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Imperial College  
London



***Demonstrating CO<sub>2</sub>  
capture in the UK  
cement, chemicals, iron  
and steel and oil refining  
sectors by 2025: A  
Techno-economic Study***

Final report

for

**DECC and BIS**

30/04/14

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While the authors consider that the data and opinions contained in this report are sound, all parties must rely upon their own skill and judgement when using it. The authors do not make any representation or warranty, expressed or implied, as to the accuracy or completeness of the report. There is considerable uncertainty around the development of industrial carbon capture and the available data are extremely limited. The authors assume no liability for any loss or damage arising from decisions made on the basis of this report. The views and judgements expressed here are the opinions of the authors and do not reflect those of the UK Government or any of the stakeholders consulted during the course of this project.

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## Executive summary

Carbon Capture and Storage (CCS) has been recognised, both internationally<sup>1</sup>, and in the UK<sup>2</sup>, as a key technology in reducing CO<sub>2</sub> emissions in the energy-intensive manufacturing industry. For industrial CCS to achieve commercial-scale deployment in the 2030s and beyond, it will be important to demonstrate this technology at a commercially relevant scale in the 2020s. This timeline, and the availability of supportive business models and CO<sub>2</sub> transport and storage infrastructure, form the starting points for this study.

In November 2013, DECC and BIS commissioned a team led by Element Energy, and comprising Carbon Counts, PSE, Imperial College and the University of Sheffield, to carry out a study of industrial CO<sub>2</sub> capture for storage or utilisation. The primary focus of this study is assessing the technical potential and cost effectiveness for retrofit deployment of different CO<sub>2</sub> capture technologies to the UK's existing largest (0.2-8 MtCO<sub>2</sub>/yr) sources of process CO<sub>2</sub> emissions in the cement, chemicals, iron and steel, and oil refining sectors by 2025.

Techno-economic modelling is carried out to understand the cost effectiveness of deployment in different sectors and sensitivity to the main cost drivers. The analysis is based on current understanding of commercial-scale costs and performance of a number of capture technologies. This is supplemented with process simulation-based analysis to provide, in a public and transparent format, detailed performance assessments, equipment requirements and cost estimates for plausible configurations for demonstration and commercial scale carbon capture projects at UK industrial sites. These assessments are combined with stakeholder interviews and literature reviews to provide overviews of barriers to uptake and current piloting and demonstration activities.

The technical and commercial maturity of CO<sub>2</sub> capture for storage or utilisation varies between different source types. Globally maturity is highest for high purity CO<sub>2</sub> sources and the upstream hydrocarbon processing industries, followed by coal and gas power. Development of CCS in the other energy intensive sectors (cement, chemicals, iron and steel, and oil refining) lag several years behind these; there are no industrial retrofit CCS projects worldwide at the scale of UK industrial CO<sub>2</sub> sources (ca. 0.1MtCO<sub>2</sub>/yr to a few MtCO<sub>2</sub>/yr) currently in operation in these sectors. This leads to significant barriers and uncertainties in feasibility, requirements, costs and performance.

## Technology and sector carbon capture potential in UK industry

Stakeholder interviews confirm that first-of-a-kind demonstration projects at the MtCO<sub>2</sub>/yr capture scale at UK sites in 2025 would need to take Final Investment Decision (FID) by 2020, and would seek to minimise risks by employing the most mature technologies with minimal integration challenges.

A number of capture technologies could be deployed in industrial retrofit demonstration scale projects in the period to 2025, including the following high technology readiness level (TRL) capture technologies:

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<sup>1</sup> The role of CCS in industry is highlighted in IPCC (2014) AR5 report on climate change mitigation in industry (available at [http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc\\_wg3\\_ar5\\_final-draft\\_postplenary\\_chapter10.pdf](http://report.mitigation2014.org/drafts/final-draft-postplenary/ipcc_wg3_ar5_final-draft_postplenary_chapter10.pdf)) and the IEA (2012) Technology Roadmap: Carbon Capture and Storage in Industrial Applications, available at: [http://www.iea.org/publications/freepublications/publication/ccs\\_industry.pdf](http://www.iea.org/publications/freepublications/publication/ccs_industry.pdf)

<sup>2</sup> See for example, DECC (2013) The future of heating: Meeting the Challenge, available at [http://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/190149/16\\_04-DECC-The\\_Future\\_of\\_Heating\\_Accessible-10.pdf](http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf) and Element Energy (2013) for BIS: The Costs of CCS for UK industry in 2030: A high level review.

- First generation amine solvents
- Physical solvents (greatest relevance for sources with high partial CO<sub>2</sub> pressure) as well as the following lower TRL capture technologies:
  - Second generation chemical solvents (including advanced amines, amino acids and blends)
  - Cryogenic technologies
  - Solid looping technologies such as calcium looping

The analysis suggests that, in the absence of significant capture technology deployment in the period to 2020, capture technologies with a high TRL would deliver the highest abatement (in tCO<sub>2</sub>/yr abated) at a cost (based on £/tCO<sub>2</sub> abated) competitive with lower TRL technologies.

With a strong technology “push”, leading to significant capture technology deployment in the period to 2020, currently lower TRL technologies could become significantly more cost effective (£/tCO<sub>2</sub> abated) and their abatement potential (in tCO<sub>2</sub>/yr abated) significantly larger.

There are significant cost and performance uncertainties for both low and high TRL technologies, and site-specific interests and issues may dominate technology selection. Additionally there are other more novel capture technologies which are especially effective when integrated in the main process. This high level of integration is usually only feasible for new build facilities and would require significant process and facility redesign in retrofit applications.

The analysis indicates a 2025 abatement potential of 1.2 - 8.2 MtCO<sub>2</sub>/yr for marginal levelised costs of 22 - 74 £/tCO<sub>2</sub> abated (excluding compression, transport and storage) by 2025 in the UK's 52 largest cement, chemicals, iron and steel and oil refining sites. However there is a significant variation in capture potential and cost effectiveness between sectors and between sites. In addition to the technology selection, the key factors affecting differences in cost effectiveness between projects in these sectors are:

1. CO<sub>2</sub> concentration of source gas streams (cost increases with dilution).
2. Degree of contamination of the gas stream (additional gas clean up may be required; some capture technologies are more sensitive to impurities).
3. Mass flow rate of the source (where costs can reduce through economies of scale).

### Barriers to deployment of industrial carbon capture in the UK

For high purity CO<sub>2</sub> sources small scale piloting is unlikely to add significant value, as CO<sub>2</sub> can potentially be captured with limited further CO<sub>2</sub> separation. However for other types of sources, the deployment scales of potential industrial CCS demonstration projects in the period to 2025 can be influenced by the number and scale of detailed engineering studies and pilot projects in the UK and worldwide in the period to 2020.

These engineering studies, pilots and demonstration projects can help reduce multiple barriers and uncertainties ahead of deployment at a commercially relevant scale. The analysis distinguishes between systemic barriers and barriers that can be addressed by pilot and demonstration projects. The most pertinent site level barriers which detailed engineering studies, pilots and demonstrations can reduce are:

- Increased operational complexity and risks (unavailability, process dependencies)
- Applications not proven at scale

- Plant integration risks (hidden costs of additional downtime, alternative product supplies, technology lock-in)
- High levels of uncertainty regarding costs

Further barriers that can be addressed by pilots include lack of staff familiarity and operating expertise, space availability, impact on product quality, effects of impurities, health, safety and environment (HSE) considerations, number of CO<sub>2</sub> streams per site, and budgeting. The report also summarises the key “systemic” barriers and enablers for industrial capture deployment.

### Pilot and demonstrations of carbon capture in UK industry

Pilot and demonstration projects should be designed to remove barriers and reduce uncertainty, and achieve this in a manner that is safe, cost effective and minimises risks. Engineering studies and pilots will have increasing value the more closely the pilot conditions resemble those of the actual UK sites for which demonstration is planned. Several UK industrial sites contacted during the course of this study, and covering all four industrial sectors, indicated a willingness-in-principle to participate in CO<sub>2</sub> capture engineering studies, pilots and/or demonstrations. Work on capture should concentrate, at least initially, on those sites for which CO<sub>2</sub> transport and storage infrastructure can be available in time for 2025.

For first generation amine solvents or physical solvents, there should be some opportunities to learn from CCS demonstration projects in the power sector, in the UK and internationally. In addition first generation amine solvent or physical solvent pilots of 0.1 Mt/yr in cement and up to 0.6 Mt/yr in oil refining in the period 2015-2020, would be valuable in advance of demonstration-scale projects. For second generation amine solvents and solid looping technologies, piloting will be necessary before industry would implement at a scale above 0.1 MtCO<sub>2</sub>/yr.

Potential timelines and project scales to achieve the DECC/BIS challenge of industrial CCS projects operational by 2025 vary between different subsectors:

- For the iron and steel sector, stakeholders confirmed that, with an ambition for a full scale project by 2030, a realistic demonstration project of 1-3 MtCO<sub>2</sub>/yr could be operational by 2025.
- To enable roll out at a scale of 0.9-1.5 MtCO<sub>2</sub> in the oil refining sector by 2025, capture pilots at a scale of 0.1-0.7 MtCO<sub>2</sub>/yr could be implemented in the period to 2020, possibly tied to individual cracker units which are considered one of the likely first capture streams by industry experts.
- In the cement sector development of a project of 0.5 MtCO<sub>2</sub>/yr scale operating in 2025 could be achieved. It may be appropriate to start with one pilot at a scale close to 0.1 MtCO<sub>2</sub>/yr by 2020, and to actively ensure knowledge transfer from international pilots.
- The other chemicals, boilers, CHP and other refinery units typically have multiple, heterogeneous small CO<sub>2</sub> streams, for which the feasibility and cost-effectiveness of CCS, relative to alternative abatement technologies are poorly understood. The next steps should mainly be focussed upon improving understanding of the individual CO<sub>2</sub> streams, their conditions, and method and feasibility for capture.

## Carbon dioxide utilisation

In theory CO<sub>2</sub> utilisation offers opportunities for improving the economics of capture or providing a use of CO<sub>2</sub> for those sites that cannot access transport and storage infrastructure. A literature review reveals that utilisation options differ in terms of technology availability, market maturity, CO<sub>2</sub> abatement potential, and relevance for large UK industrial sites. A key challenge is that existing markets for CO<sub>2</sub> are already competitively supplied with CO<sub>2</sub> produced from existing industrial processes. A step change in CO<sub>2</sub> utilisation could theoretically be achieved through the development of new markets and technologies. However, the majority of emerging technologies are at too early a stage for deployment to reach the scale of 0.1-1 MtCO<sub>2</sub>/yr in 2025 that would be needed to support industrial capture, and the costs, performance and CO<sub>2</sub> abatement potential of these are not yet well described in the literature.

Meaningful onshore CO<sub>2</sub> utilisation levels are only possible with significant and carefully designed interventions to build markets and push technology development. Stranded industrial CO<sub>2</sub> sources are unlikely to implement capture based on revenues from utilisation alone without additional policy support. Annual revenues of £25-250million may be possible if some of the hurdles identified can be overcome. An upper limit for the potential for CO<sub>2</sub> utilisation deployment in the UK by 2025 is estimated at 9 MtCO<sub>2</sub>/yr with annual revenues of up to £3 billion arising from the production of fuels, building products and chemicals based on CO<sub>2</sub> feedstocks.

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## 1 Introduction

### 1.1 The drivers for industrial carbon capture

Combustion and process CO<sub>2</sub> emissions from the four main energy intensive industries; the cement, chemicals, oil refining and iron and steel sectors, represent 25% of the UK heat-related CO<sub>2</sub> emissions<sup>3</sup>, mostly from fossil fuels, and these energy intensive sectors together contribute £10bn/yr<sup>3</sup> to the UK economy (0.7% of the UK's GDP<sup>4</sup>). Their products are, by and large, traded globally.

Current UK industrial CO<sub>2</sub> emissions are some 112Mt/yr<sup>5</sup>. Although further incremental reductions in CO<sub>2</sub> emissions are possible through improved efficiency and fuel switching, carbon capture and storage (CCS) technology is recognised for offering the potential for deep reductions in CO<sub>2</sub> emissions from these four sectors.

A number of carbon capture technologies are under development, which have diverse potential, costs, benefits and risks in the period to 2025. Understanding of their potential deployment scale, applicability to industrial sites, costs and piloting/demonstration requirements is limited.

Carbon capture, transport and storage face high costs and geographic constraints based on access to CO<sub>2</sub> transport and infrastructure. Of increasing interest is the potential for CO<sub>2</sub> utilisation as a means of deploying capture technologies, while providing an additional market based revenue stream for the producer and opportunities to reduce costs. CO<sub>2</sub> utilisation also offers a route to reducing overall UK CO<sub>2</sub> emissions for assets that are unlikely to have access to transport and storage infrastructure. The understanding of which of the many potential CO<sub>2</sub> utilisation pathways are most relevant for UK industry is also limited.

### 1.2 Study Background

In September 2013, the Department of Energy and Climate Change (DECC) and the Department of Business Innovation and Skills (BIS) jointly issued an ITT, with an industrial steering board, for consultants to provide DECC and BIS with a better understanding for the costs and potential for retrofitting carbon capture technologies and for the potential for carbon utilisation, in these four sectors in the period 2020-2025. Having this clear timescale for the implementation of these technologies as input for the study, allows the analysis to focus on those technologies that have been piloted or demonstrated and have moved beyond laboratory or bench scale testing. These dates are based on analysis for meeting the UK's climate change goals, including those in the Carbon Plan, Delivering our Low Carbon Future, published in 2011, and the Future of Heating: Meeting the Challenge, published in 2013. Government has made no commitment to implement ICCS in this timeframe.

A team led by Element Energy Ltd., and comprising Carbon Counts Ltd., Process Systems Enterprise (PSE) Ltd., Imperial College London, and the University of Sheffield, was awarded the project in November 2013. The proposed approach combined literature review, the creation of Excel-based databases and a techno-economic model to characterise the carbon capture and the utilisation potential, a program of consultations

<sup>3</sup> DECC, the future of heating (2012)

<sup>4</sup> Office of National Statistics (2012 GDP at market prices £1,500bn)

<sup>5</sup> DECC CO<sub>2</sub> emission data tables, available at <https://www.gov.uk/government/organisations/department-of-energy-climate-change/about/statistics>

with industry representatives and technology developers and process simulation case studies to “groundtruth” understanding.

The aim of deploying large scale carbon capture demonstration projects in industry by 2025 is a given starting point for this study. This could make carbon capture in industry commercially available in 2030 and can facilitate international agreements in this area. The availability of supportive business models and CO<sub>2</sub> transport and storage infrastructure also form given starting points for this study. These starting points, as well as policy needs are not assessed in this study. The scope of the study is furthermore defined by the following:

- Retrofit to existing cement, chemicals, iron and steel and oil refining sectors
- Focus on projects that could be commercially operational by 2025
- Identify steps such as pilots and demonstrations that could enable deployment projects in 2025
- Provide a techno-economic evidence base of capture options
- The scope comprises carbon capture and the opportunity for utilisation
- Focus on the capture of CO<sub>2</sub>; assuming that legal, regulatory, business model, and transport and storage barriers are solved
- CO<sub>2</sub>-Enhanced gas recovery and enhanced oil recovery (EOR) are out of scope. This has been investigated extensively in prior research<sup>6</sup>.

### 1.3 Report Structure

The remainder of this report is structured as follows:

Section 2 assesses the most appropriate technologies and sectors for industrial CCS demonstration projects in the period to 2025, based on techno-economic modelling.

Section 3 describes the main barriers to the deployment of industrial carbon captured by 2025 and the opportunity for overcoming these challenges, with a focus on technology piloting and industry application demonstrations. The section reports on qualitative drivers that may direct technology selection within specific sectors.

Section 4 reviews the current and planned capture projects worldwide, with a focus on the energy intensive industry, and explores potential pathways to reach commercial scale deployment of industrial carbon capture in the UK by 2025. The results from techno-economic analysis, barriers and capabilities review, and the review of existing piloting and demonstration activity are used to identify opportunities for industrial capture pilots and demonstrations. Insights on the potential designs of pilots and demonstration projects from process simulation are discussed.

Section 5 assesses the main CO<sub>2</sub> utilisation opportunities in the period to 2025.

Section 6 presents the report's conclusions.

The report is accompanied by an extensive Appendix. This provides details on the approach, CO<sub>2</sub> sources, sector-specific opportunities and constraints, capture and utilisation technologies, key assumptions, and results of techno-economic modelling across a wide range of scenarios/sensitivities. The appendix also provides case studies with process simulation descriptions of potential UK industrial CO<sub>2</sub> source-capture technology configurations of relevance in the period to 2025.

<sup>6</sup> For a recent assessment of the techno-economics of CO<sub>2</sub>-enhanced oil recovery, see Element Energy *et al* (2014) CCS Hub Study, for Scottish Enterprise.

## 2 The opportunity for carbon capture in the energy intensive industry in 2025

A recent literature review identified potential costs for CO<sub>2</sub> capture in UK industry, but identified significant uncertainties and inconsistencies in the published reports on costs<sup>7</sup>. Techno-economic analysis enables systematic assessment of the abatement potential and the levelised cost for the main retrofit capture technologies in four sectors within UK energy intensive industries (iron and steel, cement, oil refining and chemicals). The analysis is based on technically appropriate combinations of CO<sub>2</sub> source streams and capture technologies. The overall results of the techno-economic analysis are presented in section 2.1. The underlying sector and technology dimensions are discussed in more detail in the subsequent sections.

The four energy intensive industry sectors are further subdivided in this analysis in the below seven sub-sectors. This is done to capture the very different characteristics for carbon capture between different types of facilities within sectors, which is further detailed in section 2.2. The abatement potential and cost effectiveness within these subsectors are also assessed in section 2.2.

- High purity CO<sub>2</sub> sources (ammonia and hydrogen production)
- Iron and steel
- Cement
- Crackers
- Other refinery
- Other chemicals
- Industrial boilers and combined heat and power units (mostly gas fired)

From an extensive capture technology list, eight key retrofit capture technologies are identified for the analysis, based on a comprehensive technical and economic filtering. This shortlist has been agreed with the project's industry steering board. The abatement potential and cost effectiveness of these technologies are discussed in section 2.3.

### 2.1 The carbon capture opportunity in 2025

#### Key message:

The analysis identifies a 2025 potential for CO<sub>2</sub> capture in the four UK energy intensive industries of 1.2 – 8.2 MtCO<sub>2</sub>/yr for marginal levelised costs at 22 – 74 £/tCO<sub>2</sub> abated. This is equivalent to 1 - 7% of current UK industry total carbon emissions<sup>1</sup>. These figures are highly sensitive to abated CO<sub>2</sub> revenues and capture deployment levels.

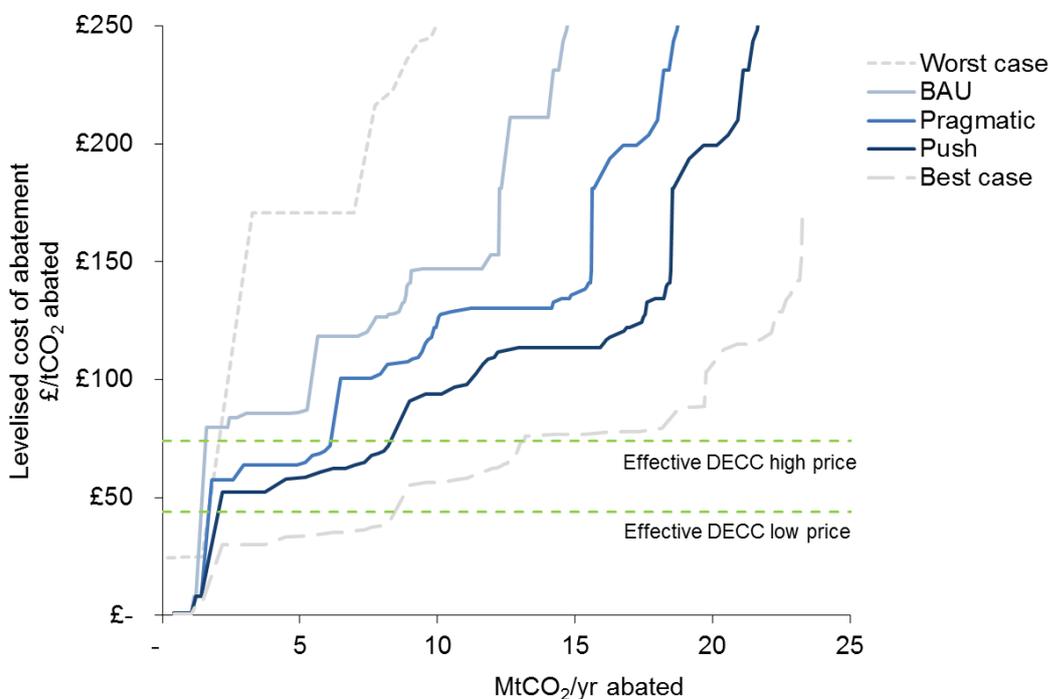
In this analysis capture potential and cost effectiveness are estimated for three capture technology deployment scenarios by 2025. Within each scenario the most cost effective available technology is selected for each source. The three scenarios; Business As Usual (BAU), Pragmatic and Push, assume different degrees of technology deployment, where BAU has the lowest deployment and Push the highest. This impacts the maximum scale at

<sup>7</sup> Element Energy (2013) The costs of CCS in for UK industry: A high level review, for BIS, available at: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/181161/bis-13-745-the-costs-of-carbon-capture-and-storage-for-uk-industry-a-high-level-review.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/181161/bis-13-745-the-costs-of-carbon-capture-and-storage-for-uk-industry-a-high-level-review.pdf)

which technologies can be deployed<sup>8</sup> and correspondingly also the realisable economies of scale.

The recent Government-industry CCS Cost Reduction Task Force identified potential levels for CCS cost reduction<sup>9</sup>. The costs for industrial CO<sub>2</sub> capture are currently significantly more uncertain than those in the power sector because much less research, development, engineering analysis, piloting, or demonstration has focussed on industrial processes, and because processes are heterogeneous and sites are brownfield.

