AECOM

Next Generation Carbon Capture Technology

Technology Review
Work Package 2

Department for Business, Energy and Industrial Strategy

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Delivering a better world

Quality information

Prepared by	Checked by	Verified by	Approved by
David Menmuir Stephen Florence Kevin Taylor	Klim MacKenzie Stephen Florence	Graeme Cook	Andy Cross

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Prepared for:

Department for Business, Energy and Industrial Strategy
1 Victoria Street
London
SW1H 0ET
United Kingdom

AECOM Limited
7th Floor, Aurora
120 Bothwell Street
Glasgow G2 7JS
United Kingdom

T: +44 141 248 0300
aecom.com

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1. Executive Summary

AECOM has been appointed by BEIS to conduct a review and technoeconomic analysis of next generation carbon capture technologies. The study will consider the potential application of carbon capture technology to different industrial, waste and power sites. The work focuses on technologies with the potential to be deployed at a scale of the order of 1,000 ton per day of CO_2 capture by 2030. Less well-developed technologies that are more likely to be deployed at scale by 2035, or later, have been reported on, but with a lower level of detail.

This document reviews a broad range of carbon capture technologies, the technoeconomic analysis of selected technologies is covered in subsequent reports.

Established Carbon Capture and Usage Applications

There are existing industrial processes where gas streams are processed that contain a high concentration of CO_2. These industries include the production of hydrogen, natural gas upgrading, brewing and distilling and biogas upgrading. It is relatively simple, and low-cost, to capture CO_2 from these sectors and it is already captured at some sites for use in industries such as food processing and drinks manufacture. However, much of the CO_2 will not be captured due to a range of factors, including limitations in market demand for CO_2.

These industries offer low-cost CO_2 capture opportunities and will be important in relation to achieving cost-effective CO_2 emission reductions in the UK. However, the total mass of CO_2 available from such sources is very small in comparison to total UK industrial emissions. The technologies for capturing the CO_2 at these sites are important but are not the focus of this assignment. This study focuses on capturing CO_2 from other emission sources including power generation, thermal treatment of waste and industrial processes such as cement production.

Cost Reduction Through Commercial Deployment

Achieving cost reduction in carbon capture is important in relation to encouraging deployment of technologies. Both the development of new processes, and the advancement of existing systems through the various stages of commercial deployment, are important elements in achieving cost reductions in the carbon capture sector.

For all technology types cost reductions are primarily achieved by progressing through the commercial readiness scale. Developing a technology to a high technology readiness level (TRL) is required for a reliable base cost to be established and to allow the process of cost reduction to commence. Advancing through the stages of commercial readiness then allows cost reductions to occur from improvements to sub-components, manufacturing techniques, maintenance strategies and financing costs.

Some solvent-based carbon capture systems have successfully completed the early stages of commercial deployment for post combustion carbon capture. These technologies have an advantage in relation to large scale deployment by 2030.

There are many technologies at a pre-commercial stage of development. As time progresses some of these may offer cost savings in industrial applications, and some will never progress to a commercial setting. Even where new technology concepts will offer cost savings in the long term, they may be more expensive during initial stages of commercialisation due to greater perceived risk and the impact this will have on contingencies and financing costs.

Understanding the value of, and difference between, technology development through incremental improvements and the development of new concepts and processes is important in relation to promoting efficient innovation and development in the carbon capture sector.

Deployment Risk Optimisation

Commercial deployment provides valuable opportunities for innovation and acceleration of the development process. However, premature commercial deployment brings a risk of delays, failing projects, inefficient use of funding and reputational damage to a technology and or industry sector.

When commercially deploying a range of new technologies and progressing along the commercial readiness pathway, a balance is required in relation to the level of risk taken to promote innovation in the technology. An excessively low risk approach is likely to result in lack of innovation and the slow development of technologies. Similarly, an excessively high-risk approach may also result in the slow development of technologies due to failed projects. Failing projects divert money away from others that could have provided useful innovation. Furthermore, they can adversely impact the perception of the technology in the investment community and in the public.

The risk associated with a project that uses a new technology is proportional to a diverse range of factors. These factors will, or at least should, be assessed by organisations making significant investments in the project. Understanding these factors for a given project allows an assessment to be made as to the level of associated risk. Factors to consider in relation to the risk of developing carbon capture project include the potential impact on main process plant, ability to revert to a known working option, relative scale of reference plant, differences in feed gas inputs, technical differences in the process, risk allocation and performance assumptions made.

Prior to commercial deployment a detailed technical assessment of performance assumptions should be undertaken by the organisation making the investment or an independent third party with appropriate skills. This process is referred to as due diligence, and effective due diligence is critical in relation to understanding the risk associated with commercial deployment of new technologies. The due diligence process unavoidably requires detailed examination and understanding of the proposed process and the performance of reference projects and or demonstration plants. If suitable test data is not available, then the only conclusion can be that the performance is not proven.

The existence of a demonstration plant does not mean that a technology has been successfully demonstrated. A small demonstration project that has shown good performance, with high availability over a sustained period, in a representative environment is of higher value in demonstrating viability than a large demonstration plant that operated poorly or is unable to provide operational information. The inability to provide evidence of sustained good operational performance is calls viable operation into doubt.

Categorisation of Technologies

The next generation technologies that are most likely to be deployable at around 1000 tpd scale by 2030 are mostly amine based solvent systems that can be developed by incremental improvements. In this report these technologies have been classified as *Demonstration Stage* technologies. Some non-amine based solvent systems also have greater potential for near-term deployment as there is commonality in the process equipment used.

Technologies that are considered more likely to be deployable at around 1000 tpd scale by 2035 or later have been classified as *Development Stage* technologies. *Research Stage* technologies are at an earlier stage of development. Details of the categorisation used for different technologies in this report are provided in Table 1. For each category, all conditions must be met.

Table 1. Technology categories used in this report

Category	Description
1. Demonstration stage Likely to be deployable at a scale in the order of 1,000 tpd by 2030.	• Incremental improvements to, or new applications of, a technology platform that is broadly consistent with at least TRL 8 and has demonstrated successful commercial deployment for at least 12 months at a similar scale. • The technology, or a previous iteration of the technology, has operated at least 50 tpd of CO_2 scale, for at least 12 months, under representative conditions. • Construction commenced, or full funding received, for a project in a similar application of at least 200 tpd scale.
2. Development stage May be deployable at a scale in the order of 1,000 tpd by 2035	• Broadly consistent with TRLs 5-8. • The technology, or a previous iteration of the technology, has operated at least 5 tpd of CO_2 scale in a similar application, and; • Current operation of demonstration project of at least 10 tpd CO_2 capture or, or full funding received, for a larger project.
3. Research stage	• Broadly consistent with TRLs 1-4.

Of the technologies in this report that have been classified as development or research stage, the potential exists for some of them to be deployed at scale by 2030 or earlier. Some of the development stage technologies such as the NET Power Technology, CO2 Capsol and the LEILAC process have conducted front end engineering and design work and are progressing demonstration projects that are intended to be implemented prior to 2030. Similarly, some new solvents, or solvent additives, being researched at lab scale have the potential to be tested and then added to existing carbon capture facilities.

Being included in the research or development categories in this report, rather than the demonstration category, should not be viewed negatively in relation to the long-term future potential of any technology. The challenges of predicting the future and categorising multiple, varied technologies, with limited information must be acknowledged.

Capture Level
For carbon capture technologies, capture level is commonly defined as the percentage of CO_2 in the incoming gas stream that is captured by the technology. There is a debate as to what the minimum capture level for new carbon capture plants should be. In this project the value of technologies being able to achieve a high capture level is recognised, but no minimum capture level criterion has been set for qualification as a next generation technology. It is possible that a technology with a limited capture level could make a valuable contribution to the carbon capture industry by offering other significant technical or economic advantages.

Demonstration Stage Technologies
Technology offerings from suppliers of amine solvent-based capture systems have been reviewed in relation to several key parameters. Within the category of solvent-based carbon capture technologies there are a range of different opportunities for innovation. Collectively, innovations across these areas have the potential to offer significant benefits. From the variety of innovation options available in solvent-based systems many have the potential to offer a good balance between risk, investment requirements and potential benefits.

Innovation opportunities include using existing technology in new applications, implementation at different scales, improvements to plant availability, advances in solvent chemistry and management, process improvements, improved flue-gas pre-treatment, construction improvements and modularisation. These options are being explored by many of the key suppliers.

