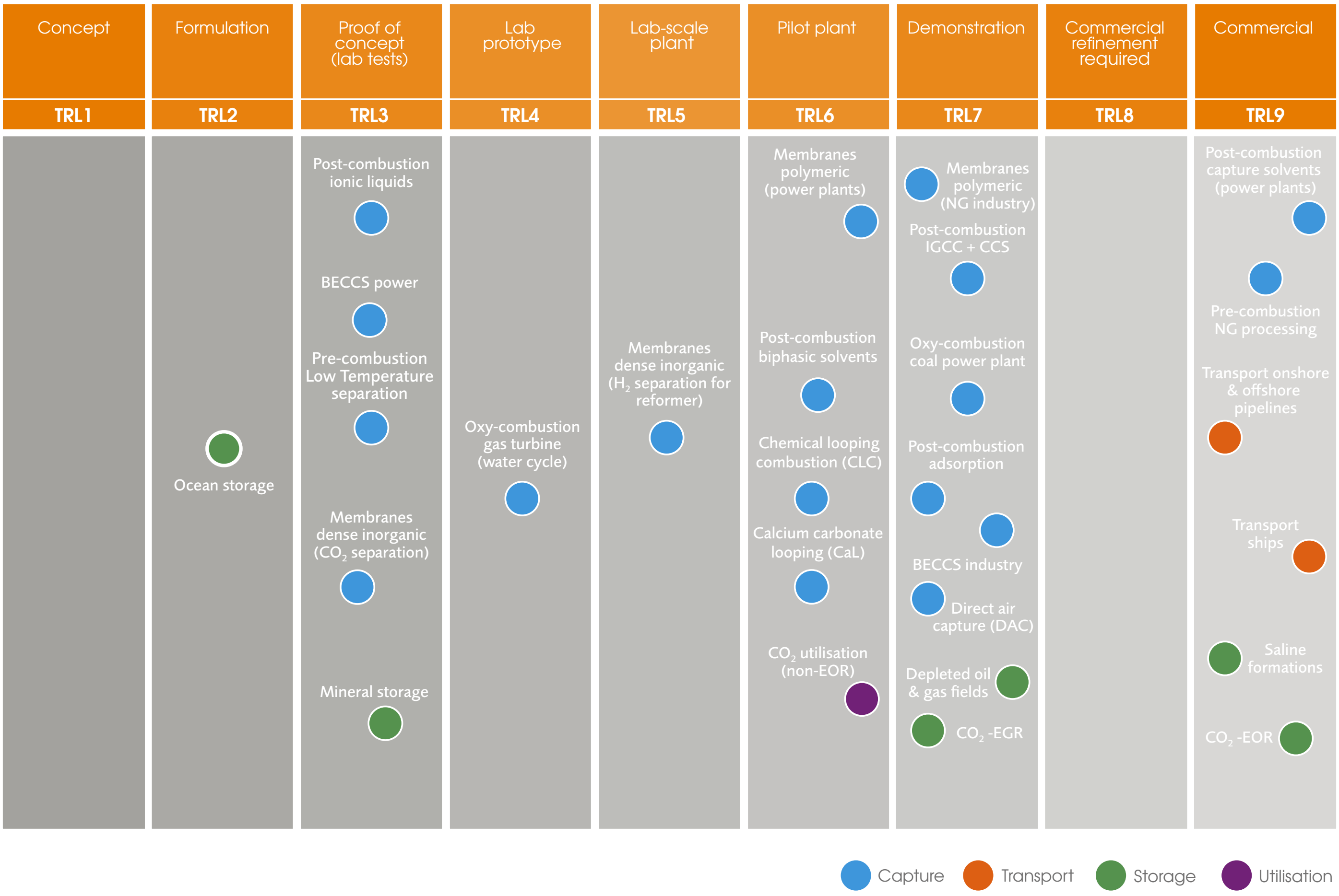

Figure 2[4]. Current development progress of carbon capture, storage and utilisation technologies in terms of technology readiness level (TRL). BECCS = Bioenergy with CCS, EGR = enhanced gas recovery, EOR = enhanced oil recovery, NG = natural gas. This list is not intended to be exhaustive. TRL is allocated based on a specific application (eg in power plants, industrial process) which has been indicated where appropriate.

At the time of writing, 37 large-scale commercial (projects that capture over 0.4 Mt CO_2 pa) CCS projects are in operation, under construction or in development planning globally (*Figure 3*) with a current collective capacity of about 35 Mt CO_2 pa. Most are either subsidised in some way often having been developed as technology or CCS-chain demonstrators. Capturing CO_2 in the power sector typically increases costs by around 45–70% (not including transport and storage) depending on the capture technology used, region and plant fuel and design[5]. Although these costs will come down with increased deployment at scale and technology improvements, in the absence of a 'cost of carbon' (eg through a carbon tax or trading systems) or other mechanisms to monetise CO_2, such as enhanced oil recovery (EOR), the financial impetus for installation is not clear. Consequently, the current deployment of CCS is limited.

The majority of CCS projects, and the largest proportion of projects operating commercially, are in the US. All except one of these projects involve EOR accompanying primary CO_2 storage. The US also has projects with the largest CO_2 capture capacity including the natural gas processing facilities at Century Plant, Texas, and Shute Creek, Wyoming, whose capacities are 8.4 Mt pa and 7 Mt pa respectively. The world's first CO_2 injection for long-term sub-surface storage was the Sleipner project, offshore Norway (where a carbon tax has been in place since 1991, currently about £54 per t CO_2 for petroleum and natural gas production), started in 1996, capturing CO_2 from natural gas with amine solvents, and storing at a rate 1 Mt pa in the highly monitored Utsira deep saline reservoir.

Canada was the first country to deploy CCS on a commercial power station at the Boundary Dam facility in 2014, driven by EOR applications in the nearby Weyburn oilfield. Early teething problems with cost overruns and maintaining the CO_2 capture rate have been overcome and illustrate how crucial learning from these large-scale projects is for future developments. In January 2017, the commercial Petra Nova facility in Texas also came online. It captures 94% of the CO_2 in the treated gas stream at the Parish coal-fired power station. The Gorgon LNG Project in Australia has commenced LNG production and it is expected that the initial subterranean injection of CO_2 will commence before the end of 2019[6].

China has eight CCS sites in development. The country is developing these facilities as it responds to growing energy demand through continuing use of fossil fuels whilst also working to reduce its considerable carbon footprint.

Figure 3. Large-scale integrated CCS projects under development or operational around the world and lifecycle stage. Circle size is proportional to the CO_2 capture capacity of the project (million tonnes per annum, Mt pa). Data from the Global CCS Institute.

2.1 Carbon capture

With current technologies, the costs of the carbon capture stage can represent up to 80% of the total CCS chain costs. This is therefore the most promising area for lowering the overall CCS cost through technical innovation and development. Whilst some capture technologies are quite mature (TRL9), having been deployed in the chemical industry for many years in addition to use in CCS demonstrators and even commercial projects, further development and deployment of more efficient, large-scale carbon capture technologies with lower energy consumption[a] is an area where chemical engineers can make major contributions to the future commercial viability of CCS.

The different CCS technologies can be incorporated into three basic types of capture process: (i) post-combustion capture, where CO_2 is removed from flue gas, leaving behind the nitrogen and other minor components; (ii) oxyfuel combustion where fuel is burned with oxygen in a stream of recycled CO_2 this makes the capture of CO_2 easier, but requires an air separation plant to provide the oxygen; (iii) pre-combustion capture, as in an integrated gasification combined cycle (IGCC) power plant in which the fuel is gasified to CO, CO_2 and H_2 and the CO_2 captured before the H_2 or syngas (CO + H_2) is burned in a gas turbine[7]. The IGCC system combines chemical processing with power generation and has higher capital costs; however it has the benefits of producing H_2 as a valuable by-product[8].

Post-combustion capture can be assessed at TRL 9 since it has been applied for many years on a variety of scales in chemical manufacturing, including methanol production (where captured CO_2 is used to adjust the carbon: hydrogen ratio in methanol synthesis gas), and in urea production, where the captured CO_2 is a principal feedstock[9]. CO_2 capture from natural gas has also been applied for many years[10] and can be adapted for use on natural gas combined cycle (NGCC) power plants (ie from high pressure natural gas to low pressure flue gas application)[11].

Chemical absorption (eg using amines) has been used to remove CO_2 from natural gas for decades[12] and is also utilised in two commercial-scale post-combustion capture facilities on coal-fired power plants (Boundary Dam and Petra Nova)[13,14,15]. If CCS eventually operates at the 10 Gt pa scale globally, there will be a huge demand for chemical solvents such as amines like monoethanolamine (MEA) and its derivatives. A typical treatment plant may, depending on the contaminants contained in the stream being treated, need a new inventory of solvent every 1–2 years due to amine degradation and solvent losses, further accentuating potential future demand. Amines are particularly sensitive to flue gas contaminants such as sulfur oxides (SO_x), nitrogen oxides (NO_x) and fly ash, thus flue gas pre-treatment may be required to minimise solvent degradation[16]. Supply limitations or health and safety concerns about amine degradation products may necessitate the development of new alternative solvents, or the use of aqueous ammonia solvents which have been demonstrated at plants in Europe and Northern America[17].

Recent developments in polymeric membrane technology have enabled them to move to commercial status at TRL 8. The commercially-available Polaris™ membrane has been used for CO_2 separation from syngas[18]. A polymeric membrane developed at the Norwegian University of Science and Technology (NTNU) is now being applied to coal-fired power plants and other combustion processes[19].