Given a highly uncertain starting point, the potential cost reduction and performance improvement for specific individual capture technology-sector combinations between now and 2025 are unclear. On the one hand cost savings and performance improvements may result from further technology development, as well as economies of scale. On the other hand, the costs may turn out to be higher, due to unforeseen complexities arising at larger scale applications. The technology deployment scenarios are discussed in more detail in section 2.3.1 and the appendix.



**Figure 1 Marginal Abatement Cost Curves for CO<sub>2</sub> capture from the four energy intensive industries in 2025 (central price scenario)**

Figure 1 shows the 2025 levelised cost of CO<sub>2</sub> capture in the four energy intensive industries against the corresponding carbon abatement potential for the three technology deployment scenarios. The green dashed lines indicate the range of effective (levelised) carbon prices for DECC carbon price projections<sup>10</sup>. At marginal levelised costs (excluding transport and storage) equivalent to these carbon prices, the CO<sub>2</sub> abatement potential

<sup>8</sup> Depending also on their current technology readiness level (TRL)

<sup>9</sup> DECC, The Crown Estate, and the CCSA (2013) Final Report for the UK CCS Cost Reduction Task Force, available at:

[https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/201021/CCS\\_Cost\\_Reduction\\_Taskforce\\_-\\_Final\\_Report\\_-\\_May\\_2013.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/201021/CCS_Cost_Reduction_Taskforce_-_Final_Report_-_May_2013.pdf)

<sup>10</sup> DECC IAG carbon prices in the “low traded” scenario and “high non-traded” scenario for a 15 year project lifetime, starting in 2025 with a 10% discount factor.

ranges from 1.2 MtCO<sub>2</sub>/yr, for low technology deployment and low marginal levelised cost, to 8.2 MtCO<sub>2</sub>/yr for a high degree of technology deployment and high marginal levelised cost.

Aside from the impact related to technology deployment level, system variables can have a very large impact on the abatement potential and levelised costs. The two main system variables are energy prices and capital cost factors. Taking optimistic (i.e. lower bound) values<sup>11</sup> for both results in a capture potential of 13MtCO<sub>2</sub>/yr at a marginal levelised cost equivalent to the DECC high carbon price and the Pragmatic technology deployment scenario, as indicated in Figure 1.

Similar cost estimations of IGCC (integrated gasification combined cycle) plant carbon capture shows carbon abatement costing around £80/tCO<sub>2</sub><sup>12</sup>. Furthermore, consumer investment in the non-domestic renewable heating technologies of biomass boilers, ground source heat pumps and solar thermal technology is cited at being around £176/tCO<sub>2</sub><sup>13</sup>. Other abatement methods, particularly involving energy efficiency are known to cost less; an example of this is cavity wall insulation, which is estimated to save consumers around £20-150/tCO<sub>2</sub><sup>14, 15</sup>.

In the next section the capture potential in the different sub-sectors is assessed in more detail for the Pragmatic scenario. The capture potential in terms of the underlying technologies is presented in section 2.3. Section 2.3.4 provides an overview of the main sensitivities at both a technology and project level as well as for system wide variables.

<sup>11</sup> DECC IAG industrial low and high scenarios for fuel prices.

<sup>12</sup> IEA GHG, this cost is based on an average of IGCC plant technologies shown.

<sup>13</sup> Non-domestic RHI Final Impact Assessment: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/263581/Impact\\_Assessment\\_RHI\\_Tariff\\_Review\\_Extensions\\_and\\_Budget\\_Management\\_Dec\\_2013.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/263581/Impact_Assessment_RHI_Tariff_Review_Extensions_and_Budget_Management_Dec_2013.pdf)

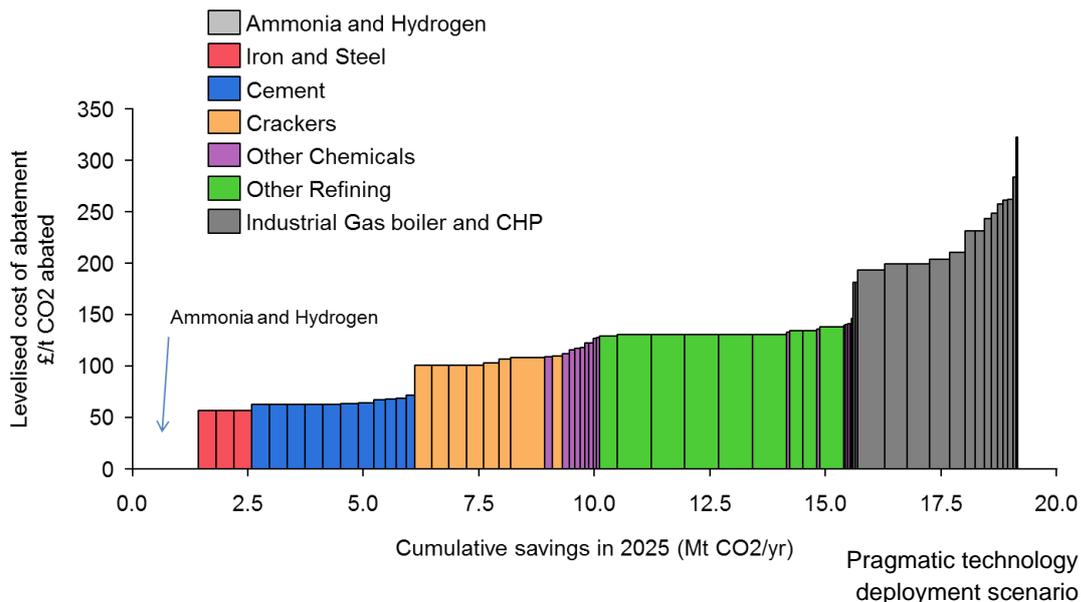
<sup>14</sup> 2020 insulation measures, Green Deal Final Impact Assessment, p.38, Figure 10: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/42984/5533-final-stage-impact-assessment-for-the-green-deal-a.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42984/5533-final-stage-impact-assessment-for-the-green-deal-a.pdf)

<sup>15</sup> These estimates provide the full CO<sub>2</sub> abatement cost. The full cost of abatement through CCS consists of capture, transport and storage. The scope of this study covers the capture part. While the capture part usually represents a large part of the cost, the cost for storage and transport can also be significant. The CCS cost reduction task force (CCSA, The Crown estate & DECC, CCS cost reduction task force final report, 2013), estimates that for 2020 new built post combustion capture on a coal fired power plant, the capture part represents around 65% of the total cost of carbon capture and storage (excluding the reference power plant). These costs are however not necessarily representative for retrofit industrial CCS applications, and moreover depend strongly on a number of aspects, including the CO<sub>2</sub> source characteristics and location, the topology of the transport infrastructure and the type and location of storage.

## 2.2 The carbon capture opportunity in industrial sub sectors in 2025

**Key message:**

Amongst the sectors analysed, the high purity sources represent the most cost effective capture opportunity, followed by the iron and steel and cement sectors.



**Figure 2 Marginal abatement cost curve for different subsectors for projects operational by 2025.**

Although overall cost uncertainties are significant (potentially spanning an order of magnitude or more), within any given scenario, the relative cost effectiveness is determined by three primary drivers, which are, in order:

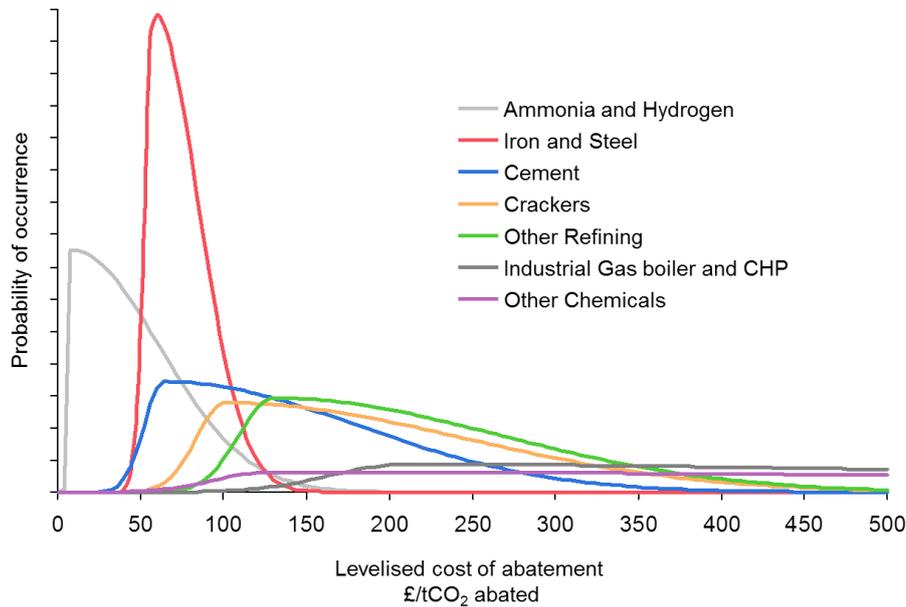
1. CO<sub>2</sub> concentration of source gas streams (cost increases with dilution)
2. Degree of contamination of the gas stream (additional gas clean up may be required; some capture technologies are more sensitive to impurities.)
3. Mass flow rate of the source (where costs can reduce through economies of scale).

The high purity (ca. 99%) CO<sub>2</sub> streams from ammonia and hydrogen production processes in the chemicals and oil refining sectors, which require only marginal clean up<sup>16</sup>, provide the lowest cost abatement opportunities. Beyond those the steel and cement sectors provide significant opportunity of some 5MtCO<sub>2</sub> abatement potential at a cost below £75/tCO<sub>2</sub> in the pragmatic scenario. These sectors have source CO<sub>2</sub> concentrations in the range 14%-44% and (predominantly) large single emission point sources.

<sup>16</sup> Costs depend on the specification of transport infrastructure and utilisation application

**Key message:**

Even when accounting for variation, there is a clear ranking of the most important subsectors.



**Figure 3 Typical distribution of levelised cost of abatement for each sub sector by 2025**

Figure 3 shows the distribution of levelised costs of abatement per sub sector, which results from project to project variations in the three main drivers of CO<sub>2</sub> concentration, contamination, and scale. The peaks correspond to “median” projects in the pragmatic scenario with central price assumptions. The width of the peaks indicates the variation in levelised cost across the scenarios explored. The range of costs is narrow for ammonia and hydrogen and iron and steel sectors. The range is largest for other chemicals and other refining sectors. There is significant overlap of projected capture costs between sectors, particularly at higher abatement costs. However the results suggesting overall cost ranking in the sequence ammonia/hydrogen < iron and steel < cement < crackers < other chemicals, refining and boilers. Focussing on the lowest cost sectors for a 2025 scenario appears most efficient, although it should be recognised that actual conditions pertaining at individual facilities may depart significantly from the “archetype” properties assumed in this study.

**2.3 The technology opportunity for carbon capture in 2025**

The techno-economic analysis makes use of eight key retrofit capture technology archetypes. From an extensive long-list, these were identified based on technical and economic filters, and ratified by the project’s industry steering board. These key technologies are summarised in Figure 4 below and described in more detail in the appendix. Note that this should not be regarded as an exhaustive list.

For the techno-economic analysis results presented in the previous sections, the most cost effective (in £/tCO<sub>2</sub> abated) of the available technologies per source was selected. The effectiveness and suitability of different technologies in the different subsectors is assessed in the following subsections.

<p><b>First generation amines</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> separation by 1<sup>st</sup> gen amine chemical solvent</li> <li>• Most commonly used capture technology for natural gas processing</li> <li>• Key element of many post-combustion CCS demonstration projects being developed in power sector at ca. 1 Mt CO<sub>2</sub> /yr</li> </ul>
<p><b>Second generation chemical solvents</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> separation by advanced chemical absorption solvents including amines, amino acids and blends.</li> <li>• Multiple technologies being piloted at 0.001-0.1 Mt/yr with higher and faster absorption rates, reduced degradation, lower environmental/safety challenges, and/or lower regeneration energy requirements.</li> </ul>
<p><b>Potassium carbonate</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> separation by chemical solvent</li> <li>• Low environmental impacts from solvent.</li> <li>• Mature technology (e.g. used at Mt/yr scale in fertiliser production)</li> <li>• Tech development focussed on blends (e.g. with promoters such as piperazine).</li> </ul>
<p><b>Chilled ammonia</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> separation by chemical absorption using aqueous ammonia</li> <li>• Pilot developed upto 0.1 MtCO<sub>2</sub>/yr capture</li> </ul>
<p><b>Physical solvents, e.g. Rectisol &amp; Selexol</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> separation by physical absorption using methanol or an ether solvent, requiring high CO<sub>2</sub> partial pressure.</li> <li>• Commercially used for CO<sub>2</sub> separation in syngas or natural gas streams at Mt/yr scale.</li> </ul>
<p><b>Cryogenics</b></p>	<ul style="list-style-type: none"> <li>• CO<sub>2</sub> liquefaction through cooling.</li> <li>• Experience at 0.1 Mt/yr scale for high purity sources only.</li> <li>• New technologies under development.</li> </ul>
<p><b>Solid looping, e.g. calcium looping</b></p>	<ul style="list-style-type: none"> <li>• Involves oxide calcium carbonate interconversion at 700-900°C</li> <li>• Draws on well understood and comparatively low capital cost processes in lime/cement industries.</li> <li>• For capture has only been demonstrated at pilot plants, applicability to diverse industrial sources is not yet clear.</li> </ul>

Figure 4 Shortlist of key retrofit capture technologies for analysis

### 2.3.1 Technology abatement potential and cost effectiveness

The modelling distinguishes three technology deployment scenarios corresponding to different roll-out rates for technologies.

In the Business As Usual (BAU) scenario, deployment is restricted to currently planned projects worldwide, so that the capture technologies available at significant scale are chemical solvents (e.g. 1<sup>st</sup> generation amines or potassium carbonate) and physical solvents (e.g. selexol or rectisol).

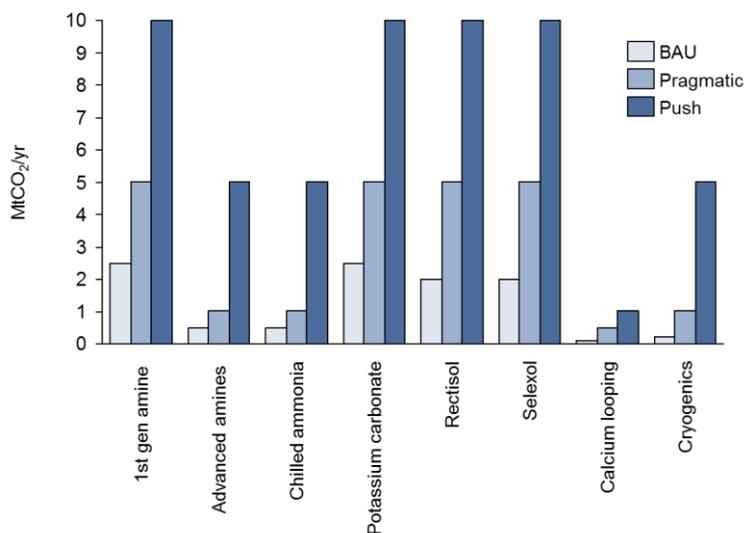
The Pragmatic scenario assumes a few demonstration-scale (e.g. >0.1 Mt/yr) capture projects using 1<sup>st</sup> generation amines or physical solvents are successful (e.g. >10,000 run

hours successful operation) in the period to 2020, combined with significant additional investments in pilot projects for 2<sup>nd</sup> generation chemical solvents, chilled ammonia, solid looping, and cryogenics in the period to 2020. With these successes, investors are assumed to be willing to support larger scale investments for a project operational in 2025.

These pilot and demonstration projects should be carried out at sites with technical configurations and commercial arrangements that resemble those at the UK sites for which demonstration is planned, and to which the stakeholders for UK industrial CCS demonstration projects have access.

The Push scenario assumes the fastest level of scale up of capture technologies, with multiple successful demonstration scale projects (e.g. tens of thousands of run hours of operation above 0.1 MtCO<sub>2</sub>/yr). To allow for maximum ramp up, it is again assumed that the pilot projects are at the same or very similar sites as the planned demonstration projects.

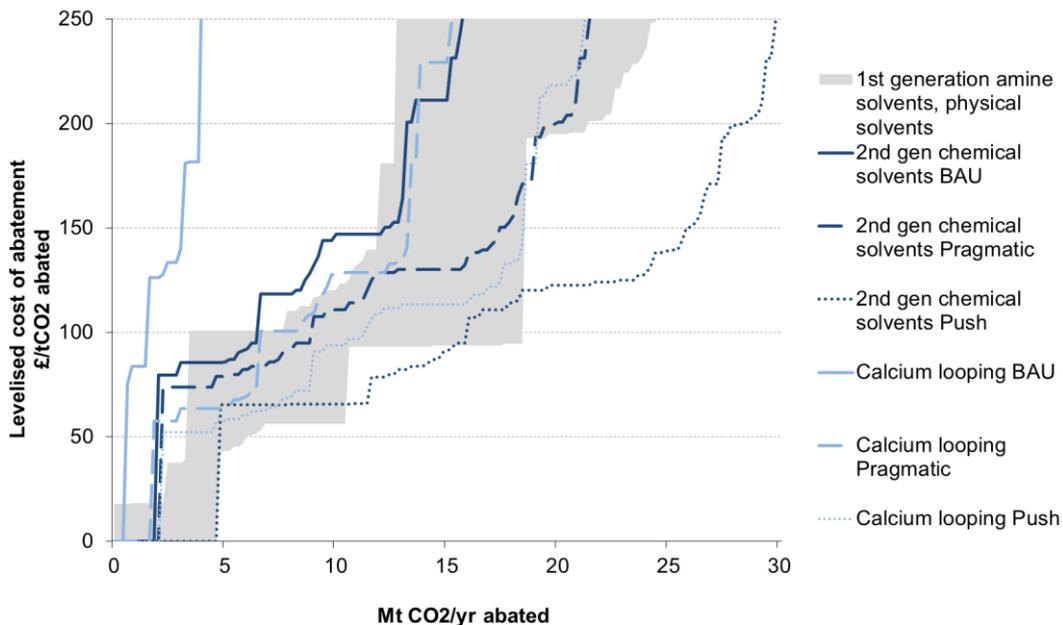
Note that these scenarios focus on technology scale available, rather than cost reduction for individual technologies per se, as it is far from clear what first-of-a-kind cost or risk premium will be needed. As highlighted by the joint DECC/industry Cost Reduction Task Force, experience with other technologies (such as flue gas desulphurisation) is that the very first projects may even show cost increases or performance reductions relative to expectations.



**Figure 5 Potential scale of deployment scenarios for capture technology projects at existing industrial sites in the period to 2025.**

**Key message:**

In the Pragmatic scenario the currently most mature technologies have the highest abatement potential and are the most cost effective. A few technologies at lower technology readiness levels may become more effective, and show a higher abatement potential and cost effectiveness in a high capture technology deployment scenario.



**Figure 6 Technology marginal abatement cost curves under different scenarios of technology deployment by 2025. The shaded area indicates the range of currently mature technologies (1<sup>st</sup> gen chemical and physical solvents) for the three technology deployment scenarios.**

The Technology Readiness Level (TRL) of each technology, defining the scale at which technologies can be deployed, has a significant impact on abatement potential and levelised costs by 2025.

The mature capture technologies are first generation amine chemical solvents (e.g. MEA) and physical absorption solvents (e.g. selexol and rectisol)<sup>17</sup>. The latter however would generally require significant electricity for compression of the source gas stream, to provide the elevated operational pressure that these physical solvent absorbents require. The abatement potential and effectiveness of these mature technologies is similar across the different technology deployment scenarios and their performance is similar (within the resolution of the analysis). In Figure 6 the grey shaded area indicates the range of the abatement curves of these currently mature technologies under the three technology deployment scenarios.

<sup>17</sup> To our knowledge, the performance of flue gas compression followed by treatment with selexol or rectisol have yet to be tested on post-combustion streams at scales of greater than 0.1 MtCO<sub>2</sub>/yr.

Of the lower TRL capture technologies, the analysis indicates that second generation chemical solvents (e.g. advanced amines, amino acids or blends) and solid looping (e.g. calcium looping) provide significant potential for improvement (see appendix)<sup>18</sup>. The performance of these technologies is also shown in Figure 6. Similarly, Figure 7 shows that the currently lower TRL technologies provide an opportunity for more cost effective carbon capture, although the absolute scale at which they can be deployed will initially be lower than for higher TRL technologies. Figure 8 summarises the leading technologies across sectors for the different technology deployment scenarios.

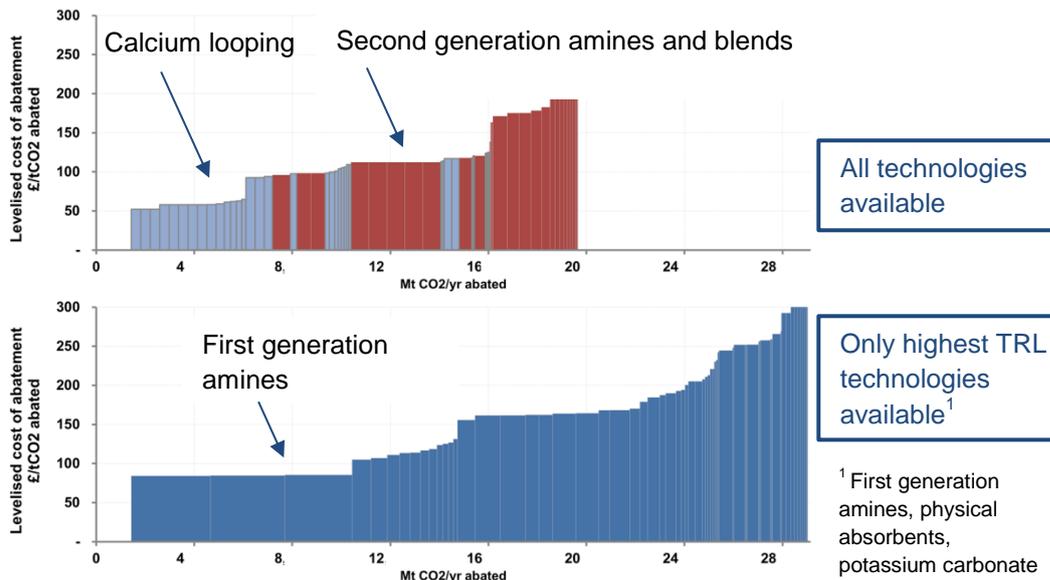


Figure 7 Comparison of marginal abatement cost curves for different technology availabilities

	BAU	Pragmatic	Push
Technology deployment scenario	Limited technology deployment	High technology deployment	Very high level of technology deployment
Leading technologies across sectors	1 <sup>st</sup> generation amines and physical solvents have the highest abatement potential, 2 <sup>nd</sup> generation amines are close in performance	1 <sup>st</sup> and 2 <sup>nd</sup> generation amines and physical solvents show the highest abatement potential, while calcium looping has similar effectiveness under some conditions	2 <sup>nd</sup> generation amines have a higher abatement potential and are significantly more cost effective than the mature technologies and the performance of calcium looping is also more competitive than mature technologies

Figure 8 Summary of the leading technologies under different technology deployment scenarios.