Development Stage Technologies
For development stage technologies there are increased levels of uncertainty in relation to costs and performance. Many of the technologies reviewed have potential advantages over more developed technologies, but it remains to be proven whether the challenges associated with scale-up and technical issues specific to the individual technologies can be overcome. These technologies must first demonstrate sustained commercial operation at scale and then prove that cost savings can be made. Technologies reviewed in this section include ones based on amine solvents, non-amine solvents, solid sorbents, fuel cells, membranes, oxy-combustion and cryogenics.

Research Stage Technologies
Research Stage technologies are at an earlier stage of development and most have only been demonstrated at lab and bench scales or small-scale pilots. Many of the research stage technologies are developing components that could be fitted into existing technology platforms such as those described in relation to the demonstration and development stage technologies. Where components are being developed that can readily be used in existing technology platforms then the potential for more rapid deployment exists. Research stage technologies include solvents, sorbents, membranes, cryogenics, chemical looping, carbonation and oxy-combustion cycles.

Technology Application Matrix
A matrix of the demonstration and development stage technologies has been developed that indicates the potential applicability of different technologies to different types of flue gasses. This provides an indication of which technologies may be most suited to different industries. The applicability of individual technologies to different types of flue gas has been assessed based upon current and past operational applications, testing performed, planned projects, and engineering judgement.

While indications can be provided in relation to which technologies may be best suited to different industrial sectors, the matching of carbon capture technology to specific gas streams containing CO_2 requires more detailed review. Careful consideration must be given to the range of chemical and physical characteristics of the target input gas stream and how these compare to the requirements and track record of any technologies under consideration.

Opportunities and Barriers
With increasing concerns relating to the climate emergency there is a growing acceptance of the urgent need to reduce anthropogenic CO_2 emissions rapidly and substantially. This creates opportunities in relation to the development and deployment of carbon capture technologies in the UK.

For potential users of carbon capture technology opportunities include the mitigation of risk associated with CO_2 emission costs, protection against tightening regulations on CO_2 emissions, corporate reputation and attracting investment. For carbon capture technology providers there are opportunities in relation to market size, availability of investment, development of new technology concepts, incremental improvements to existing technologies and modularisation. The potential for these opportunities to be realised can be increased by encouraging collaboration between different companies and industries involved in the carbon capture sector.

Common barriers relating to the deployment of carbon capture projects include the relative costs of capturing and emitting CO_2, the development of suitable policy and incentives, availability of CO_2 transport and storage infrastructure, CO_2 storage risk, planning and permitting, alternative decarbonisation options, space constraints, technology risk, time and cost associated with technology scale-up, introduction of new hazards, availability of funding and public perception.

An overview of industry specific opportunities and barriers has also been provided.

Industry Engagement Workshop
An industry engagement workshop held on 30 September 2021 in collaboration with the UK Carbon Capture and Storage Research Centre (UK CCSRC), Jon Gibbins of the University of Sheffield and BEIS. Some key messages from the workshop were:

- Carbon capture was seen by most participants as having greater potential to decarbonise than either fuel switching or process modification. Although, it should be noted that these results were obtained from attendees of an event relating to carbon capture, so attendees may be more likely to view it positively as a decarbonisation approach.
- Solvent-based technologies with improvements were seen as being the most promising next generation carbon capture technology.
- Most attendees anticipated deployment of carbon capture, and other decarbonisation technologies, by 2030.
- The majority of participants anticipated carbon capture technologies being capable of capturing more than 90% of total emissions from their plant.
- ‘False starts’ in the carbon capture industry have been a source of frustration and have the potential to undermine investor confidence.

2. Introduction

2.1 The Project

Carbon capture utilisation and storage (CCUS) is a priority area of the UK Government's Ten-Point Plan for a Green Industrial Revolution. In support of the plan, BEIS must deliver the £1 billion Net Zero Innovation Portfolio (NZIP) between April 2021 and March 2025. This requires research into advanced carbon capture technologies to promote cost effective CO_2 emission reduction.

AECOM has been appointed by BEIS to conduct a review of next generation carbon capture technologies and a technoeconomic analysis of selected options to benchmark them against a base case of current state of the art amine solvent technology. The review will consider the potential application of carbon capture technology to different industrial, waste and power sites. The outputs of the assignment are intended to inform government decisions relating to the provision of innovation support funding for carbon capture, and future policy around CCUS deployment. AECOM will be working with Professor Jon Gibbins of the University of Sheffield who has been a director of the UK CCS Research Centre since 2012.

The study commenced in August 2021 and will be completed in April 2022. The main deliverables are:

- A report on next-generation carbon capture technologies, focussing on technologies with the potential to be deployed in the order of 1,000 ton per day scale by 2030 (this report). Less well-developed technologies that are more likely to be deployed at scale by 2035, or later, have been reported on, but with a lower level of detail.
- An industry workshop to gather feedback on barriers and opportunities relating to the development of carbon capture projects, which will inform an updated report.
- A case study of a mobile carbon capture de-risking project.
- A technoeconomic methodology and benchmarking report.
- A technoeconomic analysis of carbon capture technology options considering different technologies and different industries.
- A second industry workshop to present the findings of the study and allow carbon capture technology providers to present their technologies.

This review does not cover the transportation and storage of CO_2, direct air capture technologies, hydrogen production, biochar technologies or certain other technologies detailed in Section 2.2.

For the carbon capture technologies reviewed consideration will be given to the application of these technologies to different industrial, waste and power sites. The aim is to increase understanding around which technologies may be better, or less well, suited to different applications.

The report concludes with a review of opportunities and barriers to innovation and deployment of carbon capture technology, both in general and for specific industrial applications.

Section 2 contains information on safety and environmental hazards relating to the technologies. Only hazards that are specific to the technologies being reviewed are mentioned. Hazards that will be common to all technologies such as CO_2 handling and high energy electrical systems are outside the scope of this review.

2.2 Established Carbon Capture Applications

There are existing industrial processes where emission streams contain a much higher concentration of CO_2 than the emission streams from processes like combustion, cement or steel manufacture. This means that it is relatively simple, and low-cost, to capture the CO_2. In these sectors CO_2 is already captured at some sites for use in industries such as enhanced oil recovery (EOR), food processing and drinks manufacture. However, much of the CO_2 will not be captured due to a range of factors, including limitations in market demand for CO_2.

If the market for CO_2 changes due to the development of CO_2 transportation and storage infrastructure and payment mechanisms for the capture and storage of CO_2, then opportunities will be created for increased levels of capture and storage from facilities that naturally generate a concentrated stream of CO_2.

These industries offer low-cost CO_2 capture opportunities and will be important in relation to achieving cost-effective CO_2 emission reductions in the UK. However, the total mass of CO_2 available from such sources is very small in comparison to total UK industrial emissions. The technologies for capturing the CO_2 at these sites are important but are not the focus of this assignment. A brief commentary in relation to some industries with the potential to offer low-cost carbon capture is provided below.

Hydrogen and Hydrogen Derivatives – Hydrogen is a high-volume industrial chemical used in several existing manufacturing processes including fertiliser production and hydrocarbon processing. In the future hydrogen may also be used to decarbonise energy supply to industrial, commercial and domestic users and in providing energy to the transport sector. Most of the hydrogen in the UK is currently manufactured by reforming hydrocarbons, such as natural gas. When natural gas is reformed CO_2 is generated and a proportion of this emerges from the process in a concentrated form making it relatively simple and low-cost to capture. CO_2 is currently captured from hydrogen production facilities in the UK for use in the food and drink industry. The mass of CO_2 captured during hydrogen production is currently limited by the size of the market for the CO_2.

Innovation in methane reforming technology could allow more of the CO_2 generated to be captured at a low-cost if transportation and storage infrastructure was developed and payment for the storage of CO_2 was available. Low carbon hydrogen production is not considered further in this study as it is being investigated by other work streams being conducted on behalf of BEIS.

Natural Gas Processing – Natural gas reserves contain varying quantities of CO_2 in addition to methane. Removal of CO_2 and other contaminants from raw natural gas has been practised around the world for many decades. There are established technologies available for separation of the CO_2 from the raw natural gas. Technology selection for separating CO_2 will depend on a variety of factors including the composition and physical properties of the raw natural gas stream to be refined. There will be scope for innovation in relation to the various natural gas processing technologies available. However, this area of technical innovation is not the focus of this report. The CO_2 removed during natural gas processing represents a potential source of CO_2 that could be captured, at relatively low-cost, and stored.