Capture technologies that have reached demonstration level (TRL 7) such as oxy-combustion coal power plants and a range of post-combustion adsorption technologies could also potentially reach commercial status in the near future. Physical adsorption separation methods have the potential to be lower cost and more energy efficient than chemical solvent methods in situations where gas streams are pressurised and/or contain high concentrations of CO_2. Industrial manufacturing facilities that produce higher concentrations of CO_2, could benefit from cost reductions by using these methods, as could IGCC power plants. Other promising technologies at earlier development stages include chemical looping combustion (CLC)[20]. This technology captures CO_2 from power plants where the carbon-based fuel undergoes combustion through a redox reaction with a solid oxygen carrier (usually a metal oxide).

2.2 Carbon transport

CO_2 transport and injection has been practised at scale for enhanced oil recovery (EOR) since the 1970s[21,22]. The technologies for CO_2 transport are well established, with over 6,500 km of CO_2 pipelines worldwide (both on-shore and off-shore), mostly in the US[23]. The technology for CO_2 transport using ships is also applied commercially at TRL9 and is generally a cost-effective transport method where transport distances are longer, and quantities are lower[24]. There is no fundamental engineering or scientific reason why, provided the quality/composition of the CO_2 stream is carefully managed, national and regional CO_2 transport infrastructures could not be built.

The effect of a range of impurities in captured CO_2 such as O_2, NO_x, CO and H_2S, needs to be taken into account for both health and safety and pipeline corrosion issues,

[a] The energy required to release the captured CO_2 from the solvent or adsorbate in order that it can be transported and stored. For power CCS this is provided by the power plant and so is unavailable for transmission. This is a major cost of the capture stage and so reducing the energy consumption can have a major impact on overall CCS costs.

as well as to meet reservoir injection specifications. However, water content is the single most critical issue, having the greatest impact both on the process design and the equipment metallurgy. These impacts can be classified as either direct, such as the possible formation of CO_2 hydrates at low temperatures[25] or indirect, such as the corrosion potential (for example of carbon steel pipeline material), and second tier impacts, such as NO_x-SO_x reactions leading to the deposition of elemental sulfur[26] or low pH corrosion issues. No specific maximum water content has been recommended for transportation applications, but it is accepted that at <50 ppmv the impacts are minimal. Key chemical engineering issues linking the capture-transport-storage stages of CCS are providing specifications for transport and storage of CO_2 streams and optimal processes to achieve them.

Long-distance transportation should ideally be at pressures that keep the CO_2 comfortably in the dense (supercritical fluid) phase to maximise the injected fluid density while simultaneously optimising fluid injection (low viscosity). Optimising the connectivity between CO_2 sources and sinks through a systems analysis of the source-pipeline-sink network is a key aspect of increasing CCS process efficiency and reducing costs. Connecting sources and sinks can involve significant transportation costs.

Remote emissions sources, well away from proposed storage sites, have the option of CO_2 transportation by road, rail or ship which each pose a unique set of challenges. These may be used for demonstration projects before larger-scale implementation precipitates a need for more long-lived infrastructure, such as a pipeline network and hubs.

2.3 Carbon storage

The most established storage process in terms of capacity and proven technical feasibility is subsurface geological sequestration. The global distribution and capacity of CO_2 storage locations are reasonably well characterised with estimates of global CO_2 storage capacity of approximately 11,000 Gt CO_2, equivalent to approximately four times the maximum estimated cumulative storage required by the end of this century. Of this, approximately 1,000 Gt CO_2 capacity is provided by oil and gas reservoirs with another 9,000–10,000 Gt CO_2 capacity provided by deep saline aquifers[27]. Whilst storage infrastructure is relatively well characterised in areas with significant demonstrator project activity such as the UK, EU and North America, this is not yet the case in other parts of the world such as the Asia Pacific, where less progress has been made on CCS.

Of 17 operational commercial-scale CCS projects, 13 use CO_2-EOR, so there is significant experience and knowledge of this type of operation. Deep saline aquifers have also been used for CO_2 storage at commercial-scale projects both on-shore (Quest in Canada and Illinois Industrial CCS in US) and off-shore (Sleipner and Snøhvit, Norway)[28]. This option requires extensive and costly up-front sub-surface characterisation and appraisal whereas reservoir geology is already well understood when using existing sites like depleted hydrocarbon reservoirs. In contrast, CO_2 storage by enhanced gas recovery (EGR)[29] is still in the demonstration phase (not yet implemented at commercial scale, thus TRL7), with ocean and mineral storage[30] at even earlier stages of their technological lifecycle. Other storage options with potential for EGR include shale gas reservoirs, gas hydrate sediments and coal seams, where CO_2 can be used for enhanced methane recovery (ECBM in the case of coal bed methane)[31,32]. An interesting development for the future is the accelerated mineralisation of CO_2 to carbonates by injection into deep basalt rock[33]. A pilot-scale plant using mineral carbonisation to convert CO_2 to marketable building products has been established in New South Wales, Australia[34]. Development of this and other more robust mineralisation/storage routes for CO_2 represents an interesting challenge for chemical engineers.

> "There is no fundamental engineering or scientific reason why, provided the quality/composition of the CO_2 stream is carefully managed, national and regional CO_2 transport infrastructures could not be built."

2.4. Technical opportunities and challenges – reducing costs and improving process efficiency

The growth of a viable global CCS industry will bring many challenges and opportunities for engineers over the next few decades. Strong chemical engineering input across the TRL spectrum will be needed, from development of the enabling technologies, through integration of these into viable, optimised capture-transport-storage systems, to identification of appropriate business models and implementing integrated commercially-viable CCS projects at large-scale. Successful commercialisation of CCS requires identification of opportunities to minimise costs and maximise the benefits and value it brings in to the decarbonisation of the energy system. A cradle-to-grave systems approach is needed across the CCS chain from the CO_2 source process to the storage reservoir and its long-term monitoring – applying a core competence of chemical engineers to an extremely complex system of remotely-connected processes (*Figure 5*).

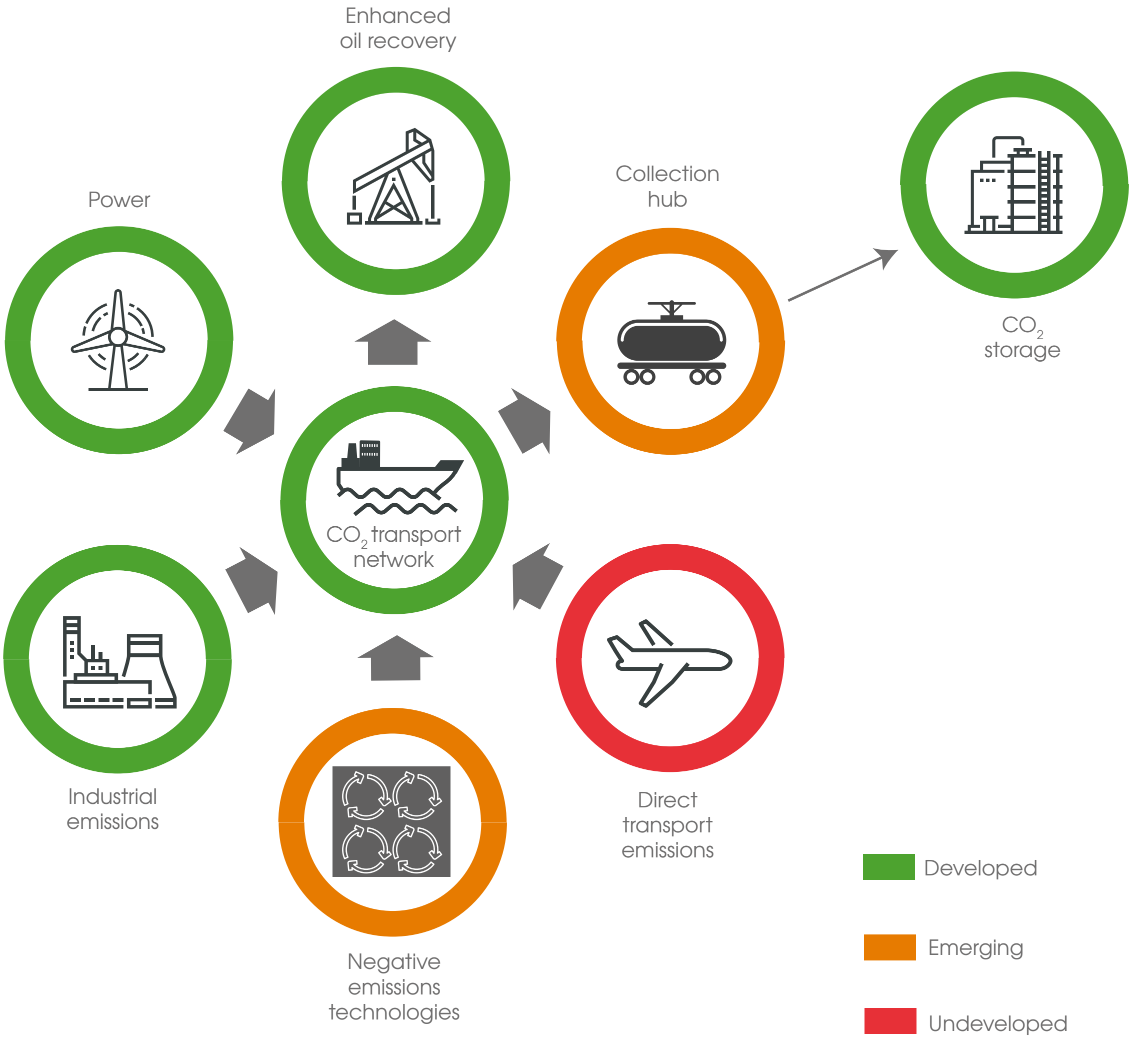

Figure 4: A systems optimisation approach considering a broad range of sectors and CCS stages is needed to define a cost-effective and flexible decarbonisation system.