<sup>18</sup> Cryogenic separation could be cost effective under certain conditions, and further developments in other technologies may change their performance and cost outlook

### 2.3.2 Technology suitability for application in different subsectors

The suitability of the eight key technologies for deployment in the six industrial sub sectors by 2025 is summarised below<sup>19</sup>. The suitability is based on the characteristics of the different technologies and sub sectors and the results of the techno economic analysis.

#### High Purity CO<sub>2</sub> sources

Worldwide, operational full-chain industrial CCS is dominated by sources where a high purity CO<sub>2</sub> stream (>95% concentration in flue gas) is available as the by-product of an (intrinsically commercially viable and technically mature) industrial process. The common sources of high purity CO<sub>2</sub> are natural gas processing, hydrogen, ammonia and biofuel production from fermentation<sup>20</sup>. For these sources the engineering requirements are dictated by the specifications for CO<sub>2</sub> transport and/or utilisation infrastructure. Without the need for expensive capture plants and novel technologies, the commercial challenge for these sources is therefore limited to developing suitable business models.

#### Iron and Steel

A large number of capture configurations are feasible in the iron and steel sector<sup>21</sup>. For techno-economic modelling, the base case assumes a central of 60% of current emissions, within a range of 50-75% of site CO<sub>2</sub> is accessible for capture, in line with other studies.

However, with a focus on deploying CCS at existing UK sites in the period to 2025, the most attractive capture options involve targeting less than half of the 6-8 Mt/yr of a site with minimal integration and base process redesign. Of particular interest are capture from Blast Furnace Gas (for which a physical solvent such as selexol or rectisol could be attractive due to the higher gas pressure, with or without a shift reaction), or afterwards from the flue gas from a Combined Heat and Power (CHP) facility. The latter configuration is explicitly examined in the process simulation described in Section 4, whereas the techno-economic modelling in this chapter assumes that up to 60% of the site CO<sub>2</sub> emissions can be collected (potentially from multiple sources, including stoves and CHP).

#### Oil refining and Other Chemicals

Oil refineries and chemical production sites are heterogeneous. A key issue is the presence of multiple vents dispersed across a large area, with a variety of capacities and CO<sub>2</sub> stream compositions. If high purity CO<sub>2</sub> sources are excluded, then the majority of streams will be combustion streams (e.g. linked to furnaces). The oil and chemical industries are familiar with the use of the wide range of separation technologies (chemical and physical solvents, solid looping, and cryogenic technologies). However significant effort may be required to understand how to tailor capture for individual source characteristics, and how best to aggregate multiple sources to realise economies of scale in CO<sub>2</sub> pre-treatment and capture (with minimal impact on the rest of the plant). Power stations, CHPs and chemicals complexes are also often relatively close by to the UK's largest refineries and chemical industry clusters.

<sup>19</sup> The overview excludes gas boilers and CHPs, as these are not the focus of this report.

<sup>20</sup> Carbon Counts (2010) CCS Roadmap for industry: High purity CO<sub>2</sub> sources: Sectoral assessment – final report for the International Energy Agency (IEA).

<sup>21</sup> IEA, & UNIDO. (2011). Technology Roadmap. Carbon Capture and Storage in Industrial Applications. p. 25

Cement

At cement sites, the use of chemical solvents CCS demonstration at some sites may be restricted in the period to 2025 by the lack of significant volumes of water for cooling<sup>22</sup>, limited experience with solvent-based technologies, absence of COMAH status. This may drive interest towards solid looping.

2.3.3 Cost breakdown and drivers of technology effectiveness

**Key message:**

The relative importance of different cost drivers vary significantly between capture technologies.

In this section the underlying drivers and main cost components for the different technologies are reviewed, for a number of illustrative sources.

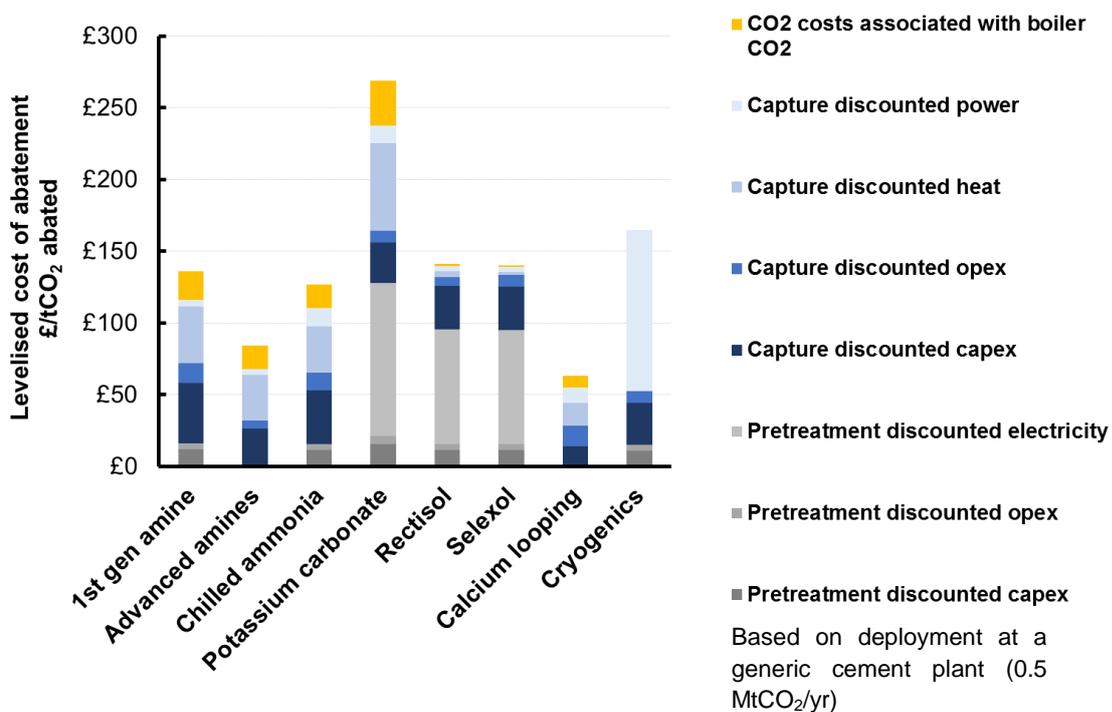


Figure 9 Levelised cost breakdown for different technologies

With significant heterogeneity and opacity in the literature on industrial CCS costs, the costs for 1<sup>st</sup> generation amine technology are benchmarked against the published Post-FEED estimate for the capital cost of Scottish Power’s Longannet Coal Power Station Retrofit CCS project using Aker’s 1<sup>st</sup> generation chemical solvent technology. The cost estimate excludes CO<sub>2</sub> compression but includes the cost of a boiler to generate steam, as well as contingencies. Pre-treatment costs are calculated separately. The capital and

<sup>22</sup> Cooling could be provided by other means, for instance evaporative cooling

operating costs for 2<sup>nd</sup> generation, and potassium carbonate based capture are then calculated based on published ratios of the costs of these systems to a 1<sup>st</sup> generation amine system.

### 1<sup>st</sup> and 2<sup>nd</sup> generation chemical solvents

The costs for 1<sup>st</sup> generation amine chemical solvents are dominated by capex and heat. If developed, 2<sup>nd</sup> generation chemical solvents should have significantly lower costs than 1<sup>st</sup> generation technologies, driven by several factors. Better compatibility with NO<sub>x</sub> and SO<sub>x</sub> could reduce (or even eliminate) the capex and opex for pre-treatment. Capture capex could be reduced if solvents with better loading and kinetic properties allow for smaller column sizes, or less corrosive solvents allow cheaper alloys to be used. Opex requirements could fall if improved solvent stability leads to lower solvent replacement rates, waste disposal or water requirements. Thermal energy costs (and associated CO<sub>2</sub> payments from ancillary boilers) could be reduced through improved process integration and using advanced solvents with lower regeneration energy.

### Chilled ammonia

Chilled ammonia has similarities with amine-based solvents. The cost breakdown is therefore also similar, although there is a slightly lower heat consumption requirement.

### Potassium carbonate

Potassium carbonate capture is a mature technology, which is often used in processes that generate high CO<sub>2</sub> purity streams. The levelised cost for this technology is high for the cement, chemicals, iron and steel and oil refining CO<sub>2</sub> sources, because of the expense of electricity for flue gas compression from ambient pressure.

### Physical solvents

Physical solvents require a high CO<sub>2</sub> partial pressure (e.g. at least 2.5 bar) to operate efficiently. Physical solvents are therefore especially appropriate for flue gas streams at higher pressures. Since most of the CO<sub>2</sub> source streams at UK energy intensive sites are identified as being at atmospheric pressure, it would be necessary to compress flue gases prior to capture. Assuming availability of compressors that are compatible with flue gas streams, then the cost of capture is dominated by the high electricity cost associated with compression. Commercially available physical solvents have been primarily applied for natural gas or syngas processing, and performance with oxygen-rich flue gas streams has not been documented, creating significant uncertainties on feasibility and costs.

### Calcium looping

Published cost estimates for calcium looping capture applications indicate that this could be a low cost technology option, with lower pre-treatment, capex and heat requirements compared to first generation amine solvents. However calcium looping has so far only been piloted at small scale. Significant technology development for the technology could allow this technology to be demonstrated at up to 1 Mt/yr scale in 2025.

### Cryogenics

Conventional cryogenic technologies are commercially applied to high purity CO<sub>2</sub> sources; application to dilute sources for the purpose of CO<sub>2</sub> purification is rare. For dilute flue gases, the levelised cost of conventional cryogenic CO<sub>2</sub> separation is dominated by the electricity cost for cooling large volumes of flue gas. Conventional cryogenic separation could be more cost competitive for sources with high CO<sub>2</sub> partial pressures, than amines. Opportunistically, cryogenic capture could also be competitive with dilute flue gas streams

if low cost cooling can be provided, for instance if integrated with an LNG regasification process<sup>23</sup> or where cooling can be mechanically coupled to another process e.g. compression.<sup>24</sup>

### 2.3.4 Technology effectiveness: sensitivity analysis

**Key message:**  
The key sensitivity parameters for the different technologies are the capital cost factor, source CO<sub>2</sub> purity, energy prices and the level of technology deployment

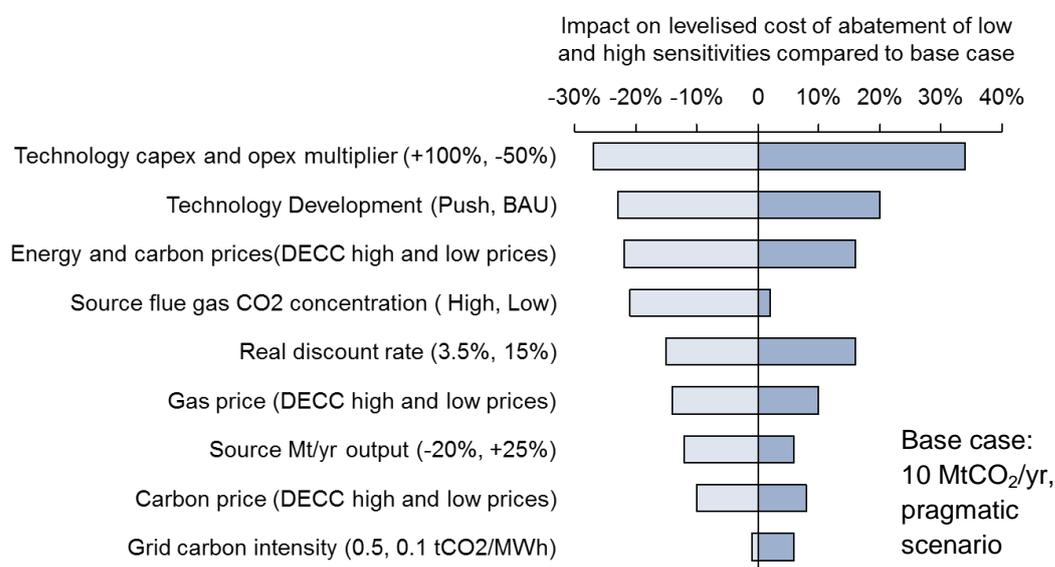


Figure 10 Sensitivity tornado for the most pertinent parameters

A sensitivity analysis has been carried out on the key parameters impacting the cost effectiveness of the capture technologies. The impact of these parameters will vary between technologies. Figure 10 provides an overview of the sensitivities for an illustrative point (10 Mt CO<sub>2</sub>/yr) at the marginal abatement cost curve in the Pragmatic scenario. The main sensitivity outcomes are summarised below and the full sensitivity analysis is provided in the appendix.

#### Capital cost uncertainty

The largest uncertainty is the capital cost uncertainty. As all technologies require significant capital investments, this is the case across technologies and sectors, although it is most pronounced for the more capital intensive technologies such as 1<sup>st</sup> generation amines and chilled ammonia. The accuracy range of cost estimates in this report should

<sup>23</sup> Tuinier, M. J. et al. (2011) Techno-economic evaluation of cryogenic CO<sub>2</sub> capture: A Comparison with absorption and membrane technology, Intl. J. Greenhouse Gas Ctrl., 5, 1559-1565;

<sup>24</sup> Novel cryogenic processes are under development for high concentration, high pressure CO<sub>2</sub> sources, where electricity demand is reduced through mechanical coupling of compressors and cooling systems, such as the Costain NGCT system (<http://www.carbon-capture-and-storage.com/ngct-benefits.htm>)

be treated as +100%/-50%<sup>25</sup> <sup>26</sup>. This cost uncertainty could derive from multiple sources, including cost index (steel, engineering, labour) variation, exchange rate, site-specific issues. Experience from the deployment of other pollution control or novel energy technologies is that cost reduction or performance improvements, though possible, should not necessarily be expected from initial projects, although uncertainties should be narrowed. Indeed these early projects may identify unexpected issues that increase costs or result in lower output.

### Source purity and pressure

One of the dominant factors impacting the levelised cost is the CO<sub>2</sub> purity of the gas stream (approximately an inverse power law), following Husebye *et al.* (2012), shown in Figure 11. At atmospheric pressure, below 20% CO<sub>2</sub> concentration, chemical solvents are favoured relative to physical solvents, while above 70% CO<sub>2</sub> concentration, physical solvents generally become more cost effective. In between these limits the relative cost effectiveness is more dependent on the specific source conditions. The apparent asymmetry in the graph reflects different source-technology combinations chosen at 10 Mt/yr at low and high source concentrations.

### Energy and carbon prices

Except for high purity sources (ammonia and hydrogen production facilities), the £/tCO<sub>2</sub> abated costs are very sensitive to electricity and gas (heat) price. As long as these move in the same direction, changes in these parameters do not materially change the ranking of the opportunities in different subsectors.

Changes in either electricity or heat cost do impact technologies differently, depending on their cost breakdown structure (see Figure 9). Figure 10 shows the sensitivities for a high heat consumption but a low electricity consumption, resulting in the low sensitivity for changes in the electricity price alone. For physical absorption solvents, with high electricity but low heat requirements, the impact will be the opposite.

Figure 10 also shows a sensitivity of the levelised cost to the carbon price. This reflects the cost of CO<sub>2</sub> emissions related to the heat and electricity requirement of the capture plant (the benefit of abating CO<sub>2</sub> emissions through capture, i.e. potential revenue stream, is not factored into the levelised cost calculation).

### Discount rate

Although the discount rate impacts the overall levelised cost of abatement for different projects, it is not a primary determinant of sector/capture technology ranking, as all the capture technologies have significant initial and ongoing costs.

<sup>25</sup> Based on AACE expected accuracy ranges for cost estimate class 4-5

<sup>26</sup> In the oil refining sector uncertainties at concept stage can be +200%/-33% (A. Roberts, UKPIA, *Personal Communication*)

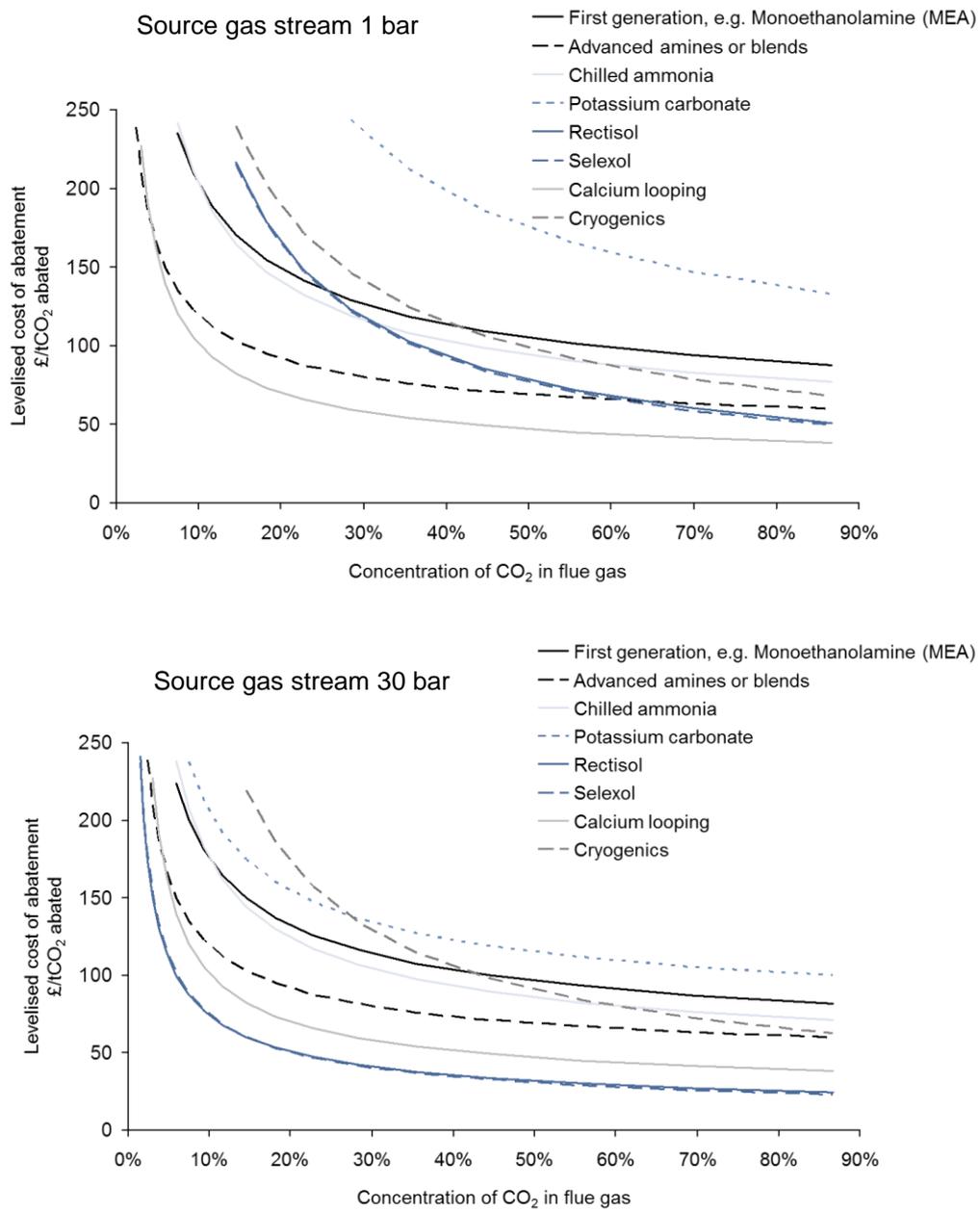


Figure 11 Levelised cost of capture against source CO<sub>2</sub> concentration for different technologies

### 3 Barriers and enablers to capture deployment

The main barriers to the deployment of industrial CCS have been identified from a combination of stakeholder consultations and literature review. These are summarised in this chapter. A total of 13 in-depth interviews have been carried out with industry representatives, technology developers and academics. The barriers articulated by stakeholders are found to be consistent with the public literature, and have similarities with barriers identified in the early power CCS literature, although there are also additional barriers unique to industrial sources<sup>27</sup>.

#### 3.1 Characterisation of barriers and enablers in deploying carbon capture in industry

For the purposes of addressing carbon capture piloting and demonstration needs, the consultation and literature review showed that the barriers may usefully be arranged by the level at which the problem exists (site, company, sector, national, system level), and the degree to which actions at these same levels can help resolve those barriers.

Based on these parameters four main categories of barriers are distinguished in Figure 12. For each barrier category, distinctive enablers can be identified, which are summarised in the text boxes in Figure 12. The next section summarises the barriers in more detail. Section 3.3 then summarises a range of enablers.