Brewing and Distilling – CO_2 is generated during the fermentation processes that take place in the manufacture of alcoholic drinks and bioethanol. The CO_2 from fermenters emerges at a high concentration, and therefore, it is relatively easy, and low-cost, to capture. This process is already conducted at some brewing and distilling sites, with the CO_2 being used for a variety of industrial purposes. If an additional market was created for the storage of CO_2, then the CO_2 generated at more breweries and distilleries could be captured and used or stored.

The volume of alcohol produced limits the volume of CO_2 available from this source. Furthermore, capture and storage of CO_2 at some sites may remain challenging if the sites are small and or not located near CO_2 users or transportation infrastructure. Nonetheless, CO_2 from fermentation represents a potential source of CO_2 that could be captured, at relatively low-cost, and stored.

Biogas Upgrading – Biogas generated at anaerobic digestion facilities and landfill gas sites contains methane, CO_2 and a range of other contaminants. The raw biogas is upgraded to biomethane at some sites to allow it to be injected into the gas grid. During the process of upgrading the biogas a stream of concentrated CO_2 is generated. This stream has the potential to be captured at relatively low-cost.

The technologies used for biogas upgrading include water wash, amine solvents, sorbents and membranes. There will be scope for innovation in relation to biogas upgrading technologies. Due to limitations in feedstock supply biogas facilities are smaller scale than natural gas processing facilities and some other industrial sources of CO_2. This could provide opportunities for the development of modular systems for biogas upgrading and some companies already have offerings in this area. For example, in 2018 Carbon Clean announced its technology was upgrading more than 500,000 m^3 of biogas per day[1].

The volume of biogas generated limits the volume of CO_2 available from this source and capture and storage of CO_2 at some sites may remain challenging if the sites are small and or not located near CO_2 users or transportation infrastructure. Nonetheless, CO_2 from biogas upgrading represents a potential source of CO_2 that could be captured, at relatively low-cost, and stored.

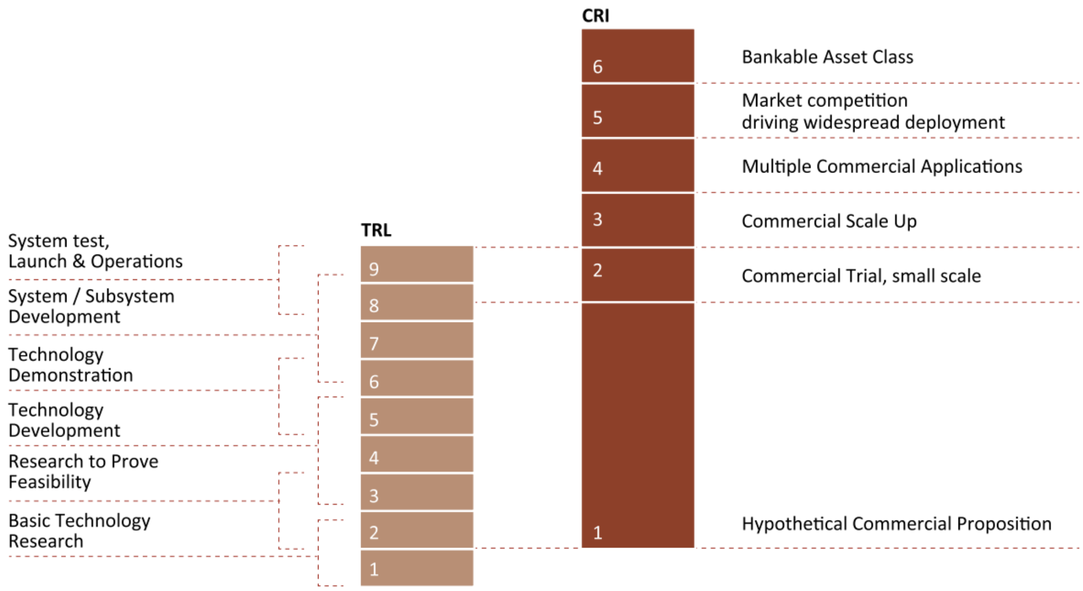
2.3 Cost Reduction through Commercial Deployment

For many carbon capture projects the low-cost of emitting CO_2 and the lack of CO_2 transport and storage infrastructure are more fundamental barriers to deployment than the availability of suitable carbon capture technology. However, with increasing concerns about the climate emergency, the commercial viability of carbon capture and storage projects is expected to improve.

Cost reduction in carbon capture is important in relation to achieving large scale deployment of technologies in the sector. Both the development of new processes, and the advancement of existing systems through the various stages of commercial deployment, are important elements in allowing cost reductions to be achieved in the carbon capture sector.

Figure 1 shows a scale of commercial readiness next to a technology readiness scale. The figure demonstrates the stages between initial commercial deployment, that usually occurs when technologies are around TRL 8 or 9 and becoming a mature commercial asset class.

Figure 1 Relationship between technological and commercial readiness[1]



For all technology types, cost reductions are primarily achieved by progressing through the commercial readiness scale, as presented in Figure 1. Developing a technology to a high TRL is required for a reliable base cost to be established and allow the process of cost reduction to commence. Advancing through the stages of commercial readiness then allows cost reductions to occur from improvements to aspects including sub-components, manufacturing techniques, maintenance strategies and financing costs.

Once a given technology has completed the early stages of successful commercial deployment technically improved subcomponents can be developed by moving these sub-components through the various TRL stages. This allows cost reductions to occur in the base technology as a result of the integration of the improved subcomponents.

Some solvent-based carbon capture systems have successfully completed the early stages of commercial deployment for post combustion carbon capture, equivalent to CRI 3 or 4 on the scale above. Some examples include, Fluor's Econoamine technology used at the Bellingham gas power plant, the Shell Cansolv technology used at the Boundary Dam coal power plant and Mitsubishi Heavy Industries KM CDR Process used at the Petra Nova coal power plant. These technologies have an advantage in relation to large scale deployment by 2030. It has been demonstrated that it is possible to reliably separate CO_2 from a variety of gaseous streams using solvents and now there are a variety of opportunities to innovate in different parts of the process; incremental cost reductions are likely to follow.

Earlier stage technologies such as some novel absorber designs or the NET Power technology, have not yet demonstrated long term reliable operation in a commercial setting. Cost predictions and the potential for cost reductions for these technologies must be considered differently.

For carbon capture there are many technologies at a pre-commercial stage of development, equivalent to CRI 1 or 2 on the scale above. As time progresses some may offer cost savings in industrial applications, and some will never progress to a commercial setting. This stage of the development and innovation process is challenging for new technologies, it is sometimes referred to as ‘the valley of death’. Even where new technology concepts will offer cost savings in the long term, they may be more expensive during the initial stages of commercialisation due to greater perceived risk and the impact this will have on contingencies and financing costs. The level of funding required to fully demonstrate and commercialise a new technology is significant and should not be underestimated. Between 2004 and 2020 the UK has Government provided over £300 million for CCUS research development and demonstration[3].

Understanding the value of, and difference between, technology development through incremental improvements and the development of new concepts is important in relation to promoting efficient innovation and development in the carbon capture sector. There is value in including both as part of an innovation program.

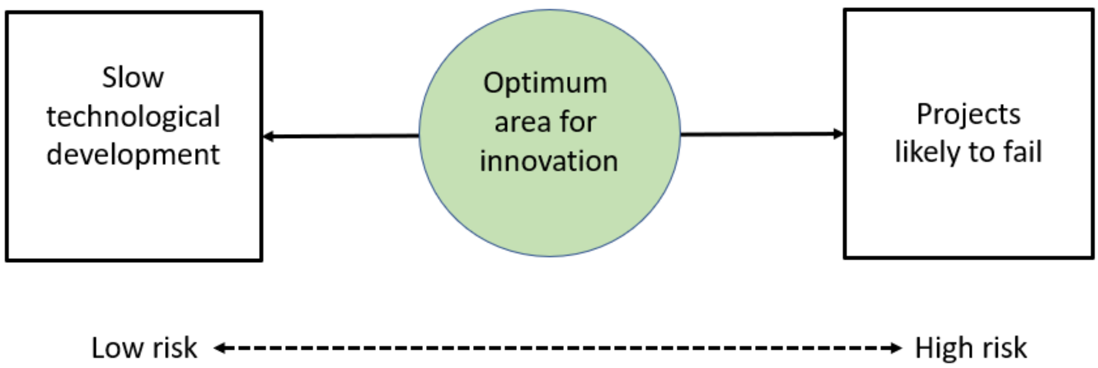
This report covers technologies that have established commercial platforms and are progressing through incremental improvements to subsystems, new technologies that have yet to demonstrate sustained reliable operation in a commercial setting, as well as technologies that do not fit clearly into either of these categories.