> “Optimising the connectivity between CO2$_2$ sources and sinks is a systems challenge which is a key aspect of increasing CCS process efficiency and reducing costs ”

Chemical engineers will continue to take a lead on the research and development of CCS technologies. Whilst commercially applicable CCS technology is already available, next generation technologies need to be brought to maturity. Research can be directed towards developing improved materials and processes for CO_2 capture with the objective of reducing capital and operating costs. Research is also needed in alternative process line-ups, flexible operations and control schemes which for example enable a CCS enabled power station to follow the rapid load variations characteristic of elements in the power network, which are unusual for chemical plant.

There are emerging technologies that show promise and have reached pilot or demonstrator scale. The Allam Cycle[35] is a new power generation process that uses CO_2 instead of steam as the working fluid to drive turbines, reducing the size and cost of the turbine. Furthermore, the process achieves efficiencies of up to 59% LHV (lower heating value, for natural gas fuel) and generates CO_2 as a high-pressure by-product suitable for EOR or sequestration[36]. Other promising technologies that could offer a highly energy-efficient way of capturing CO_2 include calcium looping[37] and membrane technology[38]. Another benefit of calcium looping is that the spent limestone can be utilised for cement or steel production, offering a means of reducing carbon emissions for these energy-intensive industrial processes[39]. Combining fuel cells with CCS also has high potential for reducing costs. Recently-molten carbonate fuel cells (MCFC) have been developed which, unlike other fuel cells, use natural gas rather than hydrogen as their fuel, to generate electricity directly whilst producing 70% CO_2 at the fuel electrode. This could be exploited to capture concentrated CO_2 from an exhaust stream using considerably less energy than conventional approaches, with no need for heating or depressurisation. ExxonMobil estimates more than 90% of natural gas power plants emissions can be captured using such technologies[40].

Many demonstration and large-scale CCS projects to date have been based on post-combustion capture of CO_2, which is the natural retrofit technology for existing power plants. However, pre-combustion capture, for example conversion of methane to CO_2 and H_2 by steam methane reforming (SMR) prior to CO_2 capture, has a number of potential advantages. The hydrogen can be used for power generation either in gas turbines or fuel cells or for decarbonised heating *(section 4.2)* with the CO_2 being produced and captured at high pressure and relatively high concentration, enabling more energy efficient separation and more compact plants at reduced cost. This gain is, however, offset to some extent by the additional energy consumption (approximately 15%) associated with conversion of the fuel to syngas, compared with burning the fuel for power directly.

As with most technologies, CCS will need multiple, large-scale deployments to enable the learnings required for further improvements in performance and cost reduction. The chemical engineering community needs to effectively communicate this message when working with other stakeholders and point out the risks of basing future commercial process costs on one-off, small-scale demonstration projects.

There are several challenges with the design and specification of optimised CO_2 transport networks that require the attention of chemical engineers. Development of shared transport and storage infrastructure, into which a wide range of diverse CO_2 generators can feed, will be a high priority to exploit the economies of scale, flexibility of access and distribution of costs across many users. Optimising the connectivity between CO_2 sources and sinks is a systems challenge which is a key aspect of increasing CCS process efficiency and reducing costs. The transport of captured CO_2 streams containing moisture and other impurities has implications for the phase behaviour of the pressurised supercritical CO_2 stream, including the need to avoid gas hydrate formation, and for the selection of the pipeline material and its possible degradation by the high pressure mixed fluid stream. Impurities have the potential to impact efficiency and safety of operation at each stage of the CCS chain, and trade-offs between the cost of purifying CO_2 streams and such impacts must be considered to define stream specifications that optimise transport and storage processes.

Expertise in areas such as multi-phase fluid transport in porous media is required to develop accurate reservoir models, which serve to optimise storage capacity and minimise the risks of CO_2 leakage. Chemical engineering expertise in reactive flow will be important in the appraisal of injection and storage potential of water-bearing carbonate aquifers and depleted oil and gas reservoirs, where the acidic CO_2 fluid will react with the limestone rock to modify the pore space during the storage process. Better models are required for design and optimisation of storage in these systems, which represent about half of the potential storage sites globally.

3. Beyond technology – the wider context of CCS

3.1 Commercial incentives for CCS

Large-scale implementation of CCS has the potential to generate substantial economic value whilst greatly reducing the whole-system costs of mitigating carbon emissions relative to strategies without CCS[41]. The cost to the UK of meeting climate change targets without a national CCS infrastructure is estimated to increase by £4bn per year for each five-year delay in implementation until 2030[42]. In the US, the price of electricity in 2050 is projected to rise by 210% on current levels without CCS, compared to 80% with CCS deployment[43] whilst the transformation of the global power sector in line with the limiting global warming to the COP21 2°C target has been estimated to be £2.6 trillion more expensive without CCS[44].

There are broader potential economic benefits to CCS adoption. CCS, as with other growing low-carbon industries, has the potential to create a significant number of jobs as fossil fuels play a diminishing role in the global energy mix. The industry will offer opportunities to many employees displaced from the oil and gas industry, such as reservoir engineers, due to the similar skills profile required[45]. In the UK, the number of jobs supported by oil and gas has decreased by 27% (relative to 2014 levels) to around 330,000 in 2016[46]. A CCS industry of the size needed to align with UK Committee on Climate Change emissions reduction targets has been estimated to create 225,000 jobs between 2017 and 2060 and generate £130bn in economic benefits[47].

Where there is a mechanism to monetise the storage of CO_2 and other greenhouse gases (GHGs) CCS is being deployed commercially, driven by the market. In other markets, carbon pricing mechanisms are necessary to stimulate CCS either through an effective carbon trading system or through carbon taxes, as for example in Norway. Enhanced oil recovery (EOR) is a mature market in areas such as the US and can make CCS profitable where it can be deployed. In such locations, EOR has the potential to provide a near-term, market-driven demand for CO_2. However, CO_2-EOR is not a panacea since it is not effective for all depleted oil and gas reservoirs, usually only being applicable before the reservoir pressure has fallen below the oil-CO_2 minimum miscibility pressure. When it can be applied, EOR can result in net storage of up to 0.8 t CO_2 per t CO_2 injected over the process lifecycle if it is operated to maximise CO_2 storage rather than oil/gas enhanced recovery, and emissions avoided by not recovering more expensive and less easy-to-decarbonise new reserves are taken into consideration[48]. Concerns about long-term storage integrity need addressing through good engineering practices and transparent site monitoring.

Another potential way of monetising CO_2 is to use it as a chemical feedstock rather than store it. Carbon dioxide utilisation (CDU) uses this waste, relatively low-cost feedstock to make products such as urea, polyurethanes and other polymers. Several studies indicate that CDU is unlikely to make a significant contribution to climate change mitigation in the short to medium-term[49]. Currently the industry accounts for the use of around 0.2 Gt CO_2 pa[50] (of which only 25% of the products can be considered to sequester CO_2 long-term), which represents only a small fraction of the 10 Gt CO_2 pa reduction needed by 2050 to meet the Paris Agreement's two degrees target. Some reports suggest that CDU might grow to around 7 Gt CO_2 pa by 2050; although this would require a sustained growth rate of over 10% pa in contrast to a current rate of growth of the entire chemical industry of around 3% pa. Much of the projected growth of CDU involves making transport fuels from CO_2, which has the potential to defer CO_2 emissions rather than leading to long-term mitigation as emissions are associated with the consequent use of such fuels. It will almost certainly play a role in developing the circular economy, especially as more renewable electricity becomes available to provide the energy needed to drive CO_2 conversion processes, but is unlikely to be a key driver for developing CCS on a large-scale.

The deployment of CCS at the scale and rate required to meet local and global decarbonisation targets will require the development and implementation of new and innovative business and commercial models especially in non-EOR markets. Several government-backed programmes have attempted to stimulate the development of CCS in markets where CO_2 has no or insufficient monetary value. Frequently however, the onus for investment and management of the financial, operational and commercial integration risks across all elements of the CCS process chain has been placed on the private sector. Whilst the private sector can manage and competitively price many of the risks associated with CCS, there are some risks which the market will only accept at a premium, and others not at all, regardless of the price[51]. This has resulted in a lack of proven commercial models across the full CCS chain where CO_2 has no intrinsic market value.

To overcome these barriers, in such markets the distribution of CCS risk between the private and public sectors needs to be reconsidered *(Figure 5)*. Key commercial risks that may require public sector support include cross-chain default, where default from capture, storage or transport operators means other stakeholders in the chain can no longer operate, and post-decommissioning CO_2 storage risks, which concern liability for CO_2 leakages occurring after storage sites have been decommissioned. Other risk factors to consider include sub-surface CO_2 storage performance (which will in turn influence achievable storage rates and capacity), and insurance market limitations for CO_2 transport and storage operations.

Transfer of the risks associated with the development of the CO_2 transport and storage infrastructure away from the private sector can boost confidence in the deliverability of CCS. In addition, the introduction of public sector financing for the transport and storage assets could serve to lower the overall cost of finance[52]. In the UK, this proposal has been made for example in the 2016 Oxburgh Report[53], which identifies a range of potential mechanisms including:

- publicly-owned national transport and storage facilities to provide secure long-term CO_2 storage capacity;
- economic regulation including financial incentives based on guaranteed future electricity prices (eg Contracts for Difference used in the UK to incentivise renewable energy);
- similar financial incentives for energy intensive industries (where often CCS is the only option for decarbonisation) obligating emitters to mitigate CO_2 emissions beyond 2020, to give a long-term trajectory that builds confidence for investors.