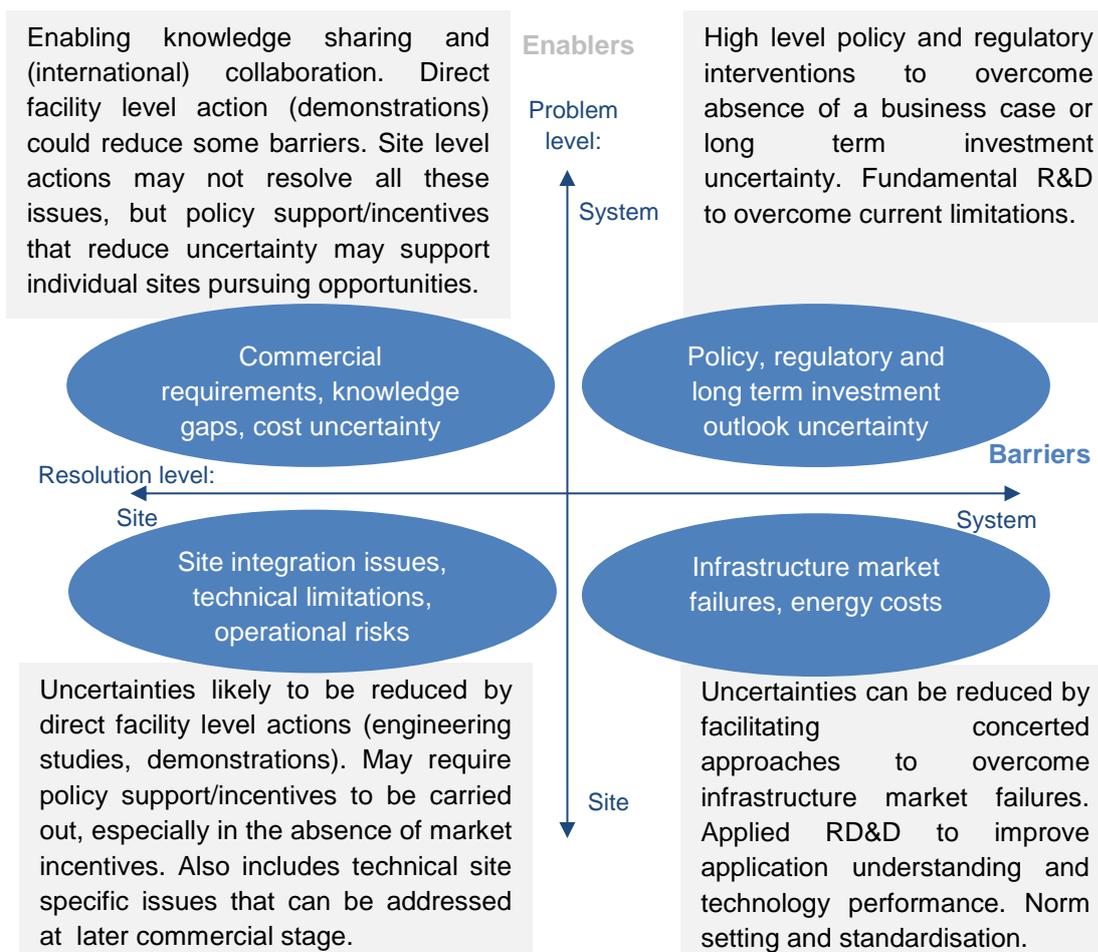


Figure 12 Characterisation of barriers and enablers

<sup>27</sup> Concawe CCS in Oil Refining; IEA High Purity Sources; ECRA Cement, GCCSI Status of CCS 2013

### 3.2 Barriers to demonstrating industrial CCS in the period to 2025

This section provides an overview of the key barriers to the development of industrial carbon capture, as identified in the stakeholder consultations and reviewed against literature sources, for the four barrier categories.

The focus of this study is on the near term deployment of the next pilot and demonstration projects and technology selection for those. The barriers that relate to technology development and site application are contained in the two “site level resolution” categories. From this long list the key barriers to industry for these aspects were identified. These key barriers are summarised in section 3.2.1.

#### System level barrier – System level resolution

There are a number of critical market and policy barriers which prohibit any meaningful commercial deployment of industrial carbon capture, which are system wide issues and require a system level solution. These are especially the lack of stable long term business models, based around appropriate incentives for CCS. These market and policy barriers are outside the scope of this study, but these barriers are identified by all stakeholders and in literature as dominating concerns around deploying capture technologies. The key barriers are summarised below:

- Lack of viable business case: weak and uncertain CO<sub>2</sub> prices/value
- Long term source availability (industry relocation or closure)
- Policy/regulatory uncertainty
- Transport and storage operational risks and liabilities
- Carbon leakage (globally traded commodities, i.e. inability to pass on costs of CCS)
- Public attitude

#### Site level barrier – System level resolution

There are a number of barriers that prohibit the development of specific projects which cannot be resolved at a site level. These are especially related to the lack of infrastructure, lack of clear downstream product specifications, and operational (energy) costs. Key barriers in this category are the following;

- Uncertain availability of storage prices/value
- Uncertain availability of transport networks
- Most technologies not developed to commercial ready level
- High capital investments vs site budget
- Technology lock-in, in particular there is a first mover disincentive as early CCS projects may be saddled with a combination of inefficient base industrial process and inefficient capture process
- Transport network entry specification (especially CO<sub>2</sub> stream composition)
- Lack of skilled employees for initial projects
- Confidentiality of industrial data

**System level barrier – Site level resolution**

There are a range of barriers that are prevalent throughout the industry and sectors, which can gradually be addressed by actions at site level. These barriers are especially related to uncertainty of costs, general unfamiliarity and lack of knowledge. Beyond those there are commercial requirements, typical across sectors, which will not be met by near future technology applications and inhibit deployment of capture projects, but which may be reduced by policy support/incentives for individual sites pursuing opportunities. Key barriers in this category are the following;

- High cost uncertainty
- Lack of funding for scale up
- Application not proven at commercial scale
- Unfamiliarity with carbon capture technologies
- Data sharing/ knowledge gaps
- Lack of real data
- Energy cost
- Decision making criterion (2yr payback)
- Lower risk appetite in non-core business
- Long life time of facilities (slow turnover)
- Limited sector specific process understanding
- Sector heterogeneity

**Site level barrier – Site level resolution**

In addition to the above barrier categories there are a range of issues that can impact the business case and technical feasibility of individual projects, which also need to be resolved at that level. Many of these barriers have to do with site integration issues, operational risks and scale up issues. Performing engineering studies and developing pilots and demonstrations are often key methods to reduce these barriers. Key barriers in this category are the following;

- Increased operational complexity and risks (unavailability, process dependencies)
- Plant integration risks
  - Hidden costs (additional downtime, alternative product supplies)
  - Long period between overhauls
- Large differences between sites limits replicability of solutions and increase cost uncertainty
- Impact on product quality
- Health, safety and environment (HSE) considerations
- Number of CO<sub>2</sub> streams per site
- Limited staff familiarity and operating expertise
- Space availability
- Cooling water availability
- Effects of impurities
- Site and individual source size
- Number of CO<sub>2</sub> streams per site
- Site budgets for pollution control measures are typically much less than required for deploying carbon capture.

Many of the barriers in this category may be present across the chemicals, cement, iron and steel and oil refining sectors, but the scale and severity differ. A few of these key barriers which vary between the sectors are;

- The issue for the high purity sub-sectors (ammonia and hydrogen production) is not technology maturity/availability, but the lack of a viable CO<sub>2</sub> transport and capture end-to-end business model.
- Typical overhaul periods of blast furnace plants are more than 7 years.
- The period between major overhauls in refineries is also very long, 5-7 years.
- The other chemicals and other refinery units (other furnaces, and boilers) are very heterogeneous and usually have many smaller vents (CO<sub>2</sub> streams).
- Of the UK cement sites, only three to four sites are in a position to transport and store CO<sub>2</sub> and have adequate water availability.
- The cement industry has limited experience with gas separation technologies and CCS in general.
- Cement sites do not always have ammonia at sites, which can result in additional barriers to uptake for chilled ammonia.
- Refineries do not always handle ammonia, which can result in additional barriers to uptake for chilled ammonia

### 3.2.1 Key barriers to the deployment of demonstration projects

An objective of this study is to provide evidence supporting the pilot and demonstration phases of ICCS deployment in the UK. From the long list of barriers in section 3.2, the key barriers for the development of pilot and demonstration projects were identified, through the semi-structured interviews with stakeholders and literature review. The ranking and severity of the barriers is based on the consistency with which they are put forward across stakeholders and literature and ranking indicated by stakeholders and literature. These key barriers are summarised below. In the appendix, sub sector specific instances and backgrounds on these barriers are provided.

<b>Barriers identified by stakeholders and literature as show stoppers and put forward consistently</b>	<b>Where is the main impact?</b> (System/ national/ sector/ organisation/ site)	<b>What is the main impact ?</b> (development time, cost, feasibility uncertainty)
Lack of funding for scale-up (absence of sufficient long term incentives to support a business case)	System/national	Development time
Increased operational complexity and risks (unavailability, process dependencies)	Sector/ site	Cost, feasibility uncertainty
Application not proven at scale	System/sector	Development time, cost, feasibility
Unavailability of storage and transport networks	System/national	Development time, feasibility

<b>Barriers identified by stakeholders and literature as major barriers and put forward often</b>	<b>Where is the main impact</b>	<b>What is the main impact</b>
Most technologies not developed to commercial ready level	Sector/ site	Development time, feasibility
Plant integration risks - Hidden costs (additional downtime, alternative product supplies, technology lock-in)	Site	Cost
High cost uncertainty	System	Cost, feasibility
Effects of impurities	Site	Cost

<b>Barriers identified by stakeholders and literature as relevant barriers and put forward in some cases</b>	<b>Where is the main impact</b>	<b>What is the main impact</b>
Plant integration risks - Long periods between overhauls	Site	Cost
Unfamiliarity with CCS technologies	Sector/organisation	Development time
Data sharing / knowledge gaps	System/ sector/organisation	Development time
Large differences between sites limit replicability of solutions and increases cost uncertainty	Site	Development time, cost, feasibility uncertainty
Limited sector specific process understanding	Sector	Development time, cost, feasibility uncertainty
Impact on product quality	Sector/ site	Cost

### 3.3 Enablers for industrial CCS demonstration in the period to 2025

As summarised in section 3.2.1 there are a distinct number of key barriers, identified by stakeholders and through literature review, for the near term next steps in developing industrial carbon capture. In the absence of sufficient market incentives to deploy capture technologies, the key enablers to address these barriers are the following:

- Support for pilot/demonstration projects, preceded where appropriate by support for FEED studies for interested sites to promote understanding and knowledge transfer.
- Ensure CCS chain end-to-end application (e.g. ensure availability of transport and storage)
- Support the further development of appropriate capture technologies that are at technology readiness levels below commercial application
- Derisk the cost uncertainty and the risk of hidden integration costs

A long list of the most pertinent enablers, for both the near term next steps and the general development of industrial carbon capture, is provided below. The overview of enablers is based on literature review and inputs from stakeholder consultations. In the overview below the enablers are characterised as technology push enablers and market pull enablers.

#### Technology push enablers

- Funding support for technology pilots and demonstration projects in industry applications can help overcome the absence of a business case and uncertainty of feasibility of scaling up. Project capital subsidies and/or performance-based ongoing subsidies or investment tax credits are the most widely used support mechanisms for first-of-a-kind demonstration projects.
- The uncertainty around costs and to a lesser extent uncertainty of feasibility can be reduced with pre-FEED and FEED studies for specific projects.
- R&D support for further technology development, simulations of process integrated applications and test centres emulating industrial conditions can all contribute to further development of existing technologies, exploration of new technologies and cost reductions.
- Utilisation of waste heat from industrial facilities provides a good opportunity for the reduction of capture energy costs. The heat component of capture costs can be very significant. The main barrier to utilising waste heat from industry is usually the lack of a heat demand. A DECC study<sup>28</sup> on the potential for heat recovery from industry identifies that some 3.2 TWh/yr of industrial waste heat per year could theoretically be made available for carbon capture plants.
- Support for applied research and knowledge transfer programs between industries can address the knowledge gaps and lack of familiarity with CCS technologies.
- Government backed technology and knowledge transfer programme between UK industry and other regions with piloting and demonstration experience can

<sup>28</sup> Element Energy *et al*, 2014, The potential for recovering and using surplus heat from industry, for DECC. Available at <https://www.gov.uk/government/publications/the-potential-for-recovering-and-using-surplus-heat-from-industry>

similarly address the knowledge gaps and lack of familiarity with CCS technologies.<sup>29</sup>

- Base process changes to facilitate other capture configurations (oxy-fuel or pre-combustion). Especially in the cement and iron&steel sectors different capture configurations involving oxy-fuel combustion are explored to provide more cost effective options for decarbonisation than post-combustion retrofits on existing facilities.
- CCS commercialisation in the power sector will help advance technologies, develop supporting transport and storage infrastructure, build political and public support, and strengthen supply chains.
- Leverage specific sector capabilities and strengths with regards to different technologies;
  - The chemicals and oil refining sectors are likely to be most comfortable with capture separation technologies (especially physical and chemical solvent-based). Plants in these sectors typically have high water availability, which is required for these technologies.
  - The cement sector is likely to be able to implement calcium looping most easily. These also do not need water<sup>30</sup> or challenging COMAH requirements.
  - Solid looping performance will increase if hot CO<sub>2</sub> is used, immediately from the furnace, rather than after cooling. However this would require a limited process intervention (although not as drastic as oxyfuel).
  - Cryogenics may be more economic where there is a significant cooling potential, e.g. LNG regasification facilities, or where cooling can be mechanically coupled to compression.

### Market pull enablers

- Long term stable market or taxation incentives and political support (e.g. global carbon pricing or taxation). The risk of carbon leakage is significantly higher in many of these industry sectors than in the power sector, as they produce for a global commoditised market. To prevent carbon leakage, the support system needs to be at a sufficiently global scale, or address carbon leakage in other ways.<sup>31</sup>
- Long term stable regulatory requirements, such as mandates and standards. Governments could mandate to implement CCS on specific installations or in specific sectors to obtain a license to operate. Alternatively standards on maximum CO<sub>2</sub> emissions per unit of production could be set. Carbon leakage under these regulatory requirements needs to be addressed similarly to market incentives.
- Sectoral agreements between governments and sector industries.
- Utilisation of CO<sub>2</sub>, providing a stable demand driven revenue stream for the captured CO<sub>2</sub>, either onshore (see Chapter 6), or offshore for enhanced oil recovery.
- Prior availability of a CO<sub>2</sub> transport and storage network (or confidence that this will be available when required).<sup>32</sup>

<sup>29</sup> Stakeholders advise that the benefits of this increase the more closely other CCS projects and host plant configurations resemble the UK sites.

<sup>30</sup> Cooling could be provided by other means, for instance evaporative cooling

<sup>31</sup> AEA (2012) Cumulative impacts of energy and climate change policies on carbon leakage, for BIS, available at <http://www.bis.gov.uk/assets/BISCore/business-sectors/docs/c/12-581-cumulative-impacts-policies-on-carbon-leakage.pdf>

- Clear specifications for CO<sub>2</sub> stream requirements at pipeline entry<sup>32</sup>.
- Underwriting of risks associated with CCS plant construction and integration, for instance downtime/lost revenue. Revenue support mechanisms such as CfD FiTs do not necessarily cover these risks, as the plant is not operational during construction.
- Development of CCS within industry clusters can provide economies of scale<sup>33</sup>, efficient utilisation of infrastructure and stimulate knowledge sharing and expertise building (examples of such initiatives are the Rotterdam Climate Initiative in the Netherlands and the Tees Valley City Deal in the UK)
- Local air quality can help enable the deployment of capture plants, especially in populous areas with local climate issues, due to accompanying reduction of contaminants.
- Strong public, commercial and political support for making the investments to tackle climate change at all levels of society.<sup>34</sup>

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<sup>32</sup> See, for example, Element Energy *et al.* (2010) CO<sub>2</sub> pipeline infrastructure – an analysis of global opportunities and challenges, for the IEA Greenhouse Gas R&D Programme. Available at <http://www.ccsassociation.org.uk/docs/2010/IEA%20Pipeline%20final%20report%20270410.pdf>

<sup>33</sup> See for example Element Energy *et al.* (2007) CO<sub>2</sub> pipeline infrastructure for the UK and Norway, for DTI on behalf of the North Sea Basin Task Force; Element Energy *et al.* (2010) The investment case for a CCS network in the Tees Valley, for One North East and NEPIC; Element Energy *et al.* (2014) CCS Hub study, for Scottish Enterprise.

<sup>34</sup> Stakeholders noted that successful industrial CCS demonstration projects could improve the prospects for a global climate deal.

## 4 Pathways to achieving 2025 commercial deployment of carbon capture

In this section pathways to achieving 2025 commercial deployment are assessed. Section 4.1 provides an overview of existing and planned carbon capture projects, focussed on the energy intensive industry. Based on this, section 4.2 considers possible technology deployment routes. Section 4.3 provides subsector demonstration timelines towards commercial scale applications in the UK in 2025, as well as plausible configurations of specific technology pilot or demonstration opportunities in different sectors, based on process simulations carried out as part of this study.

As outlined in the scope of the study, the aim of deploying capture demonstrations by 2025 is a given starting point for the study. Carbon transport and storage is furthermore outside the scope of this study. Figure 13 provides an illustrative overview of the potential fit of industrial carbon capture demonstration and pilot projects within a wider over-arching programme for CCS roll out in industry.

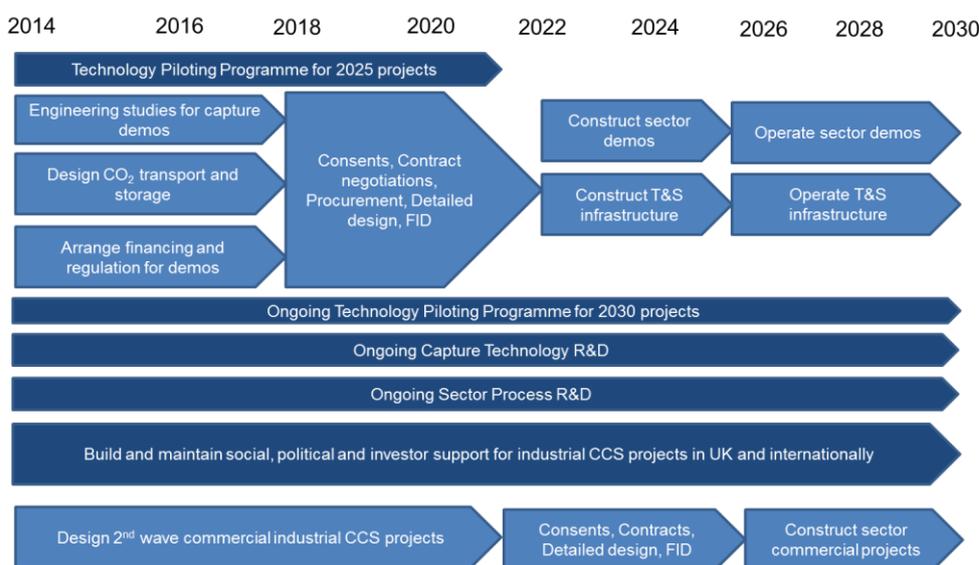


Figure 13 Illustrative potential fit of industrial carbon capture demonstration and pilot projects within a wider over-arching programme for CCS roll out in industry

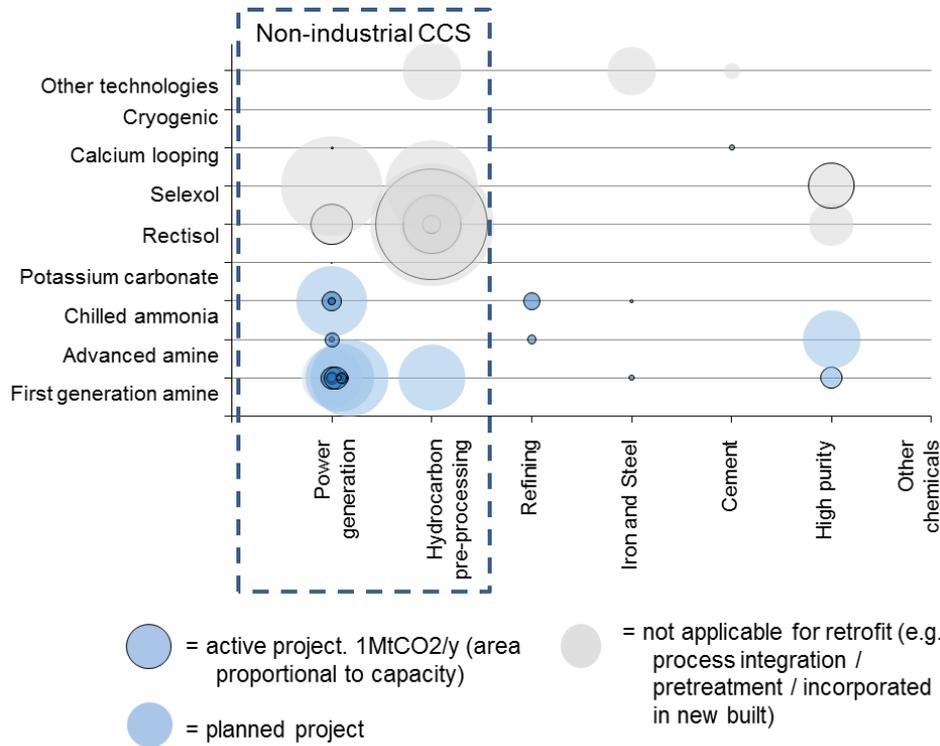
### 4.1 Current capture demonstrations and pilots

A review of existing capture plants and planned projects worldwide has been carried out. The review focusses on retrofit projects in the cement, chemicals, iron and steel and oil refining sectors, but also considers the largest, most relevant or representative projects from other sectors (new build, power, upstream oil and gas treatment, coal to gas/liquids/chemicals). The review consisted of public literature and data sets, supplemented with industry consultation inputs especially for more recent and planned initiatives.

The overview is comprehensive in examining retrofit capture in the four energy intensive sectors. For the new build, power, offshore/gas treatment sectors and the high purity sources, where CO<sub>2</sub> separation projects are developed often under different conditions, the review is limited to presenting the most representative projects, particularly latest or largest scale developments for the retrofit technologies for this study.

**Key message:**

Within the energy intensive industries there are few realised reference projects relevant for post combustion retrofit applications in industry, the maximum scale of these is ca. 0.1 MtCO<sub>2</sub>/yr. Within the power sector there are a larger number of post-combustion retrofit projects under construction or operational, mostly employing first generation amines.