2.4 Deployment Risk Optimisation

Commercial deployment provides valuable opportunities for innovation and acceleration of the development process. However, premature commercial deployment brings a risk of delays, failing projects, inefficient use of funding and reputational damage to a technology and or industry sector. This section discusses what is required for a technology to be ready for commercial deployment.

When commercially deploying new technologies and progressing along the commercial readiness pathway, a balance is required in relation to the level of risk taken to promote innovation in the technology. An excessively low risk approach is likely to result in lack of innovation and the slow development of technologies. Similarly, an excessively high-risk approach may also result in the slow development of technologies due to failed projects. While there can be a place for high-risk projects in an innovation portfolio, it is important that the level of risk associated with projects is well understood. Failing projects divert money away from other opportunities that could have provided useful innovation. Furthermore, they can adversely impact the perception of the technology in the investment community and in the public. This concept is illustrated below in Figure 2.

Figure 2 Balance of risk to promote technological innovation



The risk associated with a development of a project that uses a new technology is proportional to a diverse range of factors. These factors will, or at least should, be assessed by organisations making significant investments in the project. Understanding these factors for a given project allows an assessment to be made as to the level of associated risk. Factors to consider in relation to the risk of developing carbon capture projects are provided below.

2.4.1 Technology Risk Factors

Potential impact on main process plant – Different carbon capture technologies have different potential to impact the main process plant. If the main process plant can continue operation without the carbon capture element of the process, then the risk of the main process not being able to operate is avoided.

Ability to revert to a known working option – if the innovation can be replaced by something that is known to work if it fails then the risks are greatly reduced, with remediation costs and downtime likely to be known in advance. Examples might be trying new solvent in a plant designed to use a known one, or running with a lower cost or more efficient sub-component but leaving the option to replace or add a proven working alternative if required.

Relative scale of reference plant - Scale-up is a significant challenge in relation to the commercialisation of some new technologies. Rapid scale-up to the natural upper limit of a technology is generally beneficial in relation to economies of scale and allowing cost reductions to take place. However, rapid scale-up usually increases technical risk associated with the project and premature scale-up has led to project failures in other industries. A structured approach considering a range of factors is required to determine appropriate scale-up increments for any given technology. While successfully scaling up new technologies is a significant challenge, it is one that has been overcome by all existing large-scale process industries.

Differences in inputs – Seemingly small differences in inputs to a process can have an impact on its performance. For many carbon capture technologies small differences in the composition of the feedstock gas have the potential to impact the process. Degradation rates for solvents and sorbents are impacted by the composition of the incoming gas stream. Direct deposition or fouling has also been observed to be an issue. The degree to which a demonstration environment is relevant to other applications of a technology will be a subject for debate as carbon capture technologies are deployed in different applications.

Technical differences not relating to scale-up or feed – Technical differences between the proposed plant and the reference facility may contribute to technical risk. Technical review and understanding of the differences between two facilities is required to understand the level of process risk associated with the change. Differences may relate to the main process units or auxiliary parts of the process.

Requirement for flexible operation – The proposed mode of operation for a carbon capture plant may contribute to the level of technical risk associated with a project. Some applications may require start-stop operation or rapid capacity ramp rates. Different carbon capture technologies will have different abilities to accommodate flexible operation.

Performance assumptions – The level of technical risk associated with a project is directly dependant on the assumed performance of the proposed plant relative to other comparable plants. More conservative financial model assumptions in a proposed commercial plant reduce the risk of the assumptions not being met. Different types of underperformance will have a different level of impact on the commercial performance of a facility. For example, a 10% increase in energy consumption can have a different financial impact to a 10% increase in consumables usage rates or a 10% change in plant availability. For any process the likely reasons for, and impact of, underperformance must be analysed and understood.

Prior to commercial deployment a detailed technical assessment of performance assumptions should be undertaken by the organisation making the investment or an independent third party with appropriate skills. This process can be referred to as due diligence, and effective due diligence is critical in relation to understanding the risk associated with commercial deployment of new technologies. The due diligence process unavoidably requires detailed examination and understanding of the proposed process and the performance of reference projects and or demonstration plants. If suitable test data is not available, then the only conclusion can be that the performance is not proven.

The existence of a demonstration plant does not by itself mean that a technology has been successfully demonstrated. A small but thoroughly realistic demonstration project that has shown good performance, with high availability over a sustained period, in a similar environment will be of much higher value in demonstrating viability than a large demonstration plant that operated poorly, a negative indication of viability, or that is unable to provide operational information, a situation that also calls into doubt viable operation.

2.4.2 Other Risk Factors

There are a wide range of factors that impact the commercial viability of a project that do not relate directly to the core process technology, examples of which are listed below. These need to be considered in conjunction with the assumed performance and track record of the technology.

- Capital required
- Rate of financial return
- External economic factors. For example, price of product, price of feedstock and cost of emitting and storing CO_2
- Competition from other technologies
- Availability of utilities and service connections – including CO_2 transport infrastructure
- Contractual risk allocation
- Track record of project participants and availability of required skills
- Planning and permitting

2.5 Categorisation of Technologies

The challenges of predicting the future and categorising multiple, varied technologies, with limited information must be acknowledged. One challenge is that the scale-up process for different types of technology is very different. Some solvents may be able to use existing technology platforms, while processes such as membranes or fuel cells may be more suited to modular construction. Other technologies require a single unit to be scaled-up in increments with successful operation demonstrated at each stage.

The next generation technologies that are most likely to be deployable in the order of 1000 tpd scale by 2030 have been classified as Demonstration Stage technologies in this report. Technologies that are considered more likely to be deployable at around 1000 tpd scale by 2035 or later have been classified as Development Stage technologies. Research Stage technologies are at an earlier stage of development.

Of the technologies in this report that have been classified as Development or Research Stage, the potential exists for some of them to be deployed at scale by 2030 or earlier. For example, some new solvents being researched at lab scale have the potential to be tested and then added to existing carbon capture facilities. Being included in research or development category in this report, rather than the demonstration category, should not be viewed negatively in relation to the long-term future potential of any technology.

Details of the categorisation used for the different technologies in this report are provided in Table 2. For each category, all conditions must be met.

Table 2. Technology categories used in this report

Category	Description
1. Demonstration stage Likely to be deployable at a scale in the order of 1000 tpd by 2030.	• Incremental improvements to, or new applications of, a technology platform that is broadly consistent with at least TRL 8 and has demonstrated successful commercial deployment for at least 12 months at a similar scale. • The technology, or a previous iteration of the technology, has operated at least 50 tpd of CO_2 scale, for at least 12 months, under representative conditions. • Construction commenced, or full funding received, for a project in a similar application of at least 200 tpd scale.
2. Development stage May be deployable at a scale in the order of 1000 tpd by 2035	• Broadly consistent with TRLs 5-8. • The technology, or a previous iteration of the technology, has operated at least 5 tpd of CO_2 scale in a similar application, and; • Current operation of demonstration project of at least 10 tpd CO_2 capture or, or full funding received, for a larger project.
3. Research stage	• Broadly consistent with TRLs 1-4.

Where TRLs are mentioned in this assignment we have used the National Energy Technology Laboratory definitions provided in Table 3.

Table 3. Simplified definitions of Technology Readiness Level (TRL) (IEAGHG 2014) for CCS technologies

Category	Technology Readiness Level	Description
Demonstration	9	Normal Commercial Service
	8	Commercial demonstration, full scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles, observed, initial concept

2.6 Capture Level

For carbon capture technologies, capture level is commonly defined as the percentage of CO_2 in the incoming gas stream that is captured by the technology. There is a debate as to what the minimum capture level for new carbon capture plants should be. The debate also relates to the development of new technologies because some technologies have a capture level that is limited at a lower level because of the principals used to make the separation.