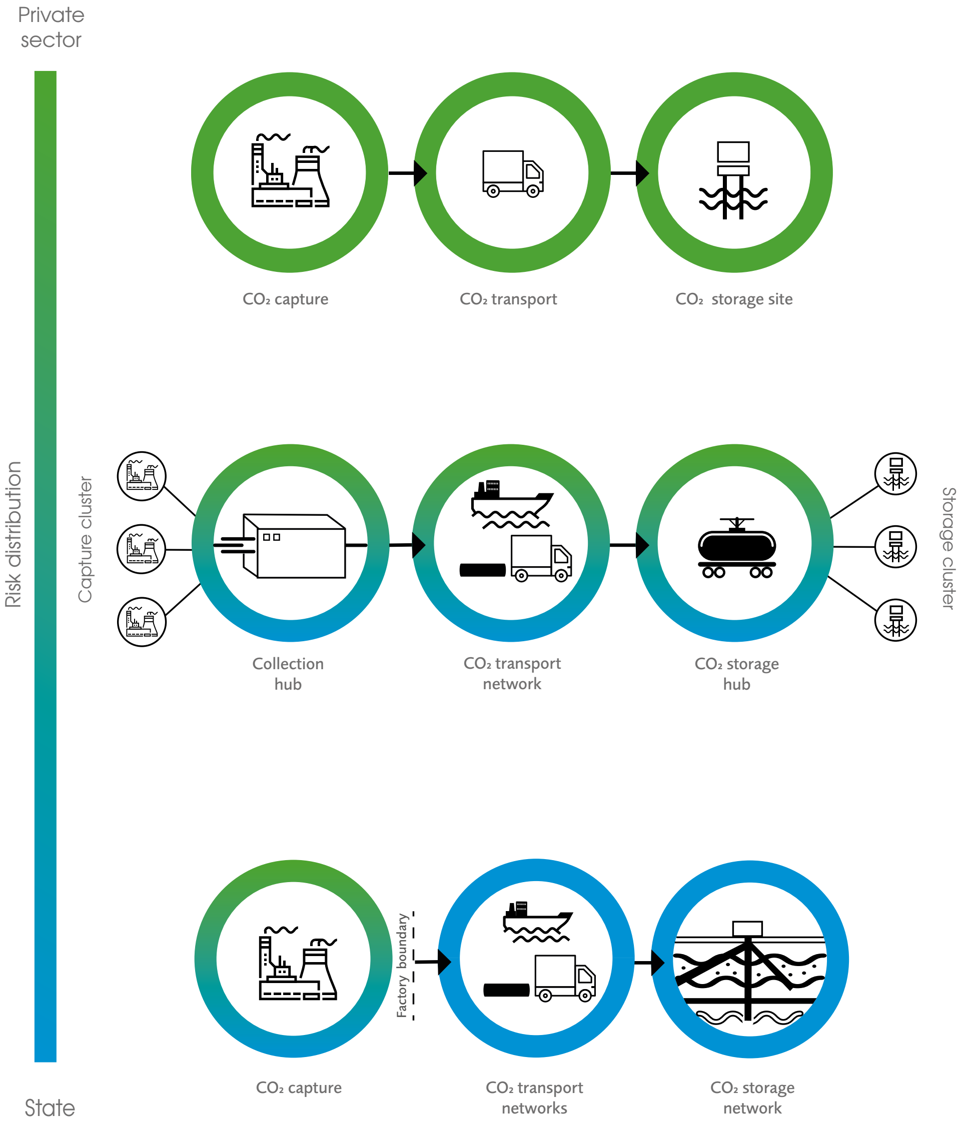

Figure 5: Alternative models of CCS delivery are associated with different distributions of financial and operational risks between private sector and state

A complementary analysis by Hackett[54] emphasises the benefits of shared, multi-user transport and storage infrastructure and the need for commercial integration between stages of the CCS chain. The need for incentives should reduce over time as CCS design and operating experience grows and consequentially, capital and operation costs reduce. Spreading the costs of CCS infrastructure across all major emitters rather than just the power generators is another funding option, which could reduce the cost burden of CCS for electricity users and spread the costs more evenly.

Whilst the examples above are UK oriented, the considerations discussed are relevant to other regions where there is an absence of strong financial drivers (such as EOR or carbon pricing) to invest in large-scale CCS developments. Such investment requires a supportive environment, particularly for first-of-a-kind projects. As more CCS projects come on-stream, the sharing of viable business models and good practice across different regions should enable opportunities for commercial projects to grow in a variety of fiscal and regulatory environments.

3.2 Policy landscape

Wide-spread deployment of CCS can be supported by a wide range of direct and indirect policies, through mechanisms such as research and deployment subsidies, market-based incentives and environmental regulations. Currently there are significant regional variations in both the status and trajectory of CCS-enabling policies.

Some nations (Canada, Norway, the UK and US) have explicitly indicated support for CCS as an emissions mitigation strategy as part of a portfolio of many decarbonisation activities. In North America, a mixture of grants, tax credits and emission performance standards have encouraged CCS development[55], which has also been driven by the application of CO_2-based EOR in the region. Other regions such as Australia and Asia are showing an increased rate of CCS policy development[56]. In the latter, China (through extensive piloting and international collaborations[57]) and South Korea (through initiatives such as the CCS Master Action Plan[58]) are beginning to support the deployment of commercial CCS through technology development and pilot projects across power generation and industry.

CCS is one of numerous carbon mitigation strategies and competes with other technologies and decarbonisation strategies for limited public funding and support. As is the case for many of the low-carbon technologies operating in a complex and fast-changing economy, the political landscape surrounding CCS has historically been unstable across many regions. In the UK a £1bn CCS commercialisation programme was cancelled before the conclusion of the competition[59], whilst in the US policies and programmes with significant influence on CCS such as the Clean Power Plan[60] have been discontinued. US government-supported demonstration projects such as the FutureGen partnership[61] have been halted prior to completion in 2015, with alternative schemes including the Petra Nova Project in Texas pursued in the following years. A 2015 review of the EU's CCS directive identified a need for more stable CCS policies such as long-term low-carbon roadmaps, extended financial support and reform of EU-wide policies such as the EU emissions trading scheme[62] to provide greater stability in the regulatory landscape, which is vital to sustaining investor confidence in CCS.

In all regions there is an urgent need for more stable and supportive CCS policies. To support the case for establishing a stable energy policy framework, the potential benefits that CCS brings to mixed energy systems which aim to deliver secure, affordable, low-carbon energy should be emphasised. CCS will enable continued use of fossil fuels in an environmentally responsible way during the transition to a low carbon economy, whilst the capacity of renewable energies increases, and its costs decrease. CCS can address decarbonisation needs not just for power, but also for heating and industrial manufacturing. When combined with biomass it can also deliver negative emissions thereby removing industrial quantities of CO_2 from the atmosphere, creating room in ever tightening carbon budgets for more difficult sectors such as aviation. The role of CCS is not to defer or slow down the rate of development and introduction of renewable energy sources or nuclear power, but to be deployed alongside other low-carbon energy sources and decarbonisation strategies, including energy efficiency measures and demand reduction, to provide the fastest and least-cost approach to meet the COP21 targets for mitigation of dangerous climate change. Fossil fuel power plants fitted with CCS provide the low-carbon base-load supply and 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 mixed energy system.

The barriers to CCS implementation vary by region so different business strategies, policy frameworks and technological options will be needed to overcome them according to location. However, political and commercial barriers pose a much bigger challenge to the widespread adoption of CCS than the development of improved CCS technologies. Its commercial viability requires a means to generate value from the CCS process and, critically in the absence of EOR options, an enabling policy framework which recognises the value of CCS including dispatchable low-carbon power generation and the decarbonisation service that the technology provides across the economy.

The CCS-enabling policy elements must be integrated into an overall energy policy, based on an economy-wide systems approach aimed at delivering optimised cross sector decarbonisation strategies and maximising the associated economic and societal benefits. Policies must be consistent with broader political aims, with clarity on how CCS helps deliver the required benefits, from the creation and retention of industrial activity and jobs through to provision of grid stability and flexibility. Policy-makers must therefore consider both the costs and the benefits of CCS and its relationship with other decarbonisation strategies, like renewable energy, energy efficiency improvements and afforestation across whole national and international systems.

Consideration of CCS costs and benefits allow the role, scale and timescales on which it is required to be operational, to be clearly defined. Taking into account the regional technological options and business priorities, this then provides the evidence-based platform for policymakers to develop a stable enabling policy framework for CCS, in close consultation with industry, government, academia, professional institutions, NGOs and other relevant stakeholders. This will identify and implement appropriate policy drivers and supporting regulation for CCS, including incentive mechanisms to ensure that all costs (operating and financing) are recoverable with reasonable returns on investment. These can include grants, subsidies, future price guarantees and arrangements for risk/cost sharing between the public sector, private operators and consumers, to ensure that mechanisms exist to make CCS projects financially feasible for private investors.

Policy frameworks should consider the domestic targets in the context of international obligations, recognising that energy cost is important across competing economies, but also that meeting the COP21 decarbonisation targets globally will only be achieved by collective action. In this context, the role of local and international carbon pricing (through mechanisms such as tax or trading systems) needs to be considered and how it could be used as a major driver for widespread CCS adoption whilst ensuring it has an equitable impact on organisations operating within the same markets. In industry, companies are often reluctant to impose additional costs for carbon emission reductions on industrial processes, due to international competition and fears of undermining competitive positions and possible job losses. Appropriate policy frameworks and government incentives are therefore very important for encouraging decarbonisation of sectors that represent a significant proportion of global emissions.