**Figure 14 Overview of carbon capture plants and planned projects (where capacity information available<sup>35</sup>).**

Figure 14 shows that there are only a limited number of carbon capture projects within the energy intensive industries, that are retrofit post combustion applications. The largest of these projects that are direct relevant references for the UK situation are below a 0.1Mt/yr scale. The most relevant other references for the UK energy intensive industries are the realised post combustion retrofit projects in the power sector (blue). There are other larger Mt/yr scale projects in the energy intensive industries (indicated in grey), power generation (indicated in grey), coal to liquid/gas/chemicals, and in the upstream hydrocarbons pre-processing sectors (blue and grey) that are less relevant references for the UK situation, as is further discussed below. There are also larger projects for high purity chemicals processes; however these are applications specifically at almost pure CO<sub>2</sub> streams.

The focus for deploying capture technologies in the UK energy intensive industries by 2025 is on retrofit applications, as the industry does not expect significant new builds in the near future, apart from perhaps smaller chemicals facilities, and retrofits of capture plants

<sup>35</sup> Other planned projects have been identified but with limited information in the public domain on technology and capacities. A range of further technologies are deployed for the nearly pure CO<sub>2</sub> streams in the high purity sector which are not covered in this overview.

that require significant process changes are not expected to be likely deployed by 2025. This is different in China, the Middle East, and the US, for instance, where new facilities are currently being built and further facilities are planned in the energy intensive industries.

CO<sub>2</sub> stream conditions in the power sector can have similarities to those in the energy intensive industries and capture applications are also often retrofits. The processes in the energy intensive industries are however much more heterogeneous and variations in stream conditions are much larger. In the power sector the most deployed technology is first generation amines, which is currently being deployed at a commercial scale of 1Mt/yr.

1<sup>st</sup> generation amines are likely to be superseded by the 2030s and so may have limited long term market potential. However they provide opportunities for industry to develop experience with CCS at the largest scales possible in the period to 2025.

**Key message:**

Conditions for most international commercial scale industrial carbon capture projects are different than for the UK energy intensive industry

The commercial scale refinery and steel projects in Figure 14 are pre-combustion and hydrocarbon-pre-processing projects that are incorporated integrally within new-build facilities from the start. The other commercial-scale projects in the energy intensive industries are in high purity facilities, where the main requirement is for the very pure CO<sub>2</sub> streams to be brought to specification.

Most of the commercial-scale CO<sub>2</sub> separation projects are at facilities for upstream hydrocarbon pre-processing (including natural gas processing), coal to liquid/gas/chemical (CTX) or other syngas) processing. In these processes CO<sub>2</sub> removal is a process requirement and the capture part is usually integrally incorporated in the facility from the start, although the CO<sub>2</sub> is not necessarily captured for storage. The technical stream conditions are also different from those in retrofit energy-intensive industry applications; the sources usually have a high partial pressure (especially beneficial conditions for the operation of physical adsorbents) and the streams are reductive instead of oxidative flue gas streams (amines oxidise). Moreover these separation processes are generally less sensitive to the energy costs of capture than the energy intensive industries, where there is a need to minimise the energy consumption of capture facilities. Physical absorption solvents (e.g. rectisol and selexol) are often employed in hydrocarbon pre-processing, as the process conditions are favourable (high partial CO<sub>2</sub> pressure) and the sector has extensive experience with these technologies for the removal of other impurities from gas.

**Key message:**

Using the development of capture applications in the power sector as a benchmark, the development to commercial scale applications in the energy intensive industry in the UK (except for high purity sources and gas treatment) may take over a decade, unless there is a step change in incentives or support.

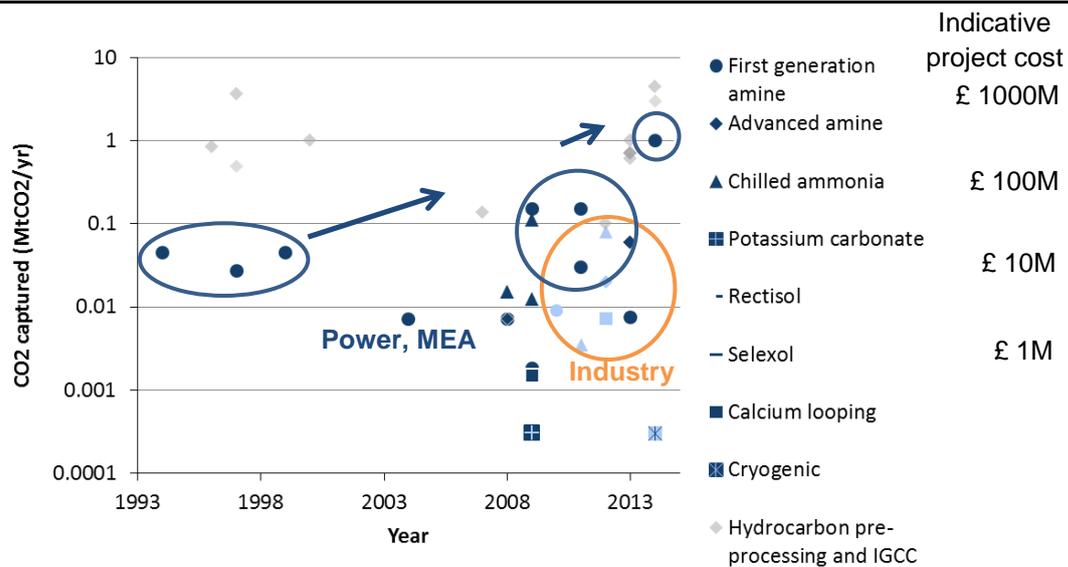


Figure 15 Development of capture project scale over time for realised projects. Order of magnitude costs are shown on the right hand side.

Figure 15 shows that it has taken over 15 years in the power sector to develop capture applications to close to commercial scale, from a starting point where the energy intensive industry is now at. The first generation amine projects in the power sector have increased in size by almost two orders of magnitude from 10 kt/yr in the late 1990s to ca. 1-2Mt/yr for projects under construction.

The challenges for scaling up CO<sub>2</sub> capture in energy-intensive industries are no less challenging than those in the power sector. Therefore a base case of significant technology development and commercial deployment timescales for capture applications should be assumed. Only a few pilot/demonstration projects have been realised at a scale up to 0.1Mt/yr in the cement, chemicals, iron and steel and oil refining sectors thus far, so increasing scale by an order of magnitude faces significant challenges

The development time to commercial scale in energy-intensive industry may differ from that in the power sector. The energy intensive industry can leverage experience from the power sector. Different capture technologies have been further developed in the last few years and applications of especially first generation amines with post-combustion capture streams have been piloted repeatedly and will soon be demonstrated with 1<sup>st</sup> generation amines and physical solvents at scales of greater than 1 Mt/yr. However, energy-intensive industrial processes and business models are more heterogeneous than coal and gas power plants, and policymaking is complicated by challenges around competitiveness and carbon leakage.

This timeline to the development of commercial applications, which is based on an analogous development path to the power sector, is also consistent with the views of industry stakeholders on feasible scale-up pathways. Industry stakeholders typically identified a minimum of 10-15 years for the development of commercial scale capture applications at individual sites. This is based on the current size of pilot projects, time between major facility overhauls, the time required to develop a project and the time to operate and learn from projects before scaling up to a larger size. Rather than focussing on a single project, any timeline should ideally fit within an overall logical but flexible programme for multiple full scale industrial CCS projects operational in the UK and

worldwide in the 2030s across the cement, chemicals, iron and steel and oil refining sectors<sup>36</sup>.

Ahead of full commercialisation of large scale novel capture technology-sector combinations applications, there is a need for the development of pilots and demonstrations. Current deployment levels in the energy intensive industry are single instances of technology-sector combinations. The IEA recommends that “in order to scale up the technology, the IEA has proposed that 100 additional commercial scale demonstration projects will be needed by 2020 in a number of countries and settings”<sup>37</sup>.

The high purity sources (ammonia and hydrogen production), are exceptions to these timelines, as highly concentrated CO<sub>2</sub> is readily available from these facilities and CO<sub>2</sub> separation is already deployed at commercial scale for these conditions.

## 4.2 Possible technology routes towards commercial scale capture

Several technology application routes are identified for the deployment of industrial CCS, these are summarised in Figure 16. The deployment routes distinguish between the incremental development routes for chemical and physical absorbents and the more step change development routes for other less mature technologies like calcium looping and cryogenics, and the integral process redesign routes, for instance for pre-combustion applications.

Across the different industries a trade-off is identified between deploying CCS at commercial scale by 2025 and missing out on more effective solutions that will likely be available at scale only after 2025, following further technology development and deployment scale up. At a national level, deployment of multiple demonstration projects at 0.5-3 MtCO<sub>2</sub>/yr scale by 2025 can most realistically be achieved using 1<sup>st</sup> generation amine technology. However within any given sector, the other routes in Figure 16 may present more effective solutions for some industries, particularly they avoid risks associated with technology lock-in (not modelled here).

For the amine route and physical absorbents deployment at scale can start directly and these routes then provide the opportunity for incremental further development. For the step change routes in Figure 16 further technology development is required before these technologies can be deployed at scales of 0.1-1 MtCO<sub>2</sub>/yr. For the integrated process redesign options the technologies are ideally deployed at full facility scale, rather than for a part.

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<sup>36</sup> See for example, Element Energy *et al.* (2010) The role of CCS in Gas Power and Industry, for the Committee on Climate Change; and Element Energy *et al.* (2014) Infrastructure Study, for the Committee on Climate Change;

<sup>37</sup> IEA Technology Roadmap Carbon capture and storage, 2009

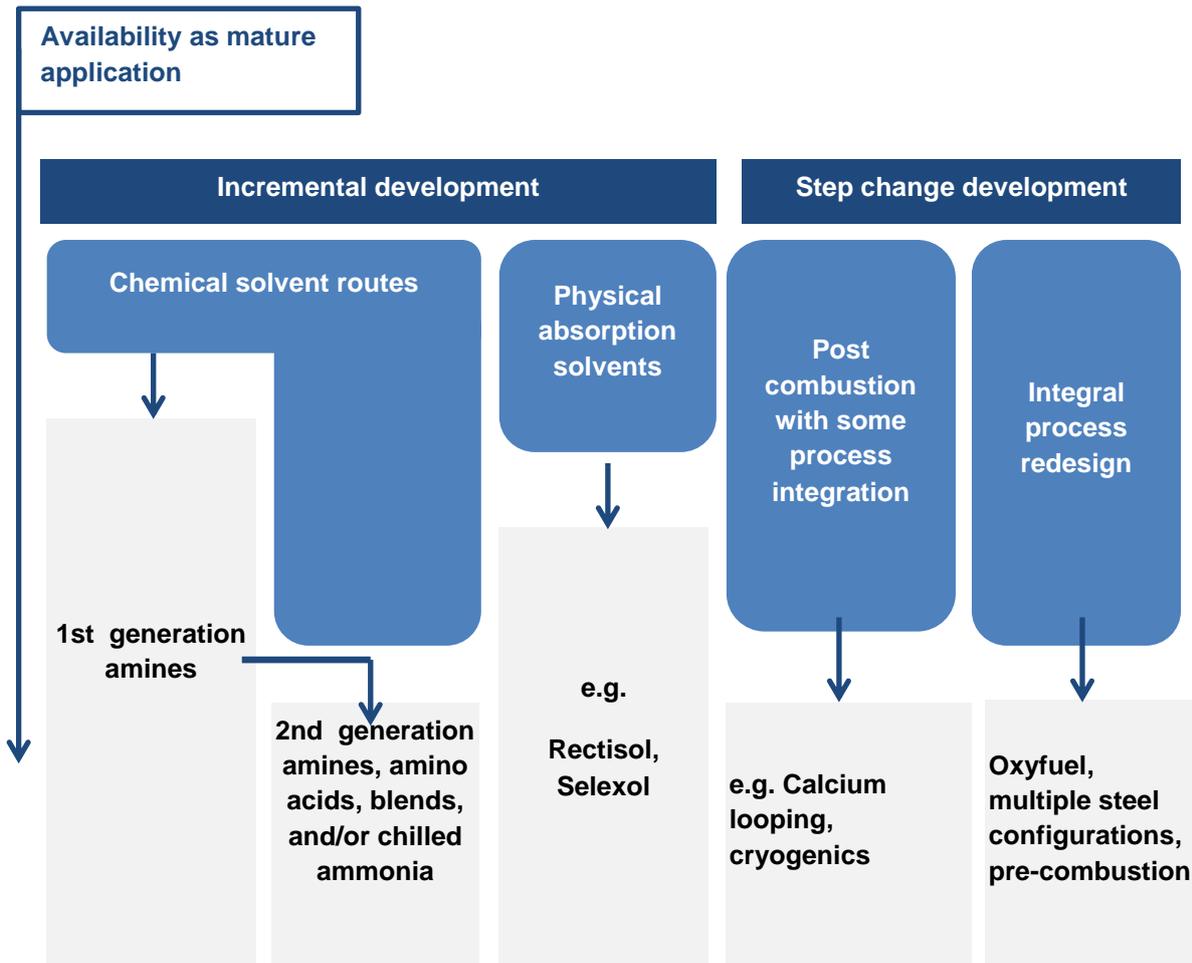


Figure 16 Capture technology deployment routes for carbon capture in industry in the 2020s

However one of the key barriers in industry for the deployment of CCS by 2025 is a lack of familiarity and experience in combining CCS with actual industrial processes (rather than just simulations) to understand process implications. This can be addressed through small scale pilots in the period to 2020.

The more closely the technical, commercial and regulatory details of pilots resemble actual site conditions at UK cement, chemicals, iron and steel or oil refining sites, the greater the likelihood that they will overcome the barriers to UK demonstrations in these sectors period to 2025. Stakeholders in any UK piloting activities would ideally co-ordinate with international piloting activities to maximise efficiency.

### Amine routes

The amines provide the opportunity to start now with 1<sup>st</sup> generation amines and lay the foundations for employing 2<sup>nd</sup> generation chemical solvents later on. In favourable cases, there could be opportunities for solvent replacement within a capture facility, thereby reducing capex. As first generation amines are available today, demonstrations can start with the shortest lead time and supply chain risk, focussing on process integration and interaction, while 2<sup>nd</sup> generation amines are being further developed.

### Physical absorption solvent route

Similar to 1<sup>st</sup> generation amines physical absorption solvents are mature technologies today, used for processes involving high partial pressure streams. However for many

industrial sources at atmospheric pressure the electricity cost to pressurise the gas to the pressure required by physical absorbents, reduces their cost effectiveness and there is little experience in operating these in oxidative environments. Due to the higher pressure, blast furnace gas at steel plants could provide an opportunity for physical absorbents. The outlook for physical absorbents could change with significant developments in the pressure requirement and corrosion resistance.

#### Limited integration routes

Some technologies show possibility for more cost effective capture, but require further technology development, small scale demonstrations, and process integration to understand cost and performance better and reduce integration risks. Although not modelled explicitly in the techno-economic study, there are opportunities for cost reduction calcium looping capture could draw on hot CO<sub>2</sub> exhaust directly from a furnace (rather than the cooled flue gases), or if cryogenic capture was coupled to other thermal or mechanical processes.

#### Integral process redesign

There are a range of opportunities for carbon capture involving integral process redesign, for instance oxyfuel, pre-combustion or the many configurations proposed in the iron and steel sector. These are however at a lower technology readiness level than some of the post-combustion options and require technology development. These options are especially suited for new-build plants where they are incorporated integrally in the design of the plant from the start. As retrofit options they imply large integration and operation risks, especially when the changes impact the mass-energy balances of facilities, potentially requiring redesign of the main facility. Experience from the refinery and power sector in other pollution control applications suggests it can sometimes be more effective to build a new unit than retrofit an existing one (driven also by additional cost of downtime for retrofit compared to relatively quick tie in of a new facility). Tying in capture as part of any major overhauls in the period to 2025 could be monitored and considered opportunistically.

### 4.3 Subsector demonstration timelines towards commercial scale applications in the UK in 2025

Potential timelines for pilots, engineering studies and demonstration project development for the cement, chemicals, iron and steel, and oil refining sectors to meet the DECC/BIS challenge of industrial CCS demonstration projects operational by 2025 is provided below.

There are likely to be opportunities to share the costs, risks, and benefits of engineering studies, pilots and demonstrations in other sectors. Therefore, for maximum efficiency, UK industrial capture technology pilots and demonstrations should continue to seek to maximise knowledge transfer within and between industrial sectors, from CO<sub>2</sub> capture projects in the power and upstream gas processing sectors, and internationally.

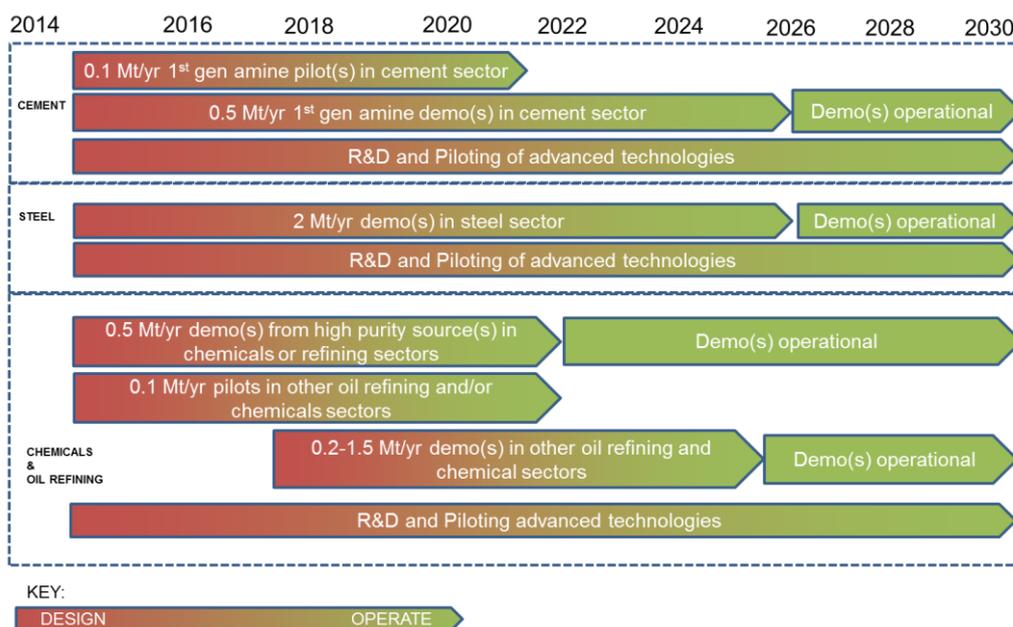


Figure 17 Sector piloting and demonstration timelines

The remainder of this section provides examples of specific technology pilot or demonstration opportunities available for sectors and sub-sectors. The section should be read closely with the process simulation descriptions in the Appendix. The process simulations provide, in a publicly available and UK plant retrofit context, capture plant designs including detailed mass and energy flow diagrams, infrastructure inventory and sizing, together with bottom-up cost estimates that can be used. Whilst other capture configurations and sizes could be considered, these data, prepared on a like-for-like basis with transparent conditions represent a significant advance in the description of industrial capture beyond that currently available publicly.

### 4.3.1 Demonstrating capture using high purity CO<sub>2</sub> sources

CO<sub>2</sub> from high purity sources (ammonia and hydrogen production), can potentially be captured with limited further CO<sub>2</sub> separation. Development of CO<sub>2</sub> capture at these sources, beyond separation for current commercial purposes, requires funding mechanisms for end-to-end pilots (i.e. compression, transport and storage). These high purity sources can be used to test and pilot business models and CO<sub>2</sub> transport and storage networks.