On one side there is a strong argument that all carbon capture plants should have a high capture rate, for example, greater than 95%. Without a high capture rate, a significant mass of CO_2 emissions will remain and, to meet net zero targets, the CO_2 will need to be removed from the atmosphere by other means. There are limited other means available for removal of CO_2 from the atmosphere. If direct air carbon capture and storage (DACCS) is to be used, logic would suggest that where a more concentrated stream of CO_2 is available it would be less costly to abate at the stream at source rather than indirectly through further direct air capture.

Users of carbon capture technologies are likely to have to pay for fossil origin CO_2 emissions that are not captured by the carbon capture equipment. If payment level is based on a net-zero emission principle for the industry, then the price paid for residual CO_2 emissions could be set at the cost of removing CO_2 from the atmosphere by other means. As this has a relatively high cost, this would encourage capture technologies with a high capture rate. The Committee for Climate Change cost estimates for 2035 indicate that DACCS may cost between £170 and £240/tCO_2 [4].

On the other side of the debate the cost of increasing capture rates in some carbon capture projects can be highly non-linear. This means that the unit cost of capturing CO_2 (£/tonne) can greatly increase when the required capture level passes certain points. There is a risk that accepting nothing other than a high capture level could reduce the overall mass of CO_2 captured as projects would become prohibitively expensive and or complex and are less likely to be built as a result.

In this project the value of technologies being able to achieve a high capture level is recognised, but no minimum capture level criterion has been set for qualification as a next generation technology. It is possible that a technology with a limited capture level could make a valuable contribution to the carbon capture industry by offering other significant technical or economic advantages.

3. Demonstration Stage Technologies

This section provides information about selected demonstration stage technologies. The focus is on technologies that are innovative and at a stage of development that means it is likely that they could be deployed at 500-1000 tpd scale by 2030. Being deployed by 2030 means all aspects of successful technology demonstration, project development, consents and connection agreements, planning and permitting, outline design, procurement, financing, design, construction, commissioning and testing being complete prior to 2030.

3.1 Overview of Technologies Reviewed

Table 4 contains an overview of the demonstration stage technologies reviewed in this section of the report. Further information on each technology is provided in subsequent tables. The demonstration stage technologies are all amine-based solvent systems.

Table 4. Demonstration stage technologies reviewed

Technology Providers	Overview
Solvent-Based Systems	
Mitsubishi Heavy Industries	MHI's KS-1 solvent was used at the 4700 tpd Petra Nova project in Texas, USA. MHI's next generation solvent is KS-21. The new solvent, along with process improvements, is anticipated to offer incremental improvements over plants using KS-1.
Shell	Shell's Cansolv technology has been demonstrated at scale at the 2740 tpd Boundary Dam site in Canada. The next generation deployment is likely to include EfW applications.
Fluor	A previous iteration of Fluor's Econoamine FG Plus technology was deployed at 320-350 tpd scale at Bellingham Gas Power Plant, Massachusetts, USA. The next generation technology will attempt to employ energy improvement features at large scale.
Carbon Clean Solutions	Carbon Clean Solutions' proprietary amine has been used at the 160 tpd scale in India on a coal plant. The technology utilises their proprietary APBS advanced solvent. Additionally, Carbon Clean has offerings of bespoke large-scale carbon capture plants and smaller modular carbon capture units.
Aker Carbon Capture	Aker Carbon Capture designed and delivered the 80,000 tpa (~240 tpd) CO_2 capture amine plant at the TCM facility which has been in continuous operation since its opening in 2013. Aker's 'Just Catch' technology utilises their proprietary S26 advanced solvent. Aker offers large-scale carbon capture plants termed 'Big Catch' and smaller modular carbon capture units termed 'Just Catch'. Aker has plans for future projects in the EfW and cement sectors.

3.2 Solvent-Based Capture

Many of the well-developed demonstration phase technologies are based on amine solvents. While there is value from an innovation perspective in developing a range of technologies based on different principles, it is important to remember that within the category of amine-based solutions there are a wide range of different opportunities for innovation. Collectively, innovations across these areas have the potential to offer significant benefits. If a supportive commercial environment for the deployment of carbon capture projects were to be established, further development of these technologies could be expected.

From the variety of innovation options available in amine-based systems many have the potential to offer a good balance between risk, investment requirements and potential benefits. A summary of some of the main areas for innovation in amine systems is provided below. Opportunities for innovation in amine-solvent-based systems are being explored by many of the key suppliers. Developments made by specific suppliers are described in the subsequent tables in Section 3.

New Applications - When an existing amine capture system is applied to a new process, or an emission stream with different properties, changes to the system will be required. These changes create opportunities for valuable learning and innovation. Areas that require attention include pre-treatment of the incoming gas stream, absorber design, solvent behaviour due to exposure to different contaminants and supply of heat, cooling and electricity.

There is a degree of risk in assuming that an amine system that has demonstrated reliable operation in one application will operate reliably in another application, even if well thought through and systematic modifications are made.

Scale - Emission streams from different industries can be very different in scale. When an existing amine capture arrangement is to be applied at a different scale, either larger or smaller, changes to the system are required. There will be sub-systems where the optimum design choice is impacted by the scale of the plant. Application of existing technologies at different scales creates opportunities for innovation.

Plant Availability - Demonstration of sustained operation with high availability can be overlooked as an innovation priority. However, demonstrating reliable operation is valuable in relation to commercial viability, building investor confidence in a sector and attracting funding for future generations of a technology.

Construction of a large-scale carbon capture demonstration project that fails to operate reliably would be a major setback to the development of a CCUS industry in the UK.

Solvent Chemistry and Solvent Health Management - Innovation in amine solvent chemistry is an active area of research where improvements have been made and further improvements are anticipated. Solvent chemistry can be changed by using different amines, through the addition of additives or by a combination of both techniques.

There are a broad range of characteristics that contribute to the overall suitability of a solvent including safety, environmental characteristics, reclaimability, cost, degradation rates, equilibrium CO_2 capacity, heat of regeneration, corrosion potential, heat capacity and viscosity.

The testing of some vital characteristics, such as reclaimability and overall solvent health management requires long term testing with exposure to a specific emission stream and set of process conditions. The use of large-scale test facilities increases confidence in the results obtained and facilitates scientific research into physical and chemical degradation mechanisms of solvents in CO_2 capture facilities. There are opportunities for innovation in relation to the effective monitoring and management of an amine solvent with a given composition. Solvent management includes the design of reclaiming systems, monitoring changes to solvent chemistry during process operation, alteration of process conditions to improve solvent lifetime and performance and management of additives.

Process Improvements - Amine-based carbon capture systems are complex process plants and there are opportunities for process plant improvements in several areas. These include plant design modifications to increase availability, thermodynamic changes to reduce energy consumption, cost reductions, increased integration with the main process plant, operational flexibility, control system improvements and reduction in plant footprint.

Flue-gas Pre-treatment - There are many opportunities for innovation in relation to optimisation of flue gas pre-treatment systems when amine based solvent systems are applied to new applications. Flue gas pre-treatment equipment is sometimes omitted in diagrams of carbon capture plants, but it is a vital part of the process.

A balance is required in relation to the level of flue gas pre-treatment applied. A reduction in contamination levels will be of benefit to the capture plant but will involve the purchase and operation of additional process equipment.

Prudent design of gas pre-treatment equipment is an important part of plant development as the impact of, and cost to control, different contaminants will vary. Furthermore, the optimum approach to gas pre-treatment is likely to be different depending on whether a capture plant is retrofitted to existing equipment or built as part of a new-build project. The effectiveness of solvent management techniques and solvent-related operating costs under different flue gas conditions will also be an important factor. The wider availability of data in this area would allow better decisions to be made in relation to the selection of flue gas pre-treatment equipment.

Construction Improvements - There are opportunities for innovation in relation to the construction techniques used to build amine-based capture plants. Large, high cost, components such as absorber columns or direct contact coolers present opportunities. These include the use of lower cost materials, new construction techniques, understanding of embedded CO_2 or better selection of site-built or prefabricated units for different scales of plant.

Modularisation - Modularisation of some or all or the process plant is a concept that has the potential to be valuable and is receiving attention from several manufacturers. Modularisation creates opportunities for cost reductions through allowing faster build times, delivery on demand, fabrication in a dedicated manufacturing facility and simplified foundation and utility system design.