3.3 Commercial and policy opportunities and challenges – new business models and stable policy

Historically, public-sector support for CCS commercialisation has frequently involved grant funding for technology development and demonstration. Whilst grant funding typically reduces the capital costs during construction for the developer, such support does not address potential risks stemming from the inherent uncertainty in how novel CCS technologies will perform or arising from changing market conditions and lack of certainty that deter potential investment in CCS. Chemical engineers have a role to play as policy advisors, project designers and managers in identifying the most appropriate commercial models for different regions and operational contexts and deploying their project management and partnership negotiation skills to bring them to fruition.

Hub and cluster networks bringing together multiple CO_2 emitters using shared transportation infrastructure represent a promising mechanism for sharing costs and risks, with open access to transportation infrastructure likely to be a prerequisite to their successful operation. Industry can play a key role in specifying its requirements for transport networks, with chemical engineers applying systems thinking to optimise the design of the whole network. Similar considerations apply to shared storage facilities, with chemical engineers providing the methodology and models to manage multi-user, multi-source allocations of CO_2 to a network of available storage sites.

Clear and stable roadmaps for the delivery of CCS as part of well thought out national energy policies can also give confidence to private investors and industry looking to fund the development of CCS. Chemical engineers can contribute to this process by advising policy makers on the technical options and characteristics of CCS, in particular around any projected scale-up of CCS technology and infrastructure that will be required for wide-spread deployment.

Whilst the technical elements of CCS are mature, public awareness of CCS is still developing in many regions[63]. Uncertainties around whether CCS will complement or provide competition for renewables in the power generation sector and the feasibility of its widespread application have also led to criticism of CCS from some public bodies and NGOs[64,65]. This, in combination with concerns around health and safety risks (particularly around storage and transport[66]), potential price increases in electricity, and relevant industry products and excessive up-front costs have dampened public and policy maker appetite for CCS in many regions.

In this context the onus is on chemical engineers (in partnership with other disciplines) to engage in a meaningful, evidence-based dialogue with these stakeholders. There is a need to listen to and discuss the legitimate concerns of the public and policymakers, and to develop a context-specific evidence base that allows CCS to be considered alongside other decarbonisation strategies in a balanced and objective manner.

> "Hub and cluster networks bringing together multiple CO_2 emitters using shared transportation infrastructure represent a promising mechanism for sharing costs and risks."

4. CCS – a multi-sector solution

4.1 Industrial processes

Industrial emissions represent around 21% of the total anthropogenic CO_2 released globally[67]. CCS technology is vital in the industrial sector since the emissions in many processes are unavoidable with current production technologies and are an intrinsic part of the production process for so-called energy intensive industries (EIIs). CCS can provide an immediate means of lowering EII emissions whilst alternative industrial processes that replace hydrocarbon with low-carbon feedstocks are developed in the long term.

Where CO_2 is generated as a by-product during the manufacturing process, CCS represents the only option for decarbonising. Iron and steel manufacture typically utilises coal-derived carbon monoxide to reduce the iron oxide, producing by-product CO_2, whilst 60% of CO_2 emissions associated with cement production occur during the limestone calcination phase[68] to produce lime. Other key industrial applications of CCS include the production of ammonia and fertilisers, aluminium smelting and petrochemical refineries.

Many industrial processes produce CO_2 as a by-product at a purity of 20% or higher where the costs of capture have already been absorbed into the production costs, reducing the incremental costs required to install CCS. An example of the potential for process innovation to reduce carbon footprint is the €12m EU Horizon 2020 Low Emissions Intensity Lime and Cement (LEILAC) Project[69] which produces an almost pure CO_2 stream from the calcination of limestone that can be captured without significant energy or cost demand increase. Another potential option for decarbonisation of the cement industry is calcium looping capture technology[70], which allows CCS to be integrated efficiently into the clinker production process in a number of configurations.

Globally, iron and steel production make the most significant contribution to direct industrial emissions of CO_2, representing around 30% of the total[71]. Currently there are four iron and steel plants using CCS globally. The largest operational plant with CCS is the Emirates Steel Project in the United Arab Emirates, which has a capture capacity of 0.8 Mt CO_2 pa[72]. Other plants in Sweden, South Korea and Japan operate on a smaller scale with capacities of around 0.0035–0.011 Mt CO_2 pa[73].

In cement production, three pilot phase plants are operational in Europe whilst the Industrial Technology Research Institute (ITRI) pilot in Taiwan plans to scale up operations to a test facility soon[74]. For hydrogen production two plants currently operating in North America utilise adsorption technologies to capture around 1 Mt CO_2 pa[75], whilst the Enid and Coffeyville fertiliser plants in the US operate at a similar scale[76].

4.2 Low-carbon power

Fossil fuels are projected to account for a significant proportion of global energy use for the coming decades for power, heating and transport[77,78]. This is driven by increasing energy demand and the need to maintain energy supply whilst low-carbon alternatives mature. If this continues to be the case and countries with significant local reserves such as India and China continue to utilise them (for reasons such as security of supply and lower production costs, although China is now investing heavily in renewables), then CCS will be an essential technology for global decarbonisation of power. Globally, CCS in the power generation market is projected to grow by over 50% per year up to 2020, with much of this growth stemming from developing nations[79].

In a highly dynamic complex energy system with many competing generation technologies, power stations equipped with CCS can operate as either base load power or flexible capacity. CCS therefore has a potential role to play in both decarbonising fossil fuel base loads and providing clean dispatchable reserve power to complement more intermittent renewable energy sources (IREs).

Whilst energy storage technologies are projected to provide an increasing share of this dispatchable power globally in the future[80], gas fired power stations equipped with CCS will also likely play a significant role. Here, CCS processes need to capture around 50% less CO_2 per unit of energy compared to coal. However, such plants are more demanding at the capture stage due to lower concentrations of CO_2 in the flue gas, and consequently the energy requirements for CCS-enabled coal and gas plants are similar over the whole lifecycle. Improved capture technology and a move to pre-combustion capture has significant potential in its use for steam methane reforming (SMR) to produce CO_2 and hydrogen, where the latter can fuel a combined cycle gas turbine (CCGT) plant, as proposed by BP for its (later abandoned) Peterhead Power Plant – Miller Field Decarbonised Fuels DF1 Project in 2006[81]. Such approaches present challenges and opportunities for chemical engineers to improve efficiencies and reduce costs, as well as brokering suitable business models *(section 3.1)*. The DF1 project was cancelled because suitable public-private financing arrangements could not be agreed. There have still been no large-scale pre-combustion CCS projects to date and, given the likely growth in gas use, evaluation of this technology using SMR on a commercial-scale CCGT plant or a polygeneration process is an important priority.

4.3 Transport

Decarbonisation of fossil fuel transport through CCS is difficult and unlikely to prove cost-effective. Decarbonisation of transport is instead likely to happen via other routes such as electric vehicles, shifts in transport modes and behaviours, and the use of cleaner fuels like hydrogen (whose production via SMR would necessitate CCS) or biofuels. The role of CCS in transport therefore comes from its influence on the wider energy system, through enabling low-carbon electricity and fuels to be produced.

4.4 Hydrogen for heating

Decarbonisation of heating systems remains a significant challenge. In the absence of readily available large-capacity, low-cost, on-demand renewable electricity, replacing natural gas fuelled heating systems with hydrogen fuels is now seen as a leading contender for addressing this challenge[82].

Low-carbon hydrogen formed from fossil fuels (eg steam methane reforming (SMR) of natural gas or via syngas from oil and heavy hydrocarbons gasification) combined with CCS to remove the co-produced CO_2 is the only current process that could deliver low-carbon hydrogen at the volumes and cost required globally. This application could be a strong driver for the commercialisation of CCS as this is one of the few routes, alongside heat pumps, to decarbonise heating at large-scale in the short to medium term.

Hydrogen gas heating has the potential to be delivered using existing gas grids that have been converted to polyethylene pipework, which is becoming increasingly common. Such a transition would also necessitate the conversion of domestic and commercial boilers from natural gas to hydrogen (like the changes introduced for the conversion from town gas to natural gas in the UK that commenced in the 1960s).

The h21 Leeds City Gate project in the UK is an example of a large-scale demonstration project. This aims to provide the 6 TWh pa required to heat a city of about 800,000 people through generation of 1,025 MW of hydrogen via steam methane reforming (SMR), linked to CCS, with the option of using local salt caverns for gas storage to manage intraday and inter-seasonal swings in heating demand. A feasibility study has shown that the project is technically and economically viable and £25m of UK government funding is being made available for further demonstration[83].

Figure 6: The h21 Leeds City Gate project will aim to decarbonise the district heating network of Leeds, UK, linking hydrogen fuel production to a local CCS network Source[84].

4.5 Negative emissions technologies

Consensus on the importance of negative emissions (ie removal of CO_2 from the atmosphere) in meeting the target proposed in the Paris Agreement of below 1.5°C temperature increase has grown in recent years.

As leading negative emissions technology, bio-energy with carbon capture and storage (BECCS) has been receiving increasing attention in the past decade[85] and has been identified as a key component in IPCC mitigation pathways[86]. It combines biomass – a carbon neutral feedstock – with the CCS-enabled capture of the CO_2 emissions released upon its conversion, resulting in a net removal of carbon from the atmosphere. As a result, BECCS has been increasingly featured in integrated assessment models (IAMs), to offset unavoidable CO_2 emissions in sectors such as agriculture and transport[87].