Example configuration

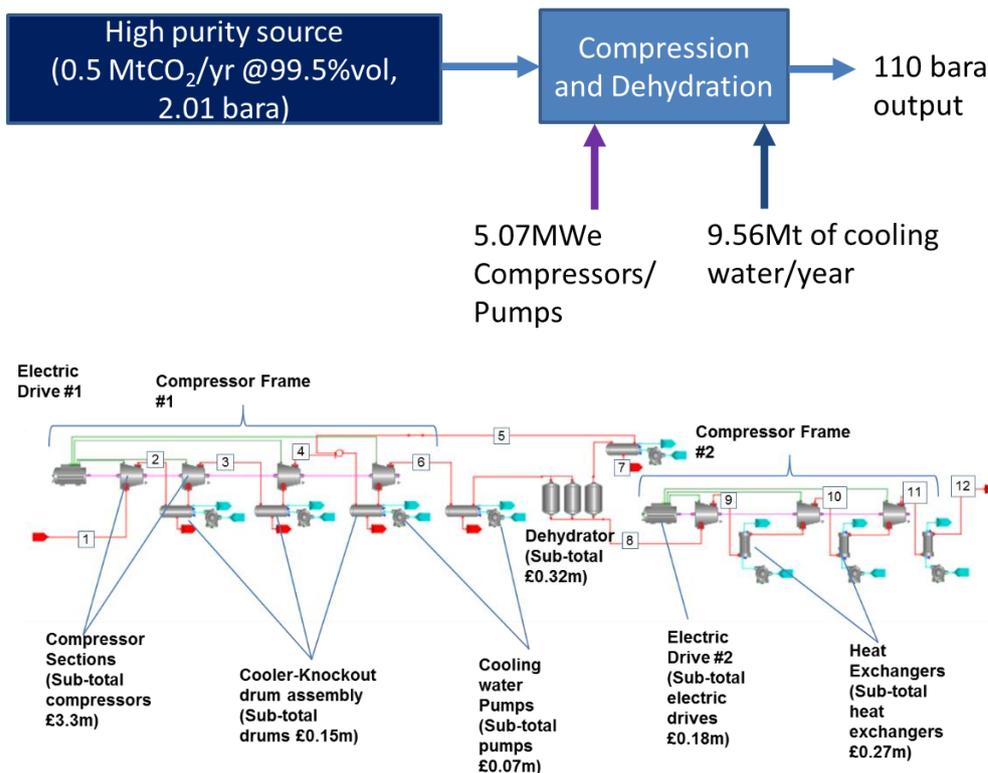
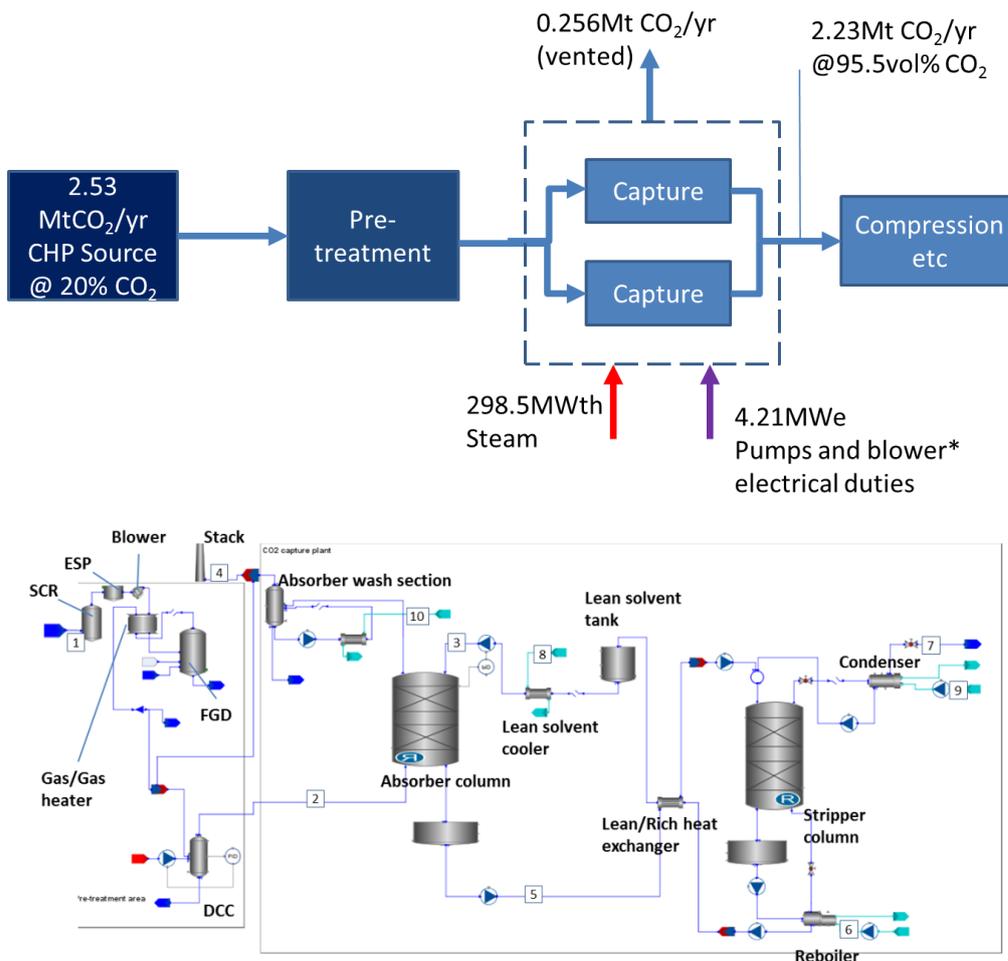


Figure 18 Overall schematic (Upper panel) and process diagram (lower panel) for multi-stage CO<sub>2</sub> compression from 2 bara to 110 bara at a high purity 0.5MtCO<sub>2</sub>/yr source (see Appendix for details)

### 4.3.2 Demonstrating capture at iron and steel integrated blast furnace sites

Expected emissions from each of the UK’s largest integrated iron and steel blast furnace plants are in the range of 5-8MtCO<sub>2</sub>/yr. Though not impossible, it is unrealistic to expect capture projects at this scale in the period to 2025 given the current status of CCS in the iron and steel sector (see section 4) and the infrequent overhaul periods of blast furnaces (typically more than 7 years). With an ambition for a full scale project by 2030, stakeholders confirmed a realistic demonstration project of scale 1-3MtCO<sub>2</sub>/yr demonstration could be operational by 2025. Retrofitting a first generation amine capture plant to a new or existing site CHP facility as part of an end-to-end CCS project is considered to offer the largest impact on CO<sub>2</sub> emissions whilst having the lowest impact on site operations, and be deliverable in the period to 2025. Use of a physical solvent (e.g. selexol or rectisol) with blast furnace gas also offers potential if suitable compression facilities are available that are compatible with blast furnace gas.



SCR – Selective Catalytic Reduction  
 ESP – Electrostatic Precipitator  
 FGD – Flue Gas Desulphurization  
 DCC – Direct Contact Cooler

**Figure 19 Schematic (Upper panel) and Process Simulation (Lower Panel) for an illustrative CO<sub>2</sub> capture demonstration scale project in the iron and steel sector.**

If necessary pilot projects could be developed in the period to 2020 to confirm the performance of the amine capture technology with the combustion streams from the CHP plant. Given the current lack of realised projects and this timescale, it is very unlikely that capture of nearly all site emissions is feasible in 2025. Moreover, given the long time between overhauls the risk of sub-optimal technology lock-in is high (multiple configurations are being explored in the iron and steel sector<sup>38 39 40 41 42</sup>). Other

<sup>38</sup> IEA GHG (2013) Iron and Steel CCS Study (Technoeconomics integrated steel mill). Report 2013/04

<sup>39</sup> IEA GHG (2013) Overview of the current state and development of CO<sub>2</sub> capture technologies in the ironmaking process (Report 2013/TR3)

<sup>40</sup> Birat, J.-P. Steel and CO<sub>2</sub> – the ULCOS program, CCS and mineral carbonation using steelmaking slag.

<sup>41</sup> Hasanbeigi *et al* (2013) Emerging Energy efficiency and CO<sub>2</sub> emissions reduction technologies for the iron and steel industry, report LBNL-6106E for the Lawrence Berkeley National Laboratory.

<sup>42</sup> Kuramochi *et al.* (2011) Techno-economic assessment and comparison of CO<sub>2</sub> Capture technologies for industrial processes: preliminary results for the iron and steel sector.

considerations are the facts that there is also limited experience with capture from Blast Furnace Gas to date, and no new UK steel plants are expected to be developed in the near future by the industry, although existing mothballed plants may be brought back on-line. Differences in the sites may be important in designing pilots and demonstrations. The SSI site in Teesside has a large blast furnace, whereas the Tata Scunthorpe facility has 4 smaller blast furnaces (2 of which are currently operational).

### 4.3.3 Demonstrating CO<sub>2</sub> capture in the oil refining sector

A typical full UK site refinery emits 2-3 MtCO<sub>2</sub>/yr, depending on the extent to which site CHP plants are included. Capturing the entirety of site emissions is not considered realistic in the period to 2025, given limited activity in this sector to date, high site complexity/heterogeneity, highly dispersed vents, and infrequent overhauls (5-7 yrs).

Full chain CCS demonstrations in the range 0.9-1.5 MtCO<sub>2</sub> operational by 2025 are plausible, bringing together multiple CO<sub>2</sub> vents, and potentially employing two 1<sup>st</sup> generation amine absorber trains in parallel.

To enable roll out at this scale, capture pilots at a scale of 0.1-0.7 MtCO<sub>2</sub>/yr using 1<sup>st</sup> generation amine technology could be implemented in the period to 2020. Industry experts consider that the most likely CO<sub>2</sub> sources within refineries would be crackers.

Pilots could also be delivered in the period to 2020 using second generation chemical solvents, solid looping, or cryogenics, although these would be at a smaller scale (e.g. 0.01-0.1 Mt/yr).

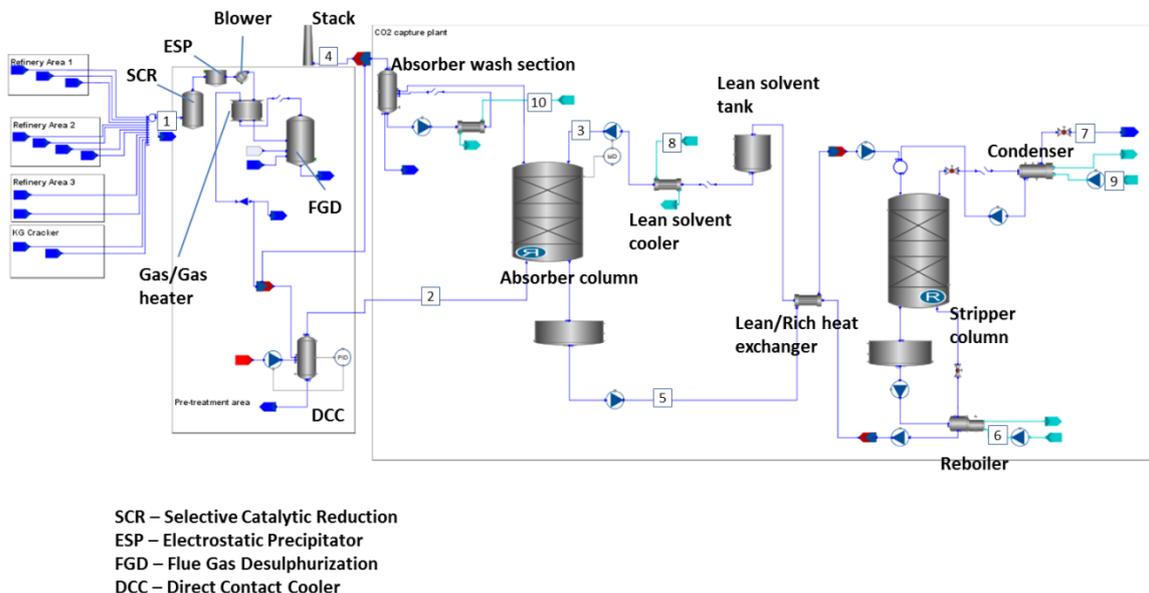
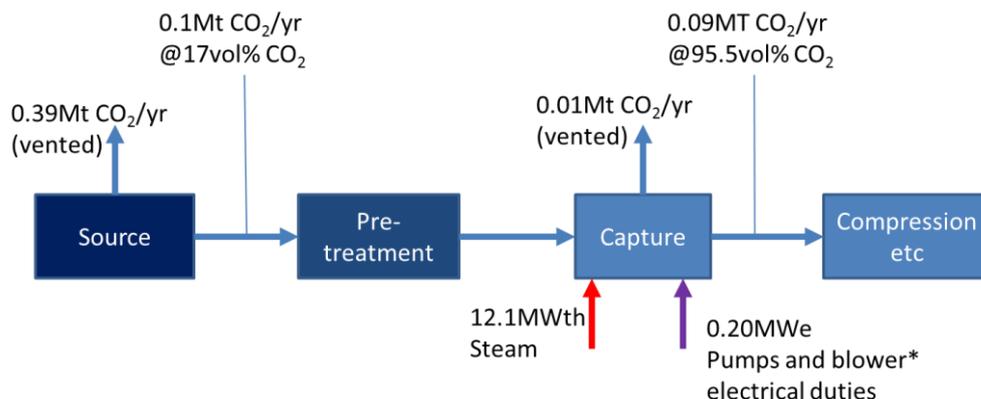


Figure 20 Illustrative process diagram for CO<sub>2</sub> capture using 1<sup>st</sup> generation amine solvents at a refinery. For details, please see appendix.





**Figure 22 Illustrative schematic for 0.1 Mt/yr capture pilot using 1st generation amines at a cement plant in 2020.**

It may be appropriate to start with one pilot at a scale close to 0.1 MtCO<sub>2</sub>/yr by 2020, and to actively ensure knowledge transfer from international pilots (for instance the small scale Norcem Brevik pilot project under construction in Norway<sup>43</sup>). With 1<sup>st</sup> generation amines, the overall process structure for a 0.1 and 0.5 MtCO<sub>2</sub>/yr should be similar, so investment in a larger (0.5 Mt/yr) scale capture plant by 2025 should be feasible if the 2020 pilot is deemed a success.

More advanced technologies, including 2<sup>nd</sup> generation chemical solvents, oxyfuel, solid looping, membranes etc. could have lower unit costs although implementation risks are currently uncertain, and these would need their own pilot projects.

Calcium looping could be of strategic interest for the cement sector, due to the greater expected familiarity of operators with calcium carbonate and calcium oxide (relative to amines), likely lower COMAH requirements and likely limited water availability at some inland UK cement sites<sup>44</sup>.

#### 4.3.5 Demonstrating CO<sub>2</sub> capture in other chemicals sector

The other chemicals, boilers, CHP and other refinery units typically have multiple, heterogeneous small CO<sub>2</sub> streams. There is little public data on individual CO<sub>2</sub> stream characteristics to allow meaningful techno-economic comparisons to be made.

The feasibility and cost-effectiveness of CCS, relative to alternative abatement technologies are poorly understood, although familiarity with the underlying CO<sub>2</sub> separation technologies may be high.

There is therefore a need for site-specific studies to better understand CCS opportunities and then to consider analysis as part of system-wide analysis of capture economics.

<sup>43</sup> See for example the plans by Aker and ECRA described at <http://www.zeroco2.no/projects/norcem-cement-plant-in-brevik-norway> or <http://www.globalccsinstitute.com/insights/authors/dennisvanpuuyvelde/2013/09/20/capturing-co2-norwegian-cement-industry>

<sup>44</sup> Cooling could be provided by other means, for instance evaporative cooling

Next steps could focus upon getting an improved understanding of the individual CO<sub>2</sub> streams, their conditions, and engineering studies to explore the methods and feasibility for capture. The Tees Valley City Deal provides an opportunity to begin this process in one geographic cluster<sup>45</sup>.

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<sup>45</sup> <http://m.middlesbrough.gov.uk/CHttpHandler.ashx?id=9773&p=0>

## 5 Opportunities for deploying CO<sub>2</sub> utilisation at UK industrial sites in the period to 2025

### 5.1 Overview

#### 5.1.1 What is CO<sub>2</sub> utilisation?

CO<sub>2</sub> capture and utilisation (CCU) technologies fundamentally differ from CCS because geological storage for the purposes of emissions reduction is not the primary objective - although CCU can be used in combination with CCS and can also help its wider deployment. As summarised graphically in Figure 23, CCU is a broad term which applies to a range of applications that can commercially utilise CO<sub>2</sub>, either as part of a conversion process, i.e. in the synthesis of new products, or in non-conversion processes, where CO<sub>2</sub> acts a solvent or working fluid (e.g. for enhanced oil recovery; CO<sub>2</sub>-EOR).<sup>46</sup>

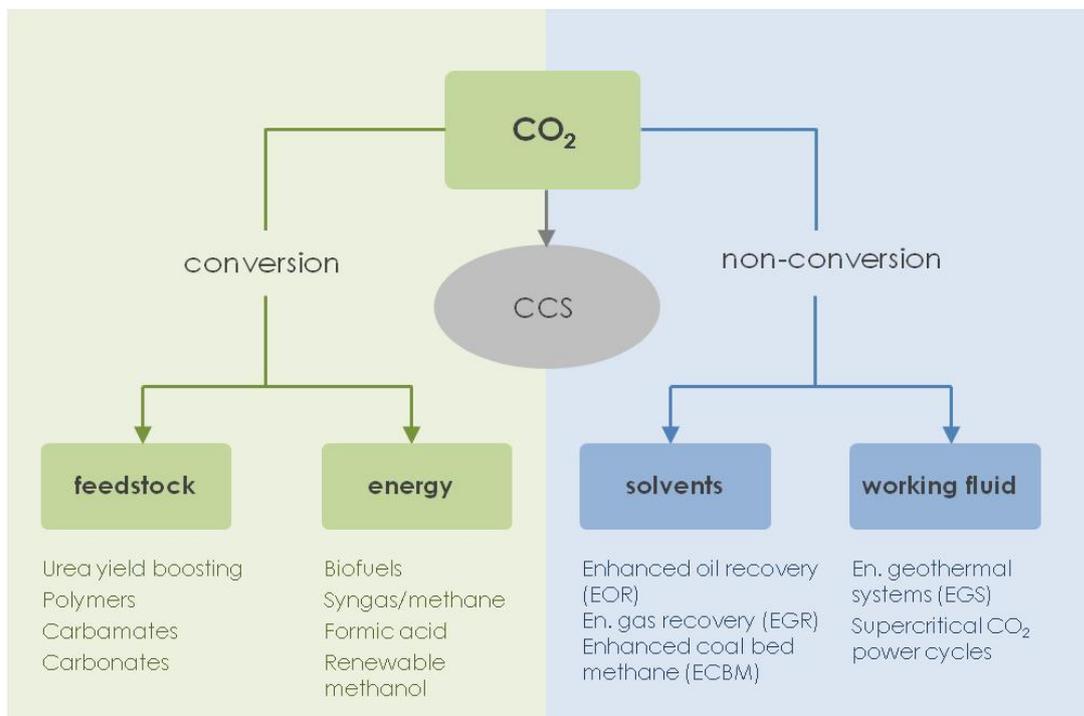


Figure 23 Summary of potential uses of CO<sub>2</sub>

Source: Adapted from Ecofys and Carbon Counts, *forthcoming*

CCU technologies can be classified according to various approaches, depending upon whether for example they are analysed from a technical, chemical, policy or economic perspective. A recent study undertaken by the European Commission (Ecofys and Carbon Counts, *forthcoming*) describes five key groupings based on the end-use applications i.e. adopting a *functional* rather than *technical* grouping, as follows (*ibid*):

- **CO<sub>2</sub> to fuels** – within this group, technologies which can provide a means for new types of energy vectors are covered. They partly consist of commercially

<sup>46</sup> These latter (non-conversion) applications are often referred to as CO<sub>2</sub> use; and the former (conversion) applications as CO<sub>2</sub> utilisation. Both categories are included within the scope of this report and collectively referred to as CCU for ease.

established technologies linked to more novel use (e.g. renewable methanol), and more embryonic forms of energy carrier development (e.g. biofuels from algae).

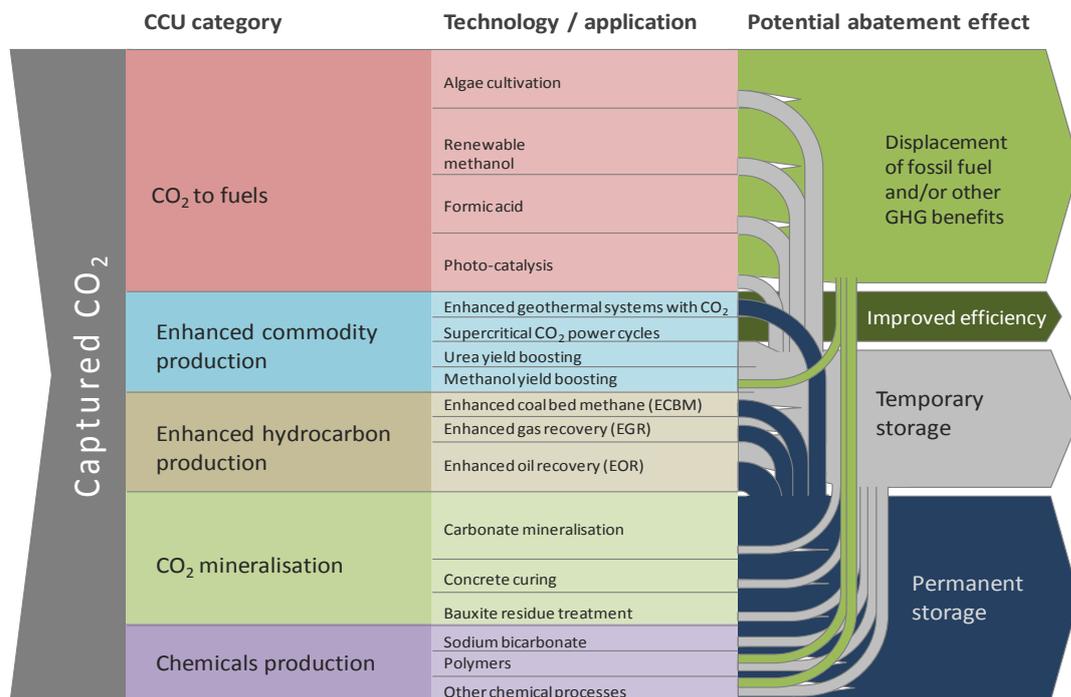
- **Enhanced commodity production** – this group of technologies involve using CO<sub>2</sub> to boost production of certain goods, typically where CO<sub>2</sub> is already used but could be modified (e.g. urea yield boosting). It also includes using CO<sub>2</sub> as a substitute in existing technologies (e.g. for steam in power cycles). These technologies generally involve applying new methods to techniques which are in commercial practice today, but could be modified to use CO<sub>2</sub>.
- **Enhanced hydrocarbon production** – this group of technologies involve using CO<sub>2</sub> as a working fluid to increase recovery of hydrocarbons from the subsurface (e.g. CO<sub>2</sub>-EOR). They range in maturity from commercially viable under certain conditions through to pilot phase;
- **Carbonate mineralisation** – this group of technologies relies on the accelerated chemical weathering of certain minerals using CO<sub>2</sub>. It can be used in a range of applications, typically involving construction materials (e.g. concrete curing) or in more niche circumstances such as mine tailing stabilisation;
- **Chemicals production** – CO<sub>2</sub> can also be used in the synthesis of a range of intermediates for use in chemical and pharmaceuticals production, including carbamates, carboxylation, insertion reactions, inorganic complexes and polymer production. Conversion methods require the use of catalysts, heat and/or pressure to break the stable CO<sub>2</sub> structure, and include photocatalysis or electrochemical reduction. One of the most promising technologies is the use of CO<sub>2</sub> to make various polymers such as polycarbonate.

The range of potential applications is diverse. Some CCU technologies have capacity to retain carbon within a cycle over at least the short-term, thereby avoiding release of CO<sub>2</sub> to the atmosphere (Styring *et al.* 2011). Different technologies have different potential to achieve this objective; for some the removal is permanent, with the carbon from CO<sub>2</sub> ending up locked up in minerals or in long-lasting products (e.g. some polymers), or stored indefinitely in geological formations (e.g. in enhanced oil recovery); for others e.g. where the carbon is converted to fuels, removal is only temporary and therefore offers only limited potential to abate CO<sub>2</sub> emissions.

However, as illustrated in Figure 24, CCU can also deliver secondary benefits which can lead to reductions in GHG emissions outside the immediate scope of the activity. Examples include improvements to process efficiency, which leads to increases in energy efficiency therefore reducing fossil fuel consumption for the same end service (e.g. enhanced power cycles using supercritical CO<sub>2</sub>), the displacement of more intensive forms of production of intermediates within a value chain (e.g. in bulk chemicals production), or through substitution of conventional fossil fuels (e.g. in algae-based biofuels production systems using CO<sub>2</sub>) (Ecofys and Carbon Counts, *forthcoming*).