3.2.1 Mitsubishi Heavy Industry

Table 5. Mitsubishi Heavy Industry Advanced KM CDR Process (KS-21 Solvent)

Parameter	Description
Name	Advanced KM CDR Process
Technology Overview	The technology is the next generation of MHI's KM CDR Process, an amine process using the KS-1 solvent. The new technology uses KS-21, which is a new amine solvent formulation from MHI.[5]
Stated Advantages	Lower volatility, greater stability against degradation, lower OPEX versus KS-1 and other amines.[5]
Target Industrial Sectors	Post combustion capture (PCC) flue gas applications
Financial Information	Quantified financial information is not available. However, CO_2 capture cost savings would be expected if the potential advantages are realised and are not outweighed by any increase to solvent cost, should it occur.
Current Demonstration Status	A previous iteration of this technology was used at the Petra Nova coal-fired power plant in Texas, USA. The Petra Nova plant used the KS-1 solvent and was able to meet the design capture rate of 4,700 tpd. The capture plant ran from December 2016 to May 2020. It was shut down due to a number of factors that included the low oil prices during the pandemic, since the financial viability of the project depends on using the CO_2 for enhanced oil recovery.[6] Testing of the Advanced KM CDR Process at the Technology Centre Mongstad (TCM) in Mongstad, Norway began in May 2021.[5]
Safety or environmental hazards	Limited release of amines and amine degradation products is common to all amine-solvent-based capture plant.
Opportunities for and barriers to implementation and innovation	The technology will be perceived as lower risk compared to some other options as it is a development of an existing technology and scale-up is not required. Lessons learned from previous iterations of the technology can be applied to this, and future iterations, of the technology. Opportunities exist to demonstrate the technology on a wider variety of emission streams.
Technology backers and funding sources	Kansai Electric Power Company (KEPCO). NETL is providing funding for a FEED study at the University of Illinois for the retrofit of the Prairie State Generation Company's coal-fired power station.
Ability to be deployed at 1000tpd CO_2 capture by 2030	Likely to be deployable at 1000tpd scale by 2030 subject to satisfactory pilot scale, or other testing. Drax has agreed to license the Advanced KM CDR process at their biomass power station in the UK.[7]

3.2.2 Shell Cansolv

Table 6. Shell Cansolv

Parameter	Description
Name	Shell Cansolv
Technology Overview	Shell's Cansolv technology utilises the next generation of their proprietary Cansolv advanced amine-based solvent.
Stated Advantages	Reduced energy use, increased absorption rate, lower volatility, decreased solvent degradation rate and improved solvent HSE characteristics versus other amines.
Target Industrial Sectors	Post combustion capture (PCC) flue gas applications
Financial Information	A carbon capture cost of \$58/t-CO_2 (£42/t-CO_2) was used by the US Department of Energy (DOE) for a 90% CO_2 capture Cansolv PCC process on a coal-fired power plant.[8] CO_2 capture cost savings would be expected if the potential advantages are realised, lessons learned applied, and advantages are not outweighed by any increase to solvent cost.
Current Demonstration Status	A previous iteration of this technology is used at Boundary Dam Coal Power Station, Saskatchewan, Canada Shell Cansolv 1,000,000 tpa (~3,000 tpd) CO_2 capture Operational since end of 2014, but with operational issues reported and availability at only 40% in 2015, relative to a target of 80%. The plant is operated by Skanska Power. Their latest blog, July 2021, indicates that a total of 4,166,419 t-CO_2 has been captured since operational start-up, this is well below the design 1M tpa which would lead to between 6M and 7M t-CO_2 to have been captured. Total CO_2 Capture in 2020 was reported as 729,092 tonnes, over 70% of the design value[9], and non-fuel OPEX of \$20/tCO2 was reported by GCCSI for BD3. Fortum Oslo Varme EfW Plant, Oslo, Norway Shell Cansolv 400,000 tpa (~1,200 tpd) CO_2 capture Project is currently at pilot stage having completed a 9-month trial capturing 3.5 tpd in 2019[10], the success of the pilot has led to DNV GL approval as a qualified technology for full-scale demonstration.[11] It is noted that a thermal reclaiming unit was not installed on the pilot and instead the concentration of degradation products was monitored by UPLC-MS (ultra-performance liquid chromatography - mass spectrometer) analysis.[12] The Norwegian government have pledged 50% funding for the full-scale project conditional on the other 50% from the EU, for which it has been shortlisted as of April 2021. If funding is received full operation is expected 2024.[13]
Safety or environmental hazards	Limited release of amines and amine degradation products is common to all amine-solvent-based capture plant.
Opportunities for and barriers to implementation and innovation	The technology will be perceived as lower risk compared to some other options as it is a development of an existing technology and scale-up is not required. Lessons learned from previous iterations of the technology can be applied to this, and future iterations, of the technology. Opportunities also exist to demonstrate the technology on a wider variety of emission streams. Shell has experience from the first large-scale amine-based capture plant at Boundary Dam thus an opportunity to apply learnings.
Technology backers and funding sources	Shell Cansolv technology backers include Technip whom they have partnered with to offer full EPC services for their carbon capture technology. Shell Cansolv is receiving funding from the Norwegian government for the Fortum EfW project.
Ability to be deployed at 1000tpd CO_2 capture by 2030	Likely to be deployable at 1000 tpd scale by 2030 subject to satisfactory pilot scale, or other, testing.

3.2.3 Fluor Econoamine FG Plus

Table 7. Fluor Econoamine FG Plus

Parameter	Description
Name	Fluor Econoamine FG Plus
Technology Overview	Fluor's technology utilises their next generation proprietary Econoamine FG Plus advanced solvent. Fluor have also developed a water-lean amine solvent.
Potential Advantages	Reduced energy use, increased absorption rate, lower volatility, decreased solvent degradation rate and improved solvent HSE characteristics versus other amines.
Target Industrial Sectors	Post combustion capture (PCC) flue gas applications
Financial Information	Quantified financial information is not available. However, CO_2 capture cost savings would be expected if the potential advantages are realised and are not outweighed by any increase to solvent cost, should it occur.
Current Demonstration Status	The Fluor website claims that the Fluor has carbon capture experience with over 30 licenced plants[14] and is the only technology to be commercially proven for CO_2 recovery from gas-turbine exhausts.[15] Details of the 30 licenced plants are available in IEAGHG report Number PH4/33 and include operational plants ranging from 2 – 320 tpd CO_2 capture and no longer operating plants ranging from 25 – 1,000 tpd CO_2 capture.[16] The 1,000 tpd CO_2 capture plant was a gas-fired power plant in Lubbock, Texas in the 1980s for enhanced oil recovery but is believed to be based on the previous iteration MEA solvent.[17] A previous iteration of Fluor's technology was deployed at Bellingham Gas Power Plant, Massachusetts, USA Fluor Econoamine FG Plus 320-350 tpd CO_2 capture Continuously operated between 1991 and 2005, with closure due to increase in natural gas prices.[15,18] E.ON Wilhelmshaven Coal Power Plant, Bremen, Germany Fluor Econoamine FG Plus 70 tpd CO_2 Capture The BAT review for PCC indicates the pilot operated for approximately 7000 hours in total between 2012 and 2015.[19] Fluor developed a water-lean solvent in 2016, in 2019 through funding from US DOE and TCM the solvent system was validated at TCM's test facilities. Test results information are available and show improvements over their previous solvent iterations. Testing was conducted on both TCM's RFCC gas and CHP gas.[20]
Safety or environmental hazards	Limited release of amines and amine degradation products is common to all amine-solvent-based capture plant.
Opportunities for and barriers to implementation and innovation	The technology will be perceived as lower risk compared to some other options as it is a development of an existing technology and less scale-up is required. Lessons learned from previous iterations of the technology can be applied to this, and future iterations, of the technology. Opportunities also exist to demonstrate the technology on a wider variety of emission streams.
Technology backers and funding sources	Fluor's technology backers include the US Department of Energy who have recently funded FEED for a 4M tpa carbon capture plant for a Coal Power Plant in North Dakota.[21] Fluor Carbon Capture has 30 licenced plants, details of licensees are available in IEAGHG report Number PH4/33.[16]
Ability to be deployed at 1000tpd CO_2 capture by 2030	Likely to be deployable at 1000 tpd scale by 2030, subject to satisfactory pilot scale, or other, testing if the formulation has changed since use at Bellingham.