According to the IPCC 2DC emissions pathways, BECCS could be required at the scale of 8.5–16.5 Gt CO_2 pa by 2100[88], with mean scenarios predicting a deployment of 12 Gt CO_2 pa[89]. Considering biomass heating values of between 18–21 GJ/t dry matter, and carbon content between 46–52%[90],1 EJ of biomass represents a carbon capture potential of between 80–106 Mt CO_2. There have been many predictions as to bioenergy potential deployment, and how much of this deployment would be sustainable. The IEA indicates biomass availability ranges as broad as 50–1,500 EJ pa by 2100, of which only 200– 250 EJ pa could be sustainably sourced[91]. Based on these estimates, with large-scale deployment of CCS technology, enough sustainable biomass could be sourced to meet negative emission targets.

Direct air capture (DAC) is a relatively new technology that has been brought to the forefront of climate change mitigation discussions by the increasing consensus on the importance of negative emissions. A number of analyses based on proposed process designs for DAC have yielded a wide range of energy consumption; from 0.9–22.7 GJ/t CO_2 for DAC[92,93]. None of these have been realised on a commercial scale; however, a few pilot projects are operational worldwide, such as the Climeworks project in Switzerland which removes around 900 t CO_2 from the air per year[94]. This process costs £450/t CO_2 today; the target is to reduce this to £75/t CO_2 by 2025 by which time Climeworks hopes to be capturing 1% of global CO_2 emissions pa. Whilst the current cost level means DAC is currently not financially viable on a large scale, potential cost reductions and rising social, environmental and economic costs of carbon emissions (the UK government estimates the overall value of mitigating CO_2 emissions may be up to £221/t CO_2 by 2050[95]) may lead to investment in DAC in the medium- to long-term. Such systems are interesting, but will require a step change in capture capacity to begin to make a significant contribution to climate change mitigation.

4.6 Systems opportunities and challenges – a fully integrated CCS chain

A systems approach to the design and optimisation of all these CCS processes (power, heating, EII manufacturing, BECCS and DAC) lies at the heart of chemical engineers' core activity. The challenge is to build new plants and retrofit existing ones to minimise the carbon footprint through a combination of feedstock choice, available energy sources, optimising process efficiency and applying CCS. Process design for near-zero greenhouse gas emissions should become as integrated into normal practice as inherent process safety. In the case of the UK h21 Leeds City Gate domestic heating project, linking the CCS system with the supply of North Sea natural gas for four SMR plants, onshore hydrogen gas storage facilities, existing pipeline distribution system and the domestic heating network will be essential to achieve optimal process and cost efficiencies.

Modelling the whole CCS process system can explore how the technical performance of CCS networks and associated energy requirements change with different operating conditions and how changes in the technical performance affect the process economics. Opportunities for cost reductions can be realised by consideration of:

- The effect of different CO_2 source stream compositions on capture technology design and operating choices. Obtaining pure CO_2 from flue gases is expensive and capture costs can be reduced considerably if significant impurities can be tolerated in transport and storage, enabling co-sequestration of eg H_2S with CO_2.
- System integration opportunities to minimise the thermal energy consumption associated with the CO_2 capture process
- Identifying opportunities for heat integration with the base power or manufacturing plant
- CO_2 recycle optimisation to concentrate the flue gas to improve capture efficiency/economics.

The direction of the future energy mix will influence the nature of CCS infrastructure within the energy system. With increasing penetration of IREs into the market CCS-enabled natural gas plants are projected to play an increasing role in global electricity generation by 2050[96], providing dispatchable generation. In instances where the carbon captured from such plants represents a significant proportion of the volume in the transport and storage networks more infrastructure will be needed, for example by identifying buffer storage mechanisms for times of peak demand. Systems analysis could be used to explore how new designs and operating procedures could act to decouple the profit-maximising behaviour of the power plant and the stable, reliable operation of the CCS capture and compression equipment.

5. Conclusions and recommendations

Most analyses now agree that CCS will be an essential technology in the decarbonisation of energy supplies and industrial processes to the extent required by the COP21 Paris Agreement. It will not defer or slow down the introduction of renewable energy sources; on the contrary they will complement one another within flexible, cost-effective energy systems. Mature and well-developed technologies (TRL9) are available at all stages of the CCS chain, have been operated in large-scale demonstrators and commercial projects safely and sustainably for over 20 years and are ready for commercial deployment now. Although lack of available technology is not currently the barrier to large-scale deployment, continuing innovation and development of improved CCS processes, especially for capture and alternative storage options, will be required to reduce costs and improve process efficiency over the next few decades.

In the power sector, CCS can be deployed alongside energy efficiency, demand reduction and other low-carbon energy sources to provide the least-cost approaches for mitigation of dangerous climate change. For direct industrial emissions from processes producing CO_2 as a by-product (such as cement manufacture and iron and steel production, which dominate industrial emissions) there are currently no low-carbon alternatives and CCS represents the only option for completely decarbonising this major global sector. CCS combined with process efficiency should be a priority for industrial plant, especially the EIIs, and companies and governments should develop the required policies, regulation, incentives and technologies to decarbonise this sector by 2030.

Hydrogen is now seen as a leading contender (alongside ground-source heat pumps) for the decarbonisation of heating using low-carbon footprint hydrogen formed from fossil fuels combined with CCS (eg via steam methane reforming (SMR) of natural gas). The viability of this approach, one of the few routes to decarbonise heating at scale in the short to medium term in advance of widespread availability of large capacity, low-cost, on-demand renewable electricity, should be investigated at large scale and could be a strong driver for the commercialisation of CCS. This could also present an opportunity for decarbonised transport and fuel cell CHP based on hydrogen, enabled by SMR-CCS. CCS also has value when combined with fossil fuels or bio-fuels to provide a flexible, reliable source of low-carbon energy to complement more intermittent renewable energy sources. Efforts to meet the COP21 targets will likely depend on some contribution from negative emissions technologies which remove CO_2 from the atmosphere, of which one of the few candidates deployable on a large enough scale is BECCS.

The strongest driver for introduction of CCS applications at the scale and rate required to meet COP21 targets is the introduction of realistic carbon pricing, through a carbon tax or an effective carbon trading system. Given the key role that almost all IAMs now demonstrate for CCS in meeting the challenging COP21 targets, we strongly recommend that governments urgently take initiatives on carbon pricing and seek regional and national agreements to introduce financial mechanisms to make it cheaper to avoid CO_2 emissions than release it to the atmosphere. For CCS this requires a carbon price of about £40 per t CO_2 to incentivise large-scale commercial processes; this will vary according to the particular business sector so should be sector-specific, as it is in Norway.

Stored CO_2 can also be monetised via enhanced oil recovery (CO_2-EOR, or CCS-EOR). The technology for CO_2-EOR is mature, having been practised successfully for many decades and has the potential to provide a near-term, market-driven demand for captured anthropogenic CO_2 by covering the costs through CO_2-enhanced oil (or gas) production prior to the CO_2 remaining permanently in the reservoir. However, CO_2-EOR is not a panacea since it is not effective for all depleted oil and gas reservoirs; when it can be applied, it can result in net storage of up to 0.8 t CO_2 per t CO_2 injected. EOR projects can also deploy CCS infrastructure at the scale of several Mt per annum, which is vital for cost reduction. Public concerns about long-term storage integrity do need addressing through good engineering practices, transparent site monitoring and effective dialogue with local communities where CCS is implemented. CO_2 chemical utilisation (CDU) is clearly of interest as a contribution to the circular economy but several studies indicate that on the timescales on which major decreases in atmospheric CO_2 levels are required, CDU is unlikely to make a major contribution to climate change mitigation, at least in the short to medium-term[97].

Despite the promising range of potential future CCS applications, large-scale deployment of CCS in situations where there are no direct financial incentives to store CO_2 (such as EOR or carbon taxes) has been limited. Successful widespread commercial deployment is dependent on reducing the overall process costs and more equitable sharing of the risks between potential stakeholders, which will increase investor confidence and lead to new and cheaper sources of funding for CCS. This could be achieved by a combination of several essential elements:

- Stable enabling policy frameworks, which identify and implement policy drivers for CCS in terms of incentives and regulation, in particular value-for-money incentive mechanisms to support the financial feasibility of CCS investments.

- New business models based on new approaches to public-private operator risk and cost sharing. For example, consideration should be given to decoupling CO_2 capture investments from the CO_2 transport and storage elements which could be provided by a publicly-backed and funded infrastructure provider. By transferring the risks of CO_2 transport and storage to the public sector, including long-term storage risks, investments in CO_2 capture would become more attractive and feasible. The commercial arrangements between the infrastructure provider and the users should consider the ability of the users to transfer CCS costs to its consumers and the availability of value-for-money market price support mechanisms.
- Multi-plant large-scale deployment leading to learnings, efficiency improvements and cost reductions with successive plants, exploiting the economies of scale and reductions in the cost of capital; single medium-scale demonstration plants will not achieve this and do not provide a realistic prediction of the eventual commercial cost.

The barriers to CCS implementation vary by region so different business strategies, policy frameworks and technological options will be needed for a given regional context. In the US where there is a mature CO_2-EOR industry, the barrier is cost reduction of capture technologies, whereas in the UK and the EU the barrier is the absence of CO_2 transport and storage infrastructure and instability of CCS-enabling policies. The development and de-risking of such infrastructure is a high priority for many regions as optimising the connectivity between CO_2 sources and sinks is a key aspect of increasing CCS process efficiency and reducing costs. The challenges associated with the successful deployment of CCS require a multi-disciplinary approach, with chemical engineering playing a major role. In addition to technical analyses (such as developing purity specifications for transportable and storable impure CO_2 streams and optimal processes for achieving them), chemical engineers can also define the role of CCS in the overall energy system and for industrial processes by applying a systems approach. Such analyses are required to optimise the benefits for all parties across the entire CCS chain (capture, transport/pipeline, storage, measurement, monitoring and verification [MMV]), to design optimal transport and storage networks and to determine the role and impact of CCS in regional and global energy mixes.