The range of alternative pathways through which CCU technologies can abate CO<sub>2</sub> emissions highlights the complexities involved in assessing the net emission reductions achieved by a particular CO<sub>2</sub> utilization option. Important factors for consideration include: the boundaries for the assessment, the scope for leakage (i.e. emission changes occurring outside the immediate project boundary, but attributable to the activity or technology), and the permanence of the reductions achieved. To date, there have only been very limited attempts to quantify the potential net benefits for CCU technologies e.g. through the use of

life-cycle analysis (LCA). Furthermore, these have typically been based on only limited, and potentially unrepresentative, case studies.



Source: Adapted from Ecofys and Carbon Counts, forthcoming

Figure 24 Illustrative emission reduction pathways for CCU technologies

CO<sub>2</sub> has long been used as a product on a commercial basis within industry. Its use for enhanced oil recovery (CO<sub>2</sub>-EOR) has been applied since the early 1970s, with over 50 MtCO<sub>2</sub> per year currently being injected into mature oil reservoirs for such purposes in the US and elsewhere.<sup>47</sup> CO<sub>2</sub> produced during the manufacture of hydrogen for conversion to ammonia has also been widely used to manufacture urea in the inorganic fertiliser industry for many years. In some cases, fertiliser plants also capture supplemental CO<sub>2</sub> from on-site boilers and other sources to provide an additional source of carbon. Presently around 120 MtCO<sub>2</sub> is used in this way worldwide<sup>48</sup>. Smaller-scale applications of CO<sub>2</sub> use globally include its use in greenhouses to enhance plant growth, as a fire retardant in fire extinguishers and in beverage carbonation and food production. Typically these processes utilise either natural sources of CO<sub>2</sub> (approximately 85% of the CO<sub>2</sub> used for EOR in the US is from natural sources), manufacture it from the burning of natural gas (e.g. in greenhouse heaters), or capture it from anthropogenic sources where industrial processes produce CO<sub>2</sub> of a fairly high-purity (e.g. steam methane reforming or gas processing).

Although some applications of CO<sub>2</sub> utilisation are currently commercial in certain circumstances, a larger share are still in a very early stage of development with only limited activities at the research and demonstration (R&D) scale. A key barrier for many CCU technologies concerns the low chemical activation state of CO<sub>2</sub>, and therefore the need for energy use in the conversion process(es).<sup>49</sup> The diversity of CCU technologies

<sup>47</sup> See, for example: IEA/UNIDO (2011); Element Energy *et al.* (2013) The economic impacts of CO<sub>2</sub>-EOR for Scotland.

<sup>48</sup> Zakkour, P., & Cook, G. (2010). CCS Roadmap for Industry : High-purity CO<sub>2</sub> sources

<sup>49</sup> Much of the present focus of R&D across most pre-commercial CCU applications is therefore around increasing process efficiency and energy optimisation; also need for scale-up to

available, and their differing levels of technical maturity, mean that a wide range of actors are directly involved in their R&D including academia, start-ups (e.g. small companies and venture capital) and industry (e.g. larger companies with internal R&D programmes). A wide range of activities are ongoing within CCU technology development and demonstration globally, notably within the US, Europe and parts of Asia. At present, the majority of CCU technologies are moving from R&D or pilot-scale stage towards and are characterised by high capital and operating costs. An assessment of costs for different CCU applications on a fair and comparable basis is extremely difficult at the current time: detailed cost studies including itemised cost elements and underlying assumptions are not available for all technologies and CO<sub>2</sub> utilisation pathways. In addition, many cost factors for CCU goods and services, as well the markets for them, are likely to be driven by highly regional, or even local, factors (e.g. energy prices and costs, product standards). However, despite the lack of clarity, it can be concluded that based on existing reviews of CCU technologies, high costs are a major barrier to wider deployment<sup>50</sup>.

Ongoing innovation and process development will be needed to overcome the high costs currently faced by many CCU technologies. It is noticeable that cost estimates are typically highest for those options which may offer step-changes in the use of energy and products from waste CO<sub>2</sub>, and also the greatest potential for emissions reduction e.g. through the production of liquid fuels and the permanent storage of CO<sub>2</sub> in building products and new chemical products. The need to achieve cost reductions is critical to their success: if the various input costs for CCU applications cannot be reduced to a point comparable with existing, or emerging, alternatives then other drivers will clearly be required for them to move beyond the pre-commercial stage and attract investment from business and industry.

### 5.1.2 Why is CCU of potential interest to the UK?

Notwithstanding the considerable challenges associated with its wider deployment and commercialisation, there are several drivers for the uptake and support for CCU technology within the UK. These include:

- **Support for UK industrial innovation and competitiveness.** The suite of technologies involved in using CO<sub>2</sub> offer a range of opportunities for industrial innovation, potentially creating means for UK companies and technology providers to increase their competitiveness, as well as increasing the sustainability of industrial practices.
- **High value product creation from waste stream.** Emergence of new techniques that have the potential to reduce emissions of CO<sub>2</sub> to the atmosphere by capturing and converting it into high value products such as speciality chemicals (e.g. polyurethane and polycarbonate, using CO<sub>2</sub> as a feedstock). Research and pilot projects are currently ongoing in many jurisdictions, including in the UK, as well as

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demonstration technology improve economics. Some CCU products can be more efficiently or cost-effectively sourced through other starting points than CO<sub>2</sub>.

<sup>50</sup> See for example: Carbon Sequestration Leadership Forum (CSLF), 2011. Phase I Final Report by the CSLF Task Force on CO<sub>2</sub> Utilization; Carbon Sequestration Leadership Forum, 2013 Phase II Final Report; and Global Carbon Capture and Storage Institute (GCCSI), (2011. Accelerating the uptake of CCS: Industrial use of captured CO<sub>2</sub>

Germany, the US and China.<sup>51</sup> Furthermore, the re-use of waste CO<sub>2</sub> can represent an efficient and productive use of resources, and important objective of national economic and industrial policy.<sup>52</sup>

- **Ability to enhance energy security and support renewable energy.** Combining CCU technologies such as e.g. renewable methanol or methane production, or formic acid production with base-load (or surplus) renewable energy generation technologies – such as offshore wind or biomass generation – offers a means to convert energy into a stored form during off-peak time. Where CCU results in permanent storage, the potential exists for so-called ‘negative emissions’ on a net basis where the CO<sub>2</sub> capture source is combustion of biomass fuel.
- **Support for national CCS deployment.** Because of its high costs and lack of revenues, CCS undertaken purely for mitigation purposes necessarily requires significant financial support for project to be economically viable. Revenues from CCU applications may provide the means to offset some or all of the costs associated with undertaking a commercial-scale integrated CCS project. The potential deployment of one or more CCU application within a CCS cluster could also offer operational and commercial flexibility for optimal use of CO<sub>2</sub>, either as a slip-stream from a single capture facility or as part of a larger site/complex. Furthermore, for those sites without access to geological storage sites, CCU may offer a potential alternative use of industrial CO<sub>2</sub>.
- **Contribution to national CO<sub>2</sub> emissions abatement.** As described above, CO<sub>2</sub> utilisation has the potential result in net reductions of CO<sub>2</sub>, depending upon the application, energy source and other factors. This can occur through permanent storage of CO<sub>2</sub> (i.e. its permanent removal from the atmosphere), through efficiency effects or through displacement of fossil fuels (e.g. oil-based products used for transport fuels). As such, it could play a role in reducing the UK’s GHG emissions across a range of sectors and industrial applications.

## 5.2 Approach to assessing CCU potential in the UK

Figure 24 shows the approach taken to assessing the potential for CCU deployment in the UK within the study. The relevant study work packages (WP) are shown, along with the key activities, outputs and sources of information/data.

<sup>51</sup> For example, this has been demonstrated for poly(urethanes) by von der Assen and co-workers at ICCDU 12 in Washington, USA where an overall net CO<sub>2</sub> emissions reduction of 9% has been achieved over the whole process by using CCU rather than the conventional synthetic process

<sup>52</sup> See for example, ‘Sweating our Assets’ – Productivity and Efficiency Across the UK Economy’ (2020 Productivity and Efficiency Group); <http://tellaurla.org.uk/resource/2020%20Report.pdf>

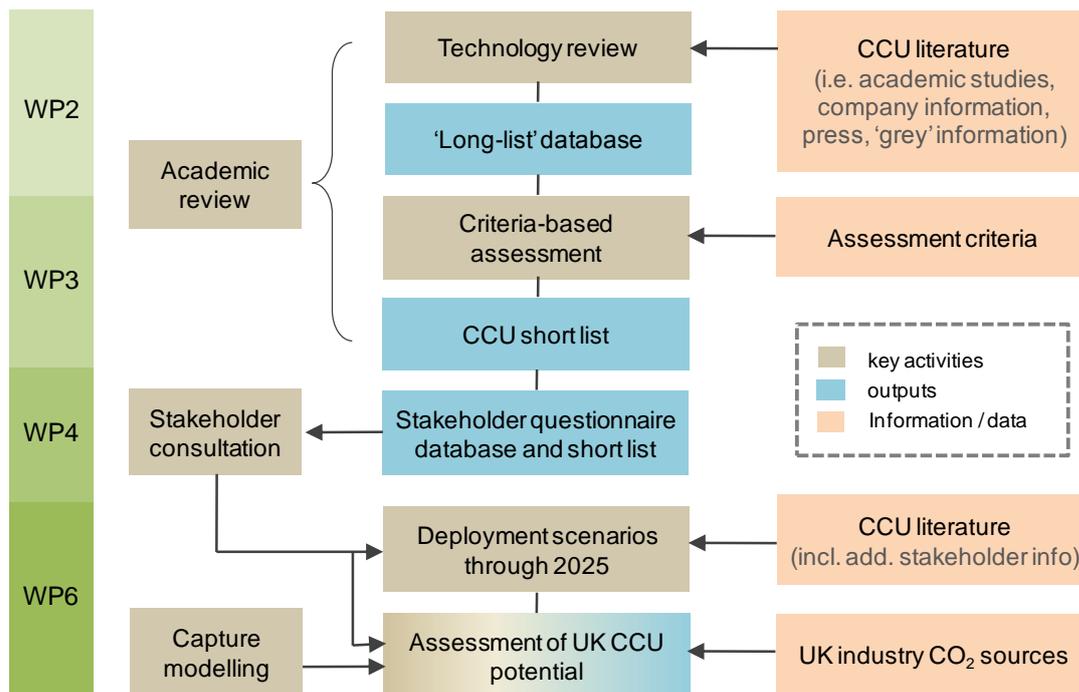


Figure 25 Schematic of approach to CCU assessment

The key steps involved in the CCU assessment can be summarised as:

1. **Technology review.** Development of a database for CCU technologies based upon the literature, company information, press and other information sources. Information and data collected across a wide range on technical, economic, market and policy factors and subjected to academic review.
2. **Criteria-based assessment for UK applicability.** A criteria-based 'screening' of CCU technologies to determine which may be most applicable for deployment in the UK through 2025; resulting CCU 'short-list' based on technology, commercial and other UK-specific factors.
3. **Stakeholder consultation.** Use of stakeholder questionnaire, interim project workshop and one-to-one discussions in order to test approach and sources of information and data used, gather additional information and seek broader views on the potential and challenges for CCU deployment at UK industrial sites.
4. **Scenario-based assessment of UK CCU deployment potential.** Development of scenarios to estimate CCU deployment potential in 2025 (moderate, high and very high); annual CO<sub>2</sub> volumes utilised and revenues estimated for combinations of 'shortlisted' CCU technologies utilising CO<sub>2</sub> from UK industrial sites.

These activities, and their associated outputs, are described further below.

### 5.3 Review and assessment of CCU technologies

In order to arrive at a comprehensive 'long list' of CCU technologies and applications, a global review was undertaken, ranging from lab-scale R&D activities reported in academic

papers and technology press through to commercially established uses of CO<sub>2</sub>.<sup>53</sup> The review sought to gather latest information and data according to the following themes:

- **Technology overview** - technical description of technology/application; technology providers; applicable CO<sub>2</sub> sources and CO<sub>2</sub> stream requirements; CO<sub>2</sub> utilisation rate per unit of product/service; destination of CO<sub>2</sub> e.g. permanence of storage
- **Technology status** - technology readiness level (TRL); current status of technology and projects; estimated time to commercial deployment; R&D activities and aims; funding and support programmes
- **Market and economics** - sources of revenue generation; cost factors e.g. capital, operating, energy and other costs; market capacity and demand; market development factors; regional considerations; barriers to widespread deployment
- **Environmental considerations** – life-cycle GHG emissions across entire process from manufacture to product end use e.g. is there a potential net GHG benefit? (whilst noting the generally low level of LCA analyses currently available for CCU); non-GHG environmental impacts or benefits

The review was based on latest publicly available information, including:

- Recent global studies on CCU technology (e.g. Carbon Sequestration Leadership Forum (CSLF), 2011. Phase I Final Report by the CSLF Task Force on CO<sub>2</sub> Utilization; Carbon Sequestration Leadership Forum, 2013 Phase II Final Report; and Global Carbon Capture and Storage Institute (GCCSI), (2011. Accelerating the uptake of CCS: Industrial use of captured CO<sub>2</sub>)
- Academic literature (there is an extensive body of scientific and technology literature relating to most areas of CCU, largely based around early R&D activities)
- Company information (e.g. project and process information/claims from start-ups and multinationals)
- Press and trade associations (project and technical information from trade and specialised press, and various trade groups)
- Various CCU technology networks and activities (e.g. CO<sub>2</sub>chem; International Conference on Carbon Dioxide Utilization (ICCDU); Foreseeing a future using CO<sub>2</sub> (4CU); Supercritical CO<sub>2</sub> Power Cycle Symposium (SCO2PCS))

Several limitations and challenges are noted in seeking to compile such information. As noted above, the majority of known CCU technologies are currently at early pre-commercial stages of R&D (e.g. TRL levels 1-3) and as such report little or no economic or financial data; noting also, that such data were it available would be likely unrepresentative of the technology scaled-up to demonstration scale or applied in other settings (e.g. using different sources of CO<sub>2</sub> and supply of energy). A related problem is that for many applications, including more mature technologies, much of the cost data is confidential to the technology providers or users. Finally, where performance and (limited) cost data is published by companies, these are typically not supported by important assumptions, boundary systems etc. As such, optimistic claims regarding commercial potential must necessarily be viewed with caution. These and other factors point to the need for improving the techno-economic evidence basis for CCU. Several such projects have recently started (e.g. an EC-JRC study assessing several CCU processes and a study

<sup>53</sup> Note that CO<sub>2</sub>-EOR was not considered within the scope of the study

undertaken through the Smart CO<sub>2</sub> transformation (SCOT) initiative. Both projects are early in their studies and therefore have yet to report significantly on their findings.

Based on this 'long list' of CCU technologies, a criteria-based 'screening' was undertaken to determine which could be most applicable for deployment in the UK. Based on the information collected, each identified technology was assessed using a simple 'traffic-light' approach (e.g. where red and green signified a low and high assessment of applicability respectively, with amber signifying a less certain, or intermediate, outcome). The aim was to arrive at a shorter list of CCU applications for further consideration within the study, in order to exclude those technologies currently not considered viable for deployment beyond R&D level in the UK over the next decade, and simultaneously to focus in on those applications considered to have most potential.

The assessment was based on the following 3 key criteria areas:

**1. Technology development and performance**

- a) Technology readiness level (TRL)<sup>54</sup>
- b) Energy performance (including energy storage potential)
- c) Abatement potential (e.g. permanent versus temporary storage; fossil fuel substitution etc)
- d) Environmental, health and safety factors/concerns (non-GHG related)

**2. Economic and commercial potential**

- a) Uptake potential (size/scale of potential market)
- b) Economic potential (various cost and market competition factors)
- c) Commercial barriers

**3. Applicability to the UK**

- a) Relevance to UK markets and sectors
- b) Geography, raw materials and other physical factors
- c) Alignment with UK technology providers, suppliers and R&D efforts/programmes

The resulting assessment is summarised in Table 1

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<sup>54</sup> Technologies at TRL levels 1-3 are not considered viable for deployment at the scales of 0.2-8 Mt/yr needed to support UK industrial CO<sub>2</sub> capture by 2025.

It can be seen that based on the chosen criteria, the following 'short-listed' CCU technologies and applications were identified:

- **Renewable methanol** - Electrolysis of water to produce hydrogen, which is then combined with CO<sub>2</sub>, compressed and reacted over a catalyst to produce methanol and water. The methanol can be blended with petroleum spirit into various grades of transport fuel. Energy provided by renewable source offers the potential for low-carbon fossil fuel substitution combined with renewable energy storage.
- **Mineral carbonation** - CO<sub>2</sub> is reacted with minerals - mostly calcium or magnesium silicates - to form (Ca or Mg) carbonates for use in building materials and other applications, resulting in permanent storage of the CO<sub>2</sub>. Unlike with most other CCU applications, the process can work directly from flue gas (i.e. no capture step is required).
- **Polymer production** - Use of captured CO<sub>2</sub> in combination with traditional feedstocks to synthesise polymers such as polypropylene carbonate (PPC) and polyethylene carbonate (PEC) for use in various products and applications. CO<sub>2</sub> can also be used as a feedstock in the polymerisation of urethanes to produce polyurethanes.
- **Existing commercial industrial uses for CO<sub>2</sub>** - in addition to EOR and urea manufacture, CO<sub>2</sub> is currently used across a wide range of smaller-scale sectors and applications including food and beverages, horticulture, pharmaceuticals, pulp and paper processing, water treatment, steel manufacture, electronics, pneumatics and welding. CO<sub>2</sub> is also used as a refrigerant gas and for fire suppression.

Stakeholders were consulted for their views on this 'short list', as well as the original long-list and the screening criteria chosen e.g. whether the approach taken was appropriate, and the technology review sufficiently comprehensive. This was undertaken through the workshop participation, questionnaire and one-to-one communication process. The resulting feedback served to validate the completeness of the technologies contained in the long-list as well as the choice of assessment criteria used and the choice of technologies in the resulting short list.

CCU category	Technology / application	Sector applicability (CO <sub>2</sub> sources)	Criteria			Selection ?
			A. Technology development and performance	B. Economic and commercial potential	C. Applicability to the UK	
CO <sub>2</sub> to fuels	Renewable methanol and methane	All sectors	TRL 5-7			Yes
	Formic acid production	All sectors	TRL 5			No
	Algae cultivation	All sectors	TRL 3-5			No
	Helioculture	All sectors	TRL 3			No
	Counter Rotating Ring Receiver Reactor Recuperator	All sectors	TRL 3			No
	Photocatalytic reduction of CO <sub>2</sub> (metallic)	All sectors	TRL 3			No
	Photocatalytic reduction of CO <sub>2</sub> (non-metallic)	All sectors	TRL 3			No
Nanomaterial catalysts	All sectors	TRL 2-3			No	
Enhanced commodity production	Enhanced Geothermal System with CO <sub>2</sub>	All sectors	TRL 4			No
	Supercritical CO <sub>2</sub> power cycles	All sectors	TRL 3			No
	Urea yield boosting	All sectors	TRL 9			No
	Methanol yield boosting (conventional)	All sectors	TRL 9			No
CO <sub>2</sub> mineralisation	Mineral carbonation	All sectors	TRL 3-7			Yes
	Sodium bicarbonate	All sectors	TRL 6			No
	CO <sub>2</sub> concrete curing	All sectors	TRL 5			No
	Bauxite residue carbonation	All sectors	TRL 8			No
CO <sub>2</sub> as chemicals feedstock	Polymer processing (polycarbonates)	All sectors	TRL 3-5			Yes
	Polymer processing (polyurethanes)	All sectors	TRL 3-5			Yes
Existing commercial applications	Food and beverage applications	High purity	TRL 9			Yes
	Horticulture	High purity	TRL 9			Yes
	Other Industrial and technical uses	High purity	TRL 9			Yes

**Table 1 Criteria-based assessment of CCU applications to the UK**

Note: TRL = Technology Readiness Level, classifications based on "Technology Readiness Levels (TRLs) in the Project Lifecycle", UK Ministry of Defence

<sup>44</sup> Based on the Sabatier reaction, which exothermically combines hydrogen and carbon dioxide to produce methane and water in the presence of a catalyst (i.e. CO<sub>2</sub> + 4H<sub>2</sub> = CH<sub>4</sub> + 2H<sub>2</sub>O). As with renewable methanol production, the hydrogen input can be produced via Polymer Electrolyte Membrane (PEM) water electrolysis using a renewable energy source. The resulting methane can be used to substitute natural gas in a range of energy applications

### 5.4 Deployment scenarios

Illustrative scenarios of CCU deployment in the UK were developed for the selected applications/technologies. The objective was to describe, at a high level, a viable range of CCU deployment in 2025 in terms of industrial CO<sub>2</sub> utilised (million tonnes CO<sub>2</sub> per year) and potential revenues from CCU products (£ million per year). The three scenarios, summarised in Table 2, present three progressively ambitious outlooks, or pathways for UK uptake of CCU technology. The ‘very high’ scenario can be considered at the very upper end of what would be feasible by 2025, given the current low-zero level of deployment within the UK (other than small-scale R&D lab and pilot efforts). Even the ‘moderate’ scenario would entail significant technology progress, policy support and/or favourable market development for CCU products over the next decade; and as such is not to be interpreted as a ‘business as usual’ type scenario.

Figure 26 compares the volume of CO<sub>2</sub> projected to be available from UK industry in 2025 against the potential CO<sub>2</sub> utilisation rates under each of the three deployment scenarios. Note that the y-axis does not in any way indicate abatement potential; it simply shows the annual volume of CO<sub>2</sub> emissions available, and how much could realistically be used for CCU. Under the ‘very high’ scenario, CCU uptake utilises around 8-9 million tCO<sub>2</sub> per year, or around 15-20% of all UK industrial emissions (or all CO<sub>2</sub> emissions from the chemicals industry). This falls to 3-4 million tCO<sub>2</sub> (approx. 7% of total emissions) under the ‘high’ scenario, and around 0.5-0.7 million tCO<sub>2</sub> (approx. 1% of total emissions) under the ‘moderate’ scenario. Although CO<sub>2</sub> utilisation rates (tCO<sub>2</sub> utilised per tonne product) vary significantly across products, the relative shares for CCU CO<sub>2</sub> utilisation shown in the bars are more reflective of the possible pathways for technology development and market development.