3.2.4 Carbon Clean

Table 8. Carbon Clean

Parameter	Description
Name	Carbon Clean
Technology Overview	Carbon Clean's technology utilises their proprietary APBS advanced solvent. Additionally, Carbon Clean has offerings of bespoke large-scale carbon capture plants and smaller modular carbon capture units.
Potential Advantages	Reduced energy use, increased absorption rate, lower volatility, decreased solvent degradation rate and improved solvent HSE characteristics versus other amines. Establishment of a modular design has potential advantages.
Target Industrial Sectors	Post combustion capture (PCC) flue gas applications
Financial Information	Carbon Clean claim a cost of capture of \$40/t-CO_2 when using APBS in their process, though it is not clear for what flue gas or conditions this is applicable.[22] CO_2 capture cost savings would be expected if the potential advantages are realised and are not outweighed by any increase to solvent cost, should it occur.
Current Demonstration Status	Tuticorin Alkali Chemical & Fertilizers Plant Coal-Fired Boiler, Tamil Nadu, India Carbon Clean 60,000 tpa (174 tpd) CO_2 capture In operation since 2016[23,24] Tata Steel Jamshedpur Plant Blast Furnace, India Carbon Clean 5 tpd CO_2 Capture The modular skid mounted unit was commissioned in 2021. Carbon Clean & Tata Steel have stated they have plans to develop a larger scale unit, but no details are available.[25] Carbon Clean has captured over 1 million tonnes of CO_2 across its projects since 2009. These include several small pilots, a large number of non-post combustion biomethane facilities in Germany, Switzerland and Denmark, 240 tpd testing at TCM, a 21 tpd kiln gas test and a 48 tpd demonstration test in Jawa Timur.[25]
Safety or environmental hazards	Limited release of amines and amine degradation products is common to all amine-solvent-based capture plant.
Opportunities for and barriers to implementation and innovation	The technology will be perceived as lower risk compared to some other options as it is a development of an existing technology and less scale-up is required. Lessons learned from previous iterations of the technology can be applied to this, and future iterations, of the technology. Opportunities also exist to demonstrate the technology on a wider variety of emission streams. Focus on offering modularised options could deliver cost savings and ability for more rapid deployment.
Technology backers and funding sources	Carbon Clean's backers include Chevron, WAVE Equity Partners, Marubeni, Equinor, ICOS Capital and Blume. In August 2021 raised \$8M (£5.79M) in new investment from CEMEX.[26]
Ability to be deployed at 1000tpd CO_2 capture by 2030	Likely to be deployable at 1000 tpd scale by 2030 subject to satisfactory pilot scale, or other, testing.

3.2.5 Aker Carbon Capture

Table 9. Aker Carbon Capture

Parameter	Description
Name	Aker Carbon Capture
Technology Overview	Aker's 'Just Catch' technology utilises their proprietary S26 advanced solvent. Aker offers large-scale carbon capture plants termed 'Big Catch' and smaller modular carbon capture units termed 'Just Catch'.
Potential Advantages	Reduced energy use, increased absorption rate, lower volatility, decreased solvent degradation rate and improved solvent HSE characteristics versus other amines. Establishment of a modular design has potential advantages.
Target Industrial Sectors	Post combustion capture (PCC) flue gas applications
Financial Information	Aker Carbon Capture quantified financial information is not available. CO_2 capture cost savings would be expected if the potential advantages are realised and are not outweighed by any increase to solvent cost, should it occur.
Current Demonstration Status	Aker Carbon Capture designed and delivered the 80,000 tpa (~240 tpd) CO_2 capture amine plant at the TCM facility which has been in continuous operation since its opening in 2013. They further performed testing of their capture technology at TCM.[29] From this Aker are moving on to deploy the next iteration of their technology at Twence EfW Plant, Hengelo, Netherlands Aker 'Just Catch' 100,000 tpa (~300 tpd) CO_2 capture Operation intended to start in 2021, currently in Build phase[30] Norcem Cement Factory, Brevik, Norway Aker 'Big Catch' 400,000 tpa (~1,200 tpd) CO_2 capture EPC start January 2021, completion in 2024[31] Aker have achieved more than 50,000 operating hours in six pilot plants globally.[35]
Safety or environmental hazards	Limited release of amines and amine degradation products is common to all amine-solvent-based capture plant.
Opportunities for and barriers to implementation and innovation	The technology will be perceived as lower risk compared to some other options as it is a development of an existing technology and scale-up would not be required if the Norcem facility is built and operates successfully. Lessons learned from previous iterations of the technology can be applied to this, and future iterations, of the technology. Opportunities also exist to demonstrate the technology on a wider variety of emission streams via Aker's Just Test unit, which has already tested natural gas, coal, refinery, cement, EfW and hydrogen flue gases across 30,000 hours of operation.[32] A focus on offering modularised options could deliver cost savings and ability for more rapid deployment.
Technology backers and funding sources	Aker Carbon Capture is listed on the Oslo Stock Exchange and in August 2021 raised NOK 840M (£70M) to support further growth.[33] Aspects of Aker's Advanced Carbon Capture process are DNV qualified[34]
Ability to be deployed at 1000tpd CO_2 capture by 2030	Likely to be deployable at 1000 tpd scale by 2030, subject to satisfactory pilot scale, or other, testing.

4. Development Stage Technologies

Development stage technologies are reviewed in this section of the report. These technologies are at an earlier stage of development than the demonstration stage technologies reviewed in Section 3. For technologies at an earlier stage of development there are increased levels of uncertainty in relation to costs and performance. Many of the technologies reviewed have potential advantages over more developed technologies, but it remains to be proven whether the challenges associated with scale-up and technical issues specific to the individual technologies can be overcome. These technologies must first demonstrate sustained commercial operation at scale and then prove that cost savings can be made. Of the technologies reviewed in this section the potential exists for some of them to be deployed at scale by 2030 or earlier. For example, NET Power and CO2 Capsol have conducted front end engineering and design work and are progressing demonstration projects that are intended to be implemented prior to 2030. Table 10 contains information on the technologies reviewed including opinions on potential advantages and challenges.

Table 10. Development stage technologies

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
Solvent-Based Systems				
BASF & Linde	BASF & Linde's technology utilises BASF's proprietary OASE® blue advanced amine solvent with Linde's process engineering developments	Reduced energy use Lower solvent losses Flexible operating range	Solvent performance not yet proven at a large scale. Scale-up of process equipment required prior to commercial application.	National Carbon Capture Centre Coal-Fired Power Plant, Wilsonville, Alabama, USA BASF Linde 30 tpd CO_2 capture. Starting in 2014 the pilot trail was operated for 4,109 hours and included evaluation of several process improvements.[15] Niederaussem Coal Power Station, Germany BASF Linde 7.2 tpd CO_2 capture. Starting in 2009 the pilot trails were operated for 26,000 hours.[15] CWLP Coal Power Plant, Springfield, Illinois, USA BASF Linde 200 tpd CO_2 capture. $47M of funding has been secured from the US Department of Energy and a further $20M from the state of Illinois. Final design is due to start June 2021 with construction in June 2022, and start-up is planned for early 2024.[27,28]
C-Capture	An amine and nitrogen free solvent process using a carboxylic acid salt in organic media	Reduced energy consumption Environmental benefits from non-hazardous solvent Lower corrosivity than other solvents Solvent capture process similar to amine-solvent process[38]	Solvent performance not yet proven at a large scale on flue gases. Scale-up of process equipment required prior to commercial application.	Independent pilot plant trials by SINTEF in 2020, scale and operational data not available.[38] Pilot plant at Drax power station of c.1 tpd CO_2 capture, commissioned in November 2018 and full operation announced February 2020.[39] Received funding from UK government to progress equipment designs to allow potential commercial deployment with Drax.[40]