There is an urgent need for those engaged in CCS development and implementation to engage in a meaningful, evidence-based dialogue with policymakers, the public and other stakeholders such as NGOs. State funding of CCS infrastructure is conditional on public acceptance of, and support for, CCS. Building awareness, fostering debate and understanding the public's views on CCS is therefore an integral part of enabling such funding, which is likely to be needed to deliver CCS on a large-scale.

Chemical engineers, alongside other stakeholders, need to convey in accessible language the potential risks and benefits of CCS, listen to public concerns (around for example excess capital costs, health, safety and environment, and the impact of CCS on the deployment of alternative decarbonisation technologies) and respond to these concerns with solutions evidence-based to ensure that decisions on how CCS can play a role in meeting the carbon mitigation targets of a country or region are reached objectively.

6. References

1 *Energy Technology Perspectives 2017*, International Energy Agency, Paris, France, 2017, available online: http://bit.ly/2oAI5mJ.

2 Stocker T F et al, *IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, NY, US, 2013, 1535 pp.

3 Fuss, S et al, 'Betting on negative emissions', *Nature Climate Change*, vol 4, 2014, pp850-853. DOI:10.1038/nclimate2392

4 Adjiman C S et al, 'Carbon capture and storage (CCS): The way forward', *Energy & Environmental Science*, in press, 2018. DOI: 10.1039/c7ee02342a.

5 *The Global Status of CCS: 2017*, Global CCS Institute, Melbourne, Australia, 2017, available online: http://bit.ly/2F2DtvH.

6 Macdonald-Smith A, *Gorgon LNG project to show business case for carbon waste storage*, Financial Review, available online: http://bit.ly/2HWx5rK, 2017 (accessed Sep 2017).

7 Leung D Y C et al, 'An overview of current status of carbon dioxide capture and storage technologies', *Renewable and Sustainable Energy Reviews*, vol 39 (Supplement C), 2014, pp426-443. DOI: 10.1016/j.rser.2014.07.093

8 Adams II T et al 'Comparison of CO_2 capture approaches for fossil-based power generation: Review and meta-study', *Processes*, vol 5, no 3, 2017, pp44-81. DOI: 10.3390/pr5030044

9 Otto A et al, 'Closing the loop: captured CO_2 as a feedstock in the chemical industry', *Energy Environ.* Sci., vol 8, no 11, 2015, pp3283-3297. DOI: 10.1039/C5EE02591E

10 Parrish W R, Ridnay A J, *Fundamentals of Natural Gas Processing*, CRC Press Taylor & Francis Group, London, UK, 2006.

11 Sipöcz N, Tobiesen F A, 'Natural gas combined cycle power plants with CO_2 capture – Opportunities to reduce cost', *Int. J. Greenh. Gas Con*., vol 7 (Supplement C), pp98-106, 2012. DOI: 10.1016/j.ijggc.2012.01.003

12 Bottoms R, *United States Patent number US1834016 A*, Washington, DC: US Patent and Trademark Office 1930.

13 Singh A, Stéphenne K, *12th International Conference on Greenhouse Gas Control Technologies* (GHGT-12), Austin, TX, US, Oct 2014.

14 Campbell M,*12th International Conference on Greenhouse Gas Control Technologies (GHGT-12)*, Austin, TX, US, Oct 2014.

15 *Petra Nova - W.A. Parish Project*, Office of Fossil Energy, US Department of Energy (DOE), Washington DC, US, 2015.

16 Huang Q et al, 'Impact of flue gas contaminants on monoethanolamine thermal degradation', *Ind. Eng. Chem*. Res., vol 53, no 2, pp553-563. DOI: 10.1021/ie403426c

17 *Aqueous or Chilled Ammonia Process*, Global CCS Institute, Melbourne, Australia, available online: *http://bit.ly/2GTunC4* (accessed January 2017).

18 *Polaris^{TM} membrane: CO_2 removal from syngas*, Membrane Technology & Research (MTR) (n.d.), available online: http://bit.ly/2CQDeC6, (accessed July 2017).

19 *Air Products And NTNU Enter Licensing Agreement For Carbon Capture Technology*, Chemical Processing, 2017, available at: http://bit.ly/2uwKHa2 (accessed July 2017).

20 Adanez J et al, ‚Progress in Chemical-Looping Combustion and Reforming Technologies', *Prog Energy Combust Sci*. Vol 38, no 2, 2012, pp215-82. DOI: 10.1016/j.pecs.2011.09.001.

21 *Terrell Natural Gas Processing Plant (formerly Val Verde Natural Gas Plants)* Projects Database, Global CCS Institute (n.d.), Melbourne, Australia available online: http://bit.ly/2FgD7oO (accessed December 2017).

22 Muggeridge A et al, 'Recovery rates, enhanced oil recovery and technological limits', *Philos Trans A Math Phys Eng Sci*, vol 372, 2014, 20120320. DOI: 10.1098/rsta.2012.0320

23 *CO_2 Pipeline Infrastructure Report: 2013/2018*, IEAGHG, Cheltenham, UK, 2013, available online: http://bit.ly/2F1yXSu

24 Brownsort P, *Ship transport of CO_2 for Enhanced Oil Recovery – Literature Survey*, Scottish Carbon Capture & Storage, Edinburgh, UK, 2015, available online: http://bit.ly/2ts1QBH.

25 Chapoy A et al, 'Effect of common impurities on the phase behaviour of carbon dioxide rich systems: Minimising the risk of hydrate formation and two-phase flow', *Offshore Europe Oil & Gas Conference and Exhibition 2009 (OE 2009)*, Aberdeen, UK, Sep 2009.

26 Dugstad A et al, *Testing of CO_2 specifications with respect to corrosion and bulk phase reactions, 12th International Conference on Greenhouse Gas Control Technologies (GHGT-12)*, Austin, TX, US, Oct 2014.

27 Dooley J J et al, *Carbon Dioxide Capture and Geologic Storage* A Core Element of a Global Energy Technology Strategy to Address Climate Change, Battelle Memorial Institute, 2006, available online: http://bit.ly/2G4Ynf9.

28 *Large-scale CCS facilities, Projects Database*, Global CCS Institute, Melbourne, Australia, 2017, available online: http://bit.ly/2oGZSbe (accessed Dec 2017).

29 Gou Y et al, 'Numerical simulation of carbon dioxide injection for enhanced gas recovery (CO_2-EGR) in Altmark natural gas field', *Acta Geotech*, vol 9, 2014, pp49-58, DOI: 10.1007/s11440-013-0221-z

30 Leung D Y C et al 'An overview of current status of carbon dioxide capture and storage technologies', *Renewable and Sustainable Energy Reviews*, vol 39 (Supplement C), 2014, pp426-443. DOI: 10.1016/j.rser.2014.07.093

31 van Bergen F et al, 'Worldwide selection of early opportunities for CO_2-enhanced oil recovery and CO2-enhanced coal bed methane production', *Energy*, vol 29, no 9-10, 2004, pp1611-1621, DOI: 10.1016/j.energy.2004.03.063

32 Mazzotti M et al, 'Enhanced coalbed methane recovery', *J Supercrit Fluid*, vol 47, no 3, 2009, 619-627, DOI: 10.1016/j.supflu.2008.08.013

33 Matter J M et al, 'Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions', *Science*, vol 352, no 6291, 2016, pp1312-1314, DOI: 10.1126/science.aad8132.

34 *Alternative storage of captured carbon dioxide*, NSW Government Planning & Environment Resource & Energy, 2017, available online: http://bit.ly/2GTzguT (accessed 12 December 2017).

35 Allam R J et al, 'The oxy-Fuel, supercritical CO_2 Allam Cycle: New cycle developments to produce even lower-cost electricity from fossil fuels without atmospheric emissions', *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*, Düsseldorf, Germany, Jun 2014, ppV03BT36A016, DOI: 10.1115/GT2014-26952.

36 Service R F, 'Goodbye smokestacks: Startup invents zero-emission fossil fuel power', *Science*, 2017, DOI: 10.1126/science.aal1228.

37 Dean C C et al, 'The calcium looping cycle for CO_2 capture from power generation, cement manufacture and hydrogen production', *Chem Eng Res Des*, vol 89, no 6, 2011, pp836-855, DOI: 10.1016/j.cherd.2010.10.013.

38 *Air Products And NTNU Enter Licensing Agreement For Carbon Capture Technology*, Chemical Processing, 2017, available online: http://bit.ly/2uwKHa2.

39 Blamey J, Anthony B, 'End use of lime-based sorbents from calcium looping systems', *Calcium and Chemical Looping Technology for Power Generation and Carbon Dioxide (CO_2) Capture*, Woodhead Publishing Ltd, Cambridge, UK. 2015, chapter 8, pp153-169.

40 *Advanced carbonate fuel cell technology in carbon capture and storage*, Exxon Mobil, 2016, available online: http://exxonmobil.co/2oHCwlF.

41 Heuberger C F et al, 'A systems approach to quantifying the value of power generation and energy storage technologies in future electricity networks', *Comput Chem Eng*, vol 107, 2017, pp247-256, DOI: 10.1016/j.compchemeng.2017.05.012.

42 *Carbon Capture and Storage Potential for CCS in the UK*, Energy Technologies Institute, Loughborough, UK, 2014, available online: http://bit.ly/2fzsxxI.