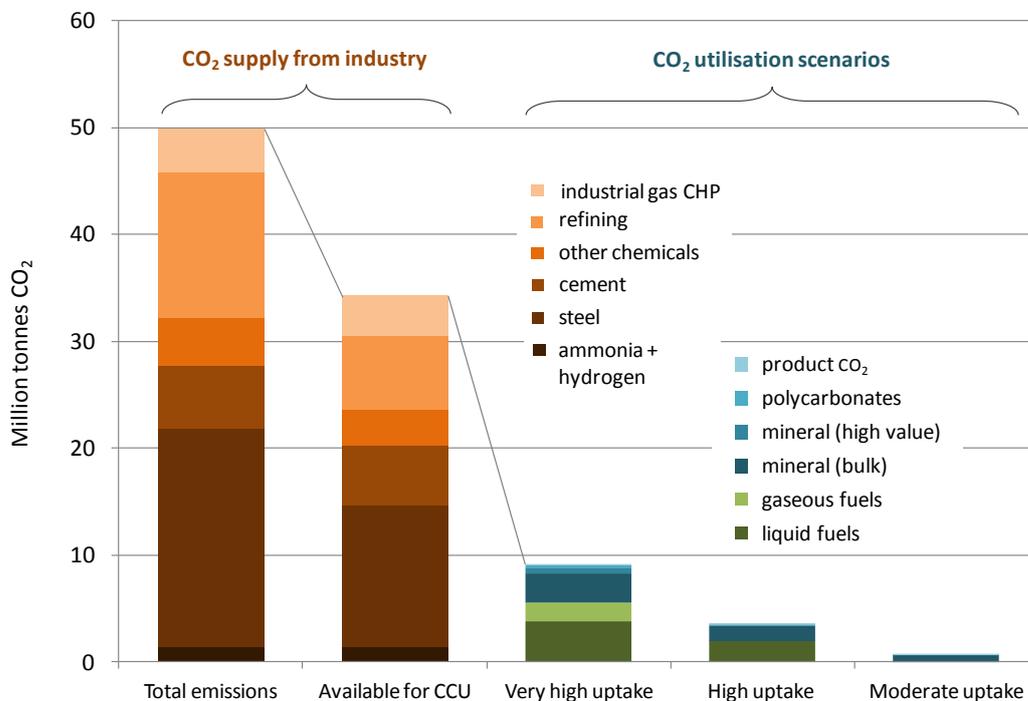


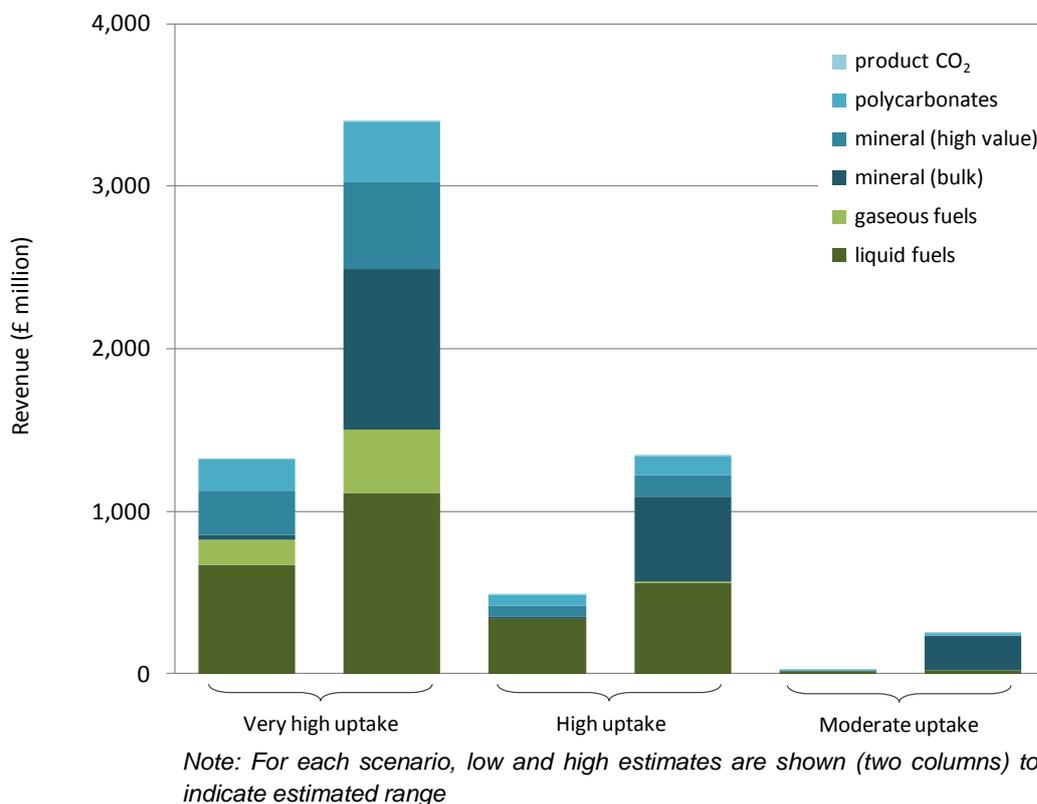
Figure 26 CCU scenarios: annual CO<sub>2</sub> supply and utilisation in 2025. (Low uptake scenario not shown)

Table 2 Scenarios for CCU deployment

CCU uptake in 2025	CCU application				
	Renewable methanol	Renewable methane	Mineral carbonation	Polycarbonates	Industrial product CO <sub>2</sub>
Very high	10% penetration of the UK road transport petroleum market in 2025. Equivalent to around 2.75 million tonnes annual methanol production (roughly one third of current methanol fuel blending globally, and around 4-7 commercial scale plants) using around 3.75 million tCO <sub>2</sub> p.a.	5% penetration of the UK natural gas power generation market (on an energy basis). Equivalent to around 11 TWh (approx. 1 billion m <sup>3</sup> ) annual methane production and around 1.8 million tCO <sub>2</sub> utilisation.	Up to 50% of the UK's cement sector emissions used for mineral carbonation products. 10% of magnesite production <sup>(3)</sup> is used in early-stage high value industrial applications; 90% is used in lower value bulk markets such as lime, filler etc. Up to 10% of bi-product APS production potential realised. <sup>(4)</sup>	1-2 commercial-scale plants by 2025 with capacity of approx. 300,000 tonnes p.a. PEC or PPT, utilising industrial CO <sub>2</sub> of approx. 150,000 tCO <sub>2</sub> p.a. Represents just 4% of the current PE market in Europe - although considerable obstacles face development of PEC production, and investor confidence, within the UK.	Assumes 20% market growth through 2015-2025, based on estimated current demand of 200,000-300,000 tCO <sub>2</sub> p.a. (i.e. additional demand of 50,000 tCO <sub>2</sub> p.a. across a range of sectors and applications e.g. beverages, horticulture, electronics, waste water, speciality chemicals.
High	5% penetration of the UK road transport petroleum market. Equivalent to around 1.37 million tonnes annual methanol production and around 1.9 million tCO <sub>2</sub> utilisation p.a. (2-4 commercial scale plants).	1 commercial-scale plant operational by 2025 with production capacity of approx. 15 million m <sup>3</sup> utilising industrial CO <sub>2</sub> from on-site or other nearby CO <sub>2</sub> sources of approx. 30,000 tCO <sub>2</sub> p.a.	Up to 25% of the UK's cement sector emissions utilised. 5% of magnesite production is used in early-stage high value industrial applications and only 5% of APS production potential is able to find a market (60-70,000 t).	1 commercial-scale plant by 2025 with production capacity of approx. 100,000 tonnes p.a. PEC or PPT, utilising industrial CO <sub>2</sub> of approx. 50,000 tCO <sub>2</sub> p.a. Represents less than 2% of the current European PE market.	10% market growth through 2015-2025 i.e. additional demand of 25,000 tCO <sub>2</sub> p.a. across a range of sectors and applications.
Moderate	1 commercial-scale plant operational in the UK by 2025 with capacity of approx. 50 million litres utilising industrial CO <sub>2</sub> from on-site or other nearby CO <sub>2</sub> sources of approx. 55,000 tCO <sub>2</sub> p.a. <sup>(1)</sup>	Pilot scale pre-commercial production only (100,000 m <sup>3</sup> methane p.a., equal to the world's current largest pilot project in Germany) supplied by c.200 tCO <sub>2</sub> p.a. <sup>(2)</sup>	Up to 10% of the UK's cement sector emissions utilised - equivalent to one typically sized cement plant of 0.6 MtCO <sub>2</sub> per year. All magnesite production is used in bulk applications and APS production is unable to find a market outlet.	Pilot scale pre-commercial production only (e.g. 10,000 tonne product p.a.) supplied by 5,000 tCO <sub>2</sub> p.a. Could operate as an R&D supported slip-stream CO <sub>2</sub> source within a larger CCS project including geological storage.	5% market growth through 2015-2025 i.e. additional demand of 10-15,000 tCO <sub>2</sub> p.a. across a range of sectors and applications.

Notes: (1) Capacity of a similar scale to a renewable (geothermal energy) methanol plant currently being planned by Carbon Recycling International (CRI) in Iceland; (2) Centre for Solar Energy and Hydrogen Research (Baden-Württemberg (ZSW)), 2012; (3) 5-6 million tonnes in total, around 50% of all current UK cementitious production according to MPA, 2013; (4) equivalent to around 270,000 t per year amorphous precipitated silica (APS), compared to current market globally of a few million tonnes per year.

Figure 27 shows corresponding estimates for the annual revenues associated with the three CCU deployment scenarios described. The figures show potential product revenues only (the potential for avoided industry carbon costs e.g. for mineral carbonation products are not modelled); costs are not included. For each scenario, an estimated range is shown with 'low' estimate and 'high' estimate columns; the high and low estimates reflect the very wide range of uncertainties and variables concerning future product prices. It can be seen that the fuel and bulk mineral products are considered to have the greatest share market potential, largely reflects their larger market size potential compared to higher value products such as polymers and amorphous precipitated silica (APS). The market size for product CO<sub>2</sub> is considered to be relatively small, as well as being met by existing mature suppliers. Under the 'very high' scenario, annual revenues are estimated to be in the range of around £1.3-3.4 billion, falling to around £0.5-1.3 billion under the 'high' scenario and around £25-250 million under the 'moderate' scenario.



**Figure 27 CCU scenarios annual revenues (low and high estimates) 2025**

The deployment scenarios presented are intended to be illustrative scale-order estimates only of CCU potential over the next decade.

As discussed above, most CCU applications remain at the pre-commercial stage; overcoming high costs represents a major barrier to wider deployment at present, and much will depend on the progress of ongoing R&D activities within the UK and globally. Demand for, and acceptance of, alternative products using CO<sub>2</sub>, will also drive the rate of CCU penetration into existing mature markets such as transport fuels, building products and petrochemicals. Although specifically excluded from the scope of this study, the scale,

maturity and economics of offshore CO<sub>2</sub>-EOR compare favourably with the utilisation options identified here<sup>55</sup>.

Finally, much will depend upon the extent to which CCU products can demonstrate net abatement benefits to a sufficiently robust degree, thereby qualifying for support and/or inclusion within various UK- and EU-level climate policies and support programmes. These will need to be demonstrated through significant LCA analyses and technology-specific studies.

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<sup>55</sup> Element Energy *et al.* (2014) CCS Hub study for Scottish Enterprise.

## 6 Conclusions

This study confirms that a range of capture technologies can be applied in the period to 2025 to the UK's carbon intensive cement, chemicals, iron and steel and oil refining industries, with the potential for meaningful cuts in CO<sub>2</sub> emissions at several sites, with associated benefits in kick-starting industrial CCS deployment in the UK and globally.

Barriers to the deployment of carbon capture in these industries have been identified through stakeholder consultations and literature review, and are characterised according to the level at which the issue resides (from project to system-wide) and the level at which these can be addressed. Aside from significant system-wide barriers (outside the scope of this project), actions at industry and sector level can remove four main barriers;

- High operational complexity and risks (unavailability, process dependencies)
- Application not proven at scale
- Most technologies not developed to a commercially ready level
- Plant integration risks and hidden costs (additional downtime, alternative product supplies, technology lock-in)

In addition the over-arching “systemic” barriers include the lack of commercial incentives to implement CCS, which has significant up-front and ongoing variable costs, a lack of CO<sub>2</sub> transport and storage infrastructure, and limited experience of operational full chain CCS projects with industrial sources.

Whereas the literature identifies many capture technologies able to play a role by the 2030s, CCS projects have very long lead times. If the UK wishes to implement a demonstration or full-scale CCS project at an industrial CO<sub>2</sub> source in the period to 2025, then project development needs to begin quickly, so that a final investment decision can be made by ca. 2020. This timeline limits the portfolio of source-capture technology combinations available to those which can draw on experience of successful demonstration projects at a close enough scale and for similar site/plant conditions. In parallel, efforts may be directed to advance next generation technologies so that these are available for implementation in the late 2020s and 2030s.

This analysis suggests that an efficient industrial CCS pathway would combine:

- High CO<sub>2</sub> purity sources (such as ammonia and hydrogen),
  - There is little need for innovative “capture” technologies as such, but mainly a need to bring CO<sub>2</sub> stream conditions to the specifications required for transport over appreciable distances and long term geological storage.
  - These projects could be operational in the period 2020-2025 and could be important to test whole-chain business and regulatory models and transport and storage infrastructure.
- For the iron and steel industry, a ca. 1-3 MtCO<sub>2</sub>/yr end-to-end demonstration project operational by 2025.
  - Site-specific pre-FEED and FEED studies would be required to identify the optimum configurations.
  - The techno-economic modelling suggests that physical solvents (applied to Blast Furnace gas) or chemical solvents (e.g. 1<sup>st</sup> generation amines retrofit to site CHP facilities) could support a project of 1-3 MtCO<sub>2</sub>/yr. Given similarities to post-combustion power CCS, these larger scale

- projects could be enabled by leveraging the experience from the power sector in the development of projects in the iron and steel sector.
- In parallel, pilot studies could explore capture configurations with longer term relevance for enabling larger scales or lower costs or risks for CO<sub>2</sub> capture for projects in the 2030s.
  - For the cement, other chemicals and oil refining sectors, chemical solvents and solid looping offer significant potential for demonstration in 2025. 1<sup>st</sup> generation amine solvents could be employed at the largest scales, although 2<sup>nd</sup> generation chemical solvents and solid looping should offer lowest unit costs. However given substantial barriers to implementation these sectors would benefit from detailed engineering studies and pilot projects.
    - In the refining sector, a plausible sequence involves the roll out of 1<sup>st</sup> generation amine solvents in end-to-end projects at up to 0.7 MtCO<sub>2</sub>/yr by 2020, scaling up to 1.5 MtCO<sub>2</sub>/yr by 2025.
    - In the cement sector which has less familiarity with CCS, a plausible sequence involves a capture pilot of 0.1 Mt/yr in the period to 2020, scaling up to an end-to-end full chain CCS demonstration project with capacity of ca. 0.5 MtCO<sub>2</sub>/yr by 2025.
    - The design of capture pilots and demonstrations for existing boilers and conventional industrial CHP systems should be taken as part of a system-wide approach to decarbonising heat and power.
  - At a UK-wide level piloting capture applications at cement and oil refining sites by 2020 could reduce multiple barriers for CCS demonstration projects operational by 2025.
  - These pilots could involve 1<sup>st</sup> generation amine technologies, 2<sup>nd</sup> generation chemical solvents or solid looping. These would then naturally facilitate the availability of 1<sup>st</sup> or 2<sup>nd</sup> generation chemical solvents for demonstrate for 2025. It should be recognised however that 1<sup>st</sup> generation amine technologies are expected to be superseded by alternative capture processes by the 2030s.
  - However the analysis also suggests that industries should have flexibility on exact choice of capture technology. There are significant differences between conditions at individual sites and several capture technologies are projected to have similar costs. The optimal technology solution may therefore vary between similar sites, reflecting specific challenges and conditions, and minimising the risk of technology lock-in.
  - Other 2<sup>nd</sup> generation bolt-on technologies such as calcium looping offer significant long-term cost reduction potential. Pilots and demo plants in the 2020s would be particularly relevant for sites which have limited access to cooling water.

There is a paucity of reference projects providing reliable cost and performance estimates, so cost uncertainties of +100%/-50% should be expected<sup>56</sup>. The limited confidence that CCS can be operated at pre-existing large industrial sites without compromising core business operations is particularly acute. Whereas CCS pilot and demonstration projects in other parts of the world or in other sectors (e.g. power) may lead to general improvements, i.e. lower cost of capital, reduced capex and opex costs, and improved performance, stakeholder discussions have confirmed that cost and performance uncertainties would ideally be reduced through a phased programme of projects at relevant UK sites with scale increasing towards commercial relevance.

<sup>56</sup> Uncertainties of greater than +200%/-33% sector are common in the oil refining for novel technologies at the concept stage, A. Roberts, UKPIA, *Personal Communication*

For high purity CO<sub>2</sub> sources, the chief constraint is the lack of a validated full chain CCS business model (i.e. including transport and storage and/or utilisation), and transport and storage infrastructure.

For iron and steel, a wide range of process configuration options are possible, and site specific analysis, including detailed process simulations covering dynamic as well as steady-state properties, are required to determine the least cost, least risk technology pathway.

For the cement sector, projects at a scale of 0.1 Mt/yr using amine solvents could be deployed to build experience by 2020, while further developing 2<sup>nd</sup> generation amines, oxyfuel or calcium looping to higher technology readiness levels. Selection of the more successful options could then be made towards 2025 based on industry application evidence. Limited availability of cooling water, COMAH status, and experience with calcium looping technologies may encourage interest in calcium looping, even though this technology is not yet well developed.

For other chemicals and refining sectors (excluding hydrogen and ammonia) the heterogeneity and complexity of tapping multiple CO<sub>2</sub> vents will be a challenge. For an oil refinery, a phased deployment appears attractive. For example, this could begin with a one train amine single flue gas absorber pilot of 0.1-0.5 Mt/yr in 2020, building up to a two train system in 2025 capturing CO<sub>2</sub> from multiple vents.

UK industry can benefit from international experiences of existing and planned capture initiatives worldwide. However there will still be a need for deployment in the UK to overcome the significant UK-sector and site specific barriers that are identified by stakeholders. A key example is the focus in the UK on retrofit applications, because especially in the iron and steel and refinery sectors, but also in the larger chemicals and cement plants, the construction of new plants in the near future is not considered likely by industry. In some other countries (China, US, Middle East) demonstrations for integrated projects in newly build facilities, have limited value for the UK.

Multiple options for onshore CO<sub>2</sub> utilisation are identified. However there is very large uncertainty as to the availability of markets and technologies to support this in the period to 2025. Therefore utilisation is unlikely to drive a decision to fit CO<sub>2</sub> capture. Utilisation is not a low risk solution for assets that are far from any potential transport and storage network, and it may be prudent to review permanent onshore CO<sub>2</sub> storage options that do not involve utilisation.

Where sites are able to use CO<sub>2</sub> transport and storage, and sites are already planning capture, then utilisation could reduce costs. Though out of scope of this study, opportunities for CO<sub>2</sub> utilisation in the short term also include the potential demand for CO<sub>2</sub>-Enhanced Oil recovery in the North Sea for which projects with scales of 5-10 Mt/yr in the period 2020-2025 have been proposed.

The high purity sources (ammonia and hydrogen production), are exceptions to these timelines, as highly concentrated CO<sub>2</sub> is readily available from these facilities and CO<sub>2</sub> separation is already deployed at commercial scale for these conditions.

## Glossary

4CU	Foreseeing a future Using CO <sub>2</sub>
AACE	Association for the Advancement of Cost Engineering
APS	Amorphous Precipitated Silica
BIS	Department of Business Innovation and Skills
Ca	Calcium
CCS	Carbon Capture and Storage/sequestration
CCSA	Carbon Capture and Storage Association
CCU	Carbon Capture and Utilisation
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CO	Carbon monoxide
CO <sub>2</sub>	Carbon dioxide
COMAH	Control of Major Accident Hazards
CTX	Carbon To Liquids/Gas
DECC	Department of Energy and Climate Change
ECBM	Enhanced Coal Bed Methane
EC-JRC	European Commission Joint Research Centre
EGR	Enhanced Gas Recovery
EGS	Enhanced Geothermal Systems
EOR	Enhanced Oil Recovery
ETS	Emissions Trading Scheme
EUR	Euro
FCC	Fluid Catalytic Cracker
FEED	Front End Engineering Design
GHG	GreenHouse Gas
HSE	Health, Safety and Environment
IAG	Interdepartmental Analysts Group
ICCDU	International Conference on Carbon Dioxide Utilization
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
ITT	Invitation To Tender
LCA	Life-Cycle Analysis
LNG	Liquefied Natural Gas
MEA	MonoEthanolAmine
Mg	Magnesium
NO <sub>x</sub>	Nitrogen Oxide
PCE	Personal Consumption Expenditures
PE	PolyEthylene
PEC	PolyEthylene Carbonate
PEM	Polymer Electrolyte Membrane
PPC	PolyPropylene Carbonate
PSE	Process Systems Enterprise
R&D	Research and Demonstration
RD&D	Research Development and Demonstration
SCO2PCS	Supercritical CO <sub>2</sub> Power Cycle Symposium
SCOT	Smart CO <sub>2</sub> Transformation
SO <sub>x</sub>	Sulphur Oxide
T&S	Transport and Storage
TGR	Top-Gas Recycling
TRL	Technology Readiness Level
ULCOS	Ultra-Low Carbon Dioxide (CO <sub>2</sub> ) Steelmaking

WEF      World Economic Forum  
WP      Work Packages

## Units of measure

GJ      gigajoules  
t      tonne  
kt      kilotonne  
Mt      megatonne (million tonnes)  
MPa      megapascal  
kWh      kilowatt-hours  
TWh      terawatt-hours