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
CO_2 Capsol (formerly Sargas)	Hot potassium carbonate solvent process with patented heat recovery	Reduced energy consumption Environmental benefits from non-hazardous solvent Higher capture rates feasible Adaption of established potassium carbonate process Increased oxygen tolerance[41,42]	Solvent and process performance not yet proven at a large scale on flue gases. Scale-up of process equipment required prior to commercial application. Flue gas requires pressurisation to raise partial pressure of CO_2, this may not be economical or feasible for some processes.	CO_2 Capsol claim three successful pilot projects with more than 3,300 operating hours.[42] Lab-scale pilot plant at University of Paderbron as part of EU funded project between 2011-2014.[43] Scale and operational data not available. Stockholm Exergi has plans to build the largest BECCS (Bioenergy with Carbon Capture and Storage) plant in Europe using CO_2 Capsol's technology. Stockholm Exergi aims to complete construction and start operations during the second half of 2025. The plant will be designed to capture up to 800,000 tpa CO2 (~2,000 tpd CO_2 Capture).[44]
CO_2 Solutions (Now owned by SAIPEM)	A carbonic anhydrase enzyme catalysed potassium carbonate solvent process	Reduced energy consumption, with ability to operate on low-grade waste heat Environmental benefits from non-hazardous solvent Adaption of established potassium carbonate process Lower corrosivity than other solvents Reduced solvent degradation[45,47]	Solvent and process performance not yet proven at a large scale on flue gases. Scale-up of process equipment required prior to commercial application. Enzyme stability and resilience.	A 10 tpd CO_2 capture pilot plant trial was performed at ParaChem industrial complex. The pilot plant was run >2,500 hours in 2015 and later for 3,000 hours between September 2017 and August 2018. A 30 tpd CO_2 capture unit at a pulp mill in Quebec was built in 2018/2019. An independent technical audit was performed by Tetratech. The unit was sold to SAIPEM along with CO_2 Solutions technology's IP in December 2019[46]. The unit is undergoing works and operation was planned to resume in summer 2020 with full commercial operation in 2021.[47]
Baker Hughes CAP (Developed by Alstom, now owned by General Electric)	A non-precipitating chilled ammonia solvent process	Reduced solvent degradation Non-proprietary solvent Increased oxygen tolerance[48]	Control of solvent emissions is required to prevents hazards to people and the environment. Low levels of solvent emissions can be achieved through chilling.	Baker Hughes claim a TRL of 7 has been achieved for their Chilled Ammonia Process (CAP) with testing conducted at TCM on flue gas ranges between 3.6 – 16% CO_2.[48] Testing of the CAP, under Alstom, was conducted at TCM in 2012-2014. The TCM testing involved over 6,000 hours of operation on two flue gases; flue gas from refinery residue fluid catalytic cracker (RFCC) off-gas at 80,000 tpa (~240 tpd) CO_2 capture and flue gas from natural gas combined heat and power (CHP) 22,000 tpa (~67 tpd) CO_2 capture.[49]
ION Clean Energy (formerly ION Engineering)	A water-lean solvent	Lower capital costs Lower O&M costs Proprietary 3D printed packing[50]	Solvent and process performance not yet proven at a large scale on flue gases.	ION completed pilot testing at the National Carbon Capture Center (NCCC) in Alabama, USA in 2015.[51] Starting in 2016, the solvent was tested at the 12 MWe scale at TCM. The campaign included 2,750 hours of testing capturing 14,000 tonnes of CO_2 on industrial flue gases to simulate coal-fired conditions.[51,52] On 6/10/2021, the US DOE announced funding of $5.8M for an engineering study to retrofit ION's technology onto the Calpine Delta Energy Center in Pittsburg, California, which is an 850 MW CCGT power plant.[53]

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
RTI International	Non-aqueous Solvent	Lower regeneration energy Higher regenerator pressures leading to lower compression energy Lower corrosivity than other solvents Lower heat stable salts[54]	Solvent and process performance not yet proven at a large scale on flue gases.	RTI has completed two pilot plant programs. Testing at the SINTEF Tiller Plant in Norway was conducted 2015-2018 for a total of 2,000 hours at 1 tpd on coal-derived flue gas.[54,55] In 2018, the solvent was tested for 580 hours with coal-fired flue gas at the NCCC in Alabama, USA at a 1 tpd scale.[55] Demonstration scale testing at 200 tpd at TCM is scheduled for 2022.[56]
Solid Sorbents				
Kawasaki CO_2 Capture (KCC)	Temperature swing adsorption (TSA) process utilising a granulated amine-coated porous sorbent	Reduced energy consumption, with ability to operate on low-grade waste heat High performance for wide range of CO_2 concentrations Higher capture rates feasible No hazardous solvents[57]	Process performance not yet proven at a large scale on flue gases, scale-up required prior to commercial application. Fixed bed system not feasible for scale-up thus requires development of moving bed system and prevention of sorbent degradation during conveying.[58]	Kawasaki conducted trials on a 10 tpd CO_2 Capture fixed bed test plant on coal-fired flue gas prior to 2013, before moving to further trials on a 5 tpd CO_2 Capture moving bed system test plant prior to 2019.52[, 57,59] A 40 tpd CO_2 Capture demonstration plant expected to start up at KEPCO's Maizuru coal-fired power plant in Japan in 2022.[60]
Svante (formerly Inventys)	Structured solid sorbent in a rotating absorption bed system	Reduced energy consumption, with ability to operate on low pressure steam Fast absorption-regeneration cycle times No hazardous solvents No sorbent conveying challenges, fixed bed[61]	Process performance not yet proven at a large scale on flue gases, scale-up required prior to commercial application. Reliability of mechanical rotating system, scalability requires multiple rotating bed units. Challenges exist with sealing under vacuum-regeneration conditions. Challenges with capillary pore condensation in the sorbent.[15]	A 30 tpd CO_2 Capture pilot plant at Husky Energy Thermal Lloydminster, Canada was constructed in 2019.[61] Initial engineering analysis for feasibility of a 2M tpa (~6,000 tpd) CO_2 Capture facility for Holcim cement plant and natural gas-fired steam generator in Colorado, USA, also known as LH CO2MENT, was awarded DOE funding in September 2020 with an initial scoping study already completed in June 2020.[62]
TDA Research	Isothermal process based on a granulated alkalised alumina sorbent	Reduced energy consumption, with ability to operate on low pressure steam No hazardous solvents No sorbent transport challenges, fixed bed, claimed lower cost No pressure or temperature swing, regeneration via low pressure steam Higher capture rates feasible[63]	Process performance not yet proven at a large scale on flue gases, scale-up required prior to commercial application. Use of multiple fixed beds could lead to increased footprint and potentially higher cost	A 10 tpd CO_2 capture pilot plant testing is being conducted at the NCCC on coal flue gas. Work will be conducted both on the coal flue gas and on simulated natural gas flue gas using diluted coal flue gas. The project is due to complete in July 2022.[63] TDA has published some of their pilot plant results.

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
Fuel Cells				
FuelCell Energy	Molten carbonate fuel cell (MCFC)	Generates low carbon electricity. Potential availability of low carbon hydrogen. Lower risk scalability via modular fuel cell units. Net water producer, as a product of methane oxidation. NOx destruction.[64]	Process performance not yet proven at a large scale on flue gases, scale-up required prior to commercial application. Low level of contaminants is required in feed gas, thus requirement for extensive upstream gas treatment for many applications.[15] Limited capture rates feasible, high percentage capture rates i.e. greater than 90% may not be achievable.[15]	A pilot 2.8 MWe MCFC power plant capturing CO_2 from the exhaust of a coal-fired power plant was supported by the US DOE in 2015. Subsequently in 2016 partnering with Exxon Mobil, another pilot at a coal and gas-fired power plant in Alabama, USA, was tested at 54 tpd CO_2 Capture.[65] In 2019 FuelCell Energy extended their relationship with Exxon Mobil and will install a demonstration unit at Exxon's Rotterdam Refinery, data on the scale of the unit is not available.[66] In the same year a FEED study was announced for an 85 tpd CO_2 Capture unit for Drax Power Station, UK.[67]
Membranes				
Membrane Technology and Research (MTR)	Polaris polymeric membrane	Reduced energy consumption. No chemical use or related emissions. No steam use Fast response and simple turndown. Passive operation, limited moving mechanical parts. Lower risk scalability via modular membrane units. Lower maintenance and operator requirements. Greatest advantage as bulk removal step, suitable for hybrid capture approach by combining with another capture technology.[68]	Process performance not yet proven at a large scale on flue gases, scale-up required prior to commercial application. Limited capture rates feasible, high percentage capture rates i.e. greater than 90% may not be achievable.[15]	MTR has evaluated their membranes on a slipstream of coal flue gas. A 20 tpd CO_2 Capture pilot plant was operated at the NCCC