43 James R, *The Power to Reduce CO_2 Emissions:* The Full Portfolio 2009 Technical Report, Rep 1020389, EPRI, Palo Alto, CA, US, 2009, available online: http://bit.ly/2oQoEGM.

44 *20 years of Carbon Capture and Storage* – Accelerating Future Deployment, International Energy Agency, 2016, Paris, France, available online: http://bit.ly/2HRFLQI.

45 *Technology Innovation Needs Assessment (TINA)*, Carbon Capture & Storage in the Power Sector Summary report, Low Carbon Innovation Coordination Group, UK, 2012, available online: http://bit.ly/2HWS25N.

46 *Economic Report 2016*, Oil & Gas UK, Aberdeen UK and London, UK, 2016, available online: http://bit.ly/2GWdd6H.

47 *Clean Air, Clean Industry, Clean Growth: How Carbon Capture will boost the UK Economy,* East Coast UK Carbon Capture and Storage Investment Study, Summit Power, Cardiff, UK, 201available online: http://bit.ly/2t9FGUy.

48 *Storing CO_2 through Enhanced Oil Recovery*, Combining EOR with CO_2 storage (EOR+) for profit, International Energy Agency, Paris, France, 2015, available online: http://bit.ly/2F6cOyc.

49 Mac Dowell N et al, 'The role of CO_2 capture and utilization in mitigating climate change', *Nat Clim Change*, vol 7, 2017, pp243-249, DOI: 10.1038/nclimate3231.

50 Naims H, 'Economics of carbon dioxide capture and utilization: a supply and demand perspective', *Environ Sci Pollut Res*, vol 23, 2016, pp22226-22241, DOI: 10.1007/s11356-016-6810-2.

51 Hackett L A, *Commercialisation of CCS What needs to happen?* IChemE Energy Centre, Rugby, UK, 2016, available online: http://bit.ly/2F3EC6j.

52 ibid

53 Oxburgh R, *Lowest Cost Decarbonisation for the UK: The Critical Role of CCS*, Report to the Secretary of State for Business, Energy and Industrial Strategy, Parliamentary Advisory Group on Carbon Capture and Storage (CCS), London, UK, 2016, available online: http://bit.ly/2vNDjqG.

54 Hackett L A, *Commercialisation of CCS What needs to happen?* IChemE Energy Centre, Rugby, UK, 2016, available online: http://bit.ly/2F3EC6j.

55 *World Energy Resources 2016,* World Energy Council, London, UK, 2016, available online: http://bit.ly/2CRDwc2

56 Consoli C P et al, 'Carbon capture and storage readiness index: comparative review of global progress towards wide-scale deployment', *Energy Proced*, vol 114, 2017, pp7348-7355, DOI: 10.1016/j.egypro.2017.03.1585.

57 *US-China Joint Announcement on Climate Change*, The White House Office Press Secretary, Washington DC, US, Nov 2014, available online: http://bit.ly/2FIsngO.

58 *Framework Act on Low Carbon, Green Growth*, Office for Government and Policy Coordination, South Korea, 2010, available online: http://bit.ly/2CQ3QDd.

59 *Future of carbon capture and storage in the UK Second Report of Session 2015-2016*, House of Commons Energy and Climate Change Committee, London, UK, 2016, available online: http://bit.ly/2F2NCwt.

60 *Trump starts process of cancelling US Clean Power Plan*, Modern Power Systems, Mar 2017, available online: http://bit.ly/2uwlnRN.

61 *FutureGen Fact Sheet: Carbon Dioxide Capture and Storage Project*, MIT, Boston, US, 2016, available online: http://bit.ly/2fziXv1 (accessed 11 August 2017).

62 *Study to support the review and evaluation of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive)*, European Commission, Luxembourg, 2015, DOI: 10.2834/972014.

63 *Special Eurobarometer 364*, Public Awareness and Acceptance of CO_2 capture and storage, European Commission, 2011, available online: http://bit.ly/2F1uFum.

64 Ash K et al, *Carbon Capture SCAM (CCS)*, How false climate solutions bolster big oil, Greenpeace US, Washington DC, US, 2015, available online: http://bit.ly/2F6fEDm.

65 Hanrahan G, *Pathways to power: Scotland's route to clean, renewable, secure electricity by 2030*, WWF Scotland, Edinburgh, UK, 2015, available online: http://bit.ly/2oGR9pj.

66 Upham P et al, *Public perceptions of CCS:* The results of NearCO2 European Focus Groups, University of Manchester, Manchester, UK, 2010, available online: http://bit.ly/2F5sBNQ.

67 Edenhofer et al, *Climate Change 2014: Mitigation of Climate Change*, Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Cambridge University Press, New York, NY, US, 2014, available online: http://bit.ly/2oT2JOW.

68 Blamey J et al, 'The calcium looping cycle for large-scale CO_2 capture', *Prog Energ Combust Sci*, vol 36, no 2, pp260-279, DOI: 10.1016/j.pecs.2009.10.001.

69 Hills T et al, 'LEILAC: Low Cost CO_2 Capture for the Cement and Lime Industries' *Energy Proced*, vol 114, 2017, pp6166-6170, DOI: 10.1016/j.egypro.2017.03.1753.

70 Romano M et al, 'The Calcium Looping Process for Low CO_2 Emission Cement Plants', *Energy Proced*, vol 61, pp500-503, DOI: 10.1016/j.egypro.2014.11.1158.

71 *Energy Technology Perspectives 2015*, Mobilising Innovation to Accelerate Climate Action, International Energy Agency, Paris, France, 2015, available online: http://bit.ly/2oHFg2x.

72 *Global CCS Institute welcomes world's first commercial steel CCS project in Abu Dhabi*, Global CCS Institute, Melbourne, Australia, 2016, available online: http://bit.ly/2GVoSme.

73 Zapantis A, 'Overview of Industrial CCS', *CSLF Workshop – Tokyo*, Tokyo, Japan, Sep 2016, available online: http://bit.ly/2oHbMBW.

74 *ITRI Calcium Looping Pilot*, Global CCS Institute, Melbourne, Australia, 2014, available online: http://bit.ly/2CQHC47.

75 *Large-scale CCS facilities*, Global CCS Institute, Melbourne, Australia, 2017, http://bit.ly/2oGEanr, (accessed 11 Dec 2017).

76 Zapantis A, 'Overview of Industrial CCS', *CSLF Workshop* – Tokyo, Tokyo, Japan, Sep 2016, available online: http://bit.ly/2oHbMBW.

77 *International Energy Outlook 2017*, US Energy Information Administration, Washington DC, US, 2017, available online: http://bit.ly/2ozxloL.

78 *World Energy Resources 2016*, World Energy Council, London, UK, 2016, available online: http://bit.ly/2CRDwc2.

79 *Global CCS in Power Generation Market 2016-2020*, TechNavio, Toronto, ON, Canada, 2016, available online: http://bit.ly/2oHPYWK.

80 *World Energy Resources 2016,* World Energy Council, London, UK, 2016, available online: http://bit.ly/2CRDwc2.

81 Beavis R, 'Industrial Application of Hydrogen Manufacture from Fossil fuels with Geological Storage of CO_2', Lead Project Workshops – Large CCS Projects Meeting, Brussels, Belgium, Sep 2006, available online: http://bit.ly/2oIcmiv.

82 *Next steps for UK heat policy,* Committee on Climate Change, London, UK, 2016, available online: http://bit.ly/2owHuCz.

83 *Leeds City Gate h21*, Northern Gas Networks, Leeds, UK, 2016, available online: **http://bit.ly/2F5nXPE**

84 ibid

85 Kemper J, 'Biomass and carbon dioxide capture and storage: A review', *Int J Greenh Gas Con*, vol 40, 2015, pp401-430, DOI: 10.1016/j.ijggc.2015.06.012.

86 Edenhofer et al, *Climate Change 2014: Mitigation of Climate Change,* Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Cambridge University Press, New York, NY, US, 2014, available online: http://bit.ly/2oT2JOW.

87 Azar C et al, The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS), *Climatic Change*, vol 100, 2010, pp195-202, DOI: 10.1007/s10584-010-9832-7

88 ibid

89 Smith P et al, 'Biophysical and economic limits to negative CO_2 emissions', *Nature Clim. Change*, vol 6, 2016, pp42-50, DOI: doi:10.1038/nclimate2870

90 *Phyllis2,* Database for biomass and waste, Energy Research Centre of the Netherlands, available online: http://bit.ly/2GWk6VY.

91 Bauen A et al, *Bioenergy – a Sustainable and Reliable Energy Source*, A review of status and prospects, IEA Bioenergy, 2009, available online: http://bit.ly/2HhOx9f.

92 House K Z et al 'Economic and energetic analysis of capturing CO_2 from ambient air', *PNAS,* vol 108, no 51, 2011, pp20428-20433, DOI: 10.1073/pnas.1012253108.

93 Socolow R H et al, *Direct Capture of CO_2 with Chemicals*, A Technology Assessment for the APS Panel on Public Affairs, American Physical Society, College Park, MD, US, 2011, available online: http://bit.ly/2G6BB6J

94 *World-first Climeworks plant:* Capturing CO_2 from air to boost growing vegetables, Climeworks, Hinwil, Switzerland, 2017, available online: http://bit.ly/2t3QsvR.

95 *Valuation of energy use and greenhouse gas,* Department for Business, Energy & Industrial Strategy, London, UK, 2017, available online: http://bit.ly/2CQgF0x.

96 *Energy Technology Perspectives 2016*, International Energy Association, Paris, France, 2016, available online: http://bit.ly/2Fc2Yy6.

97 ibid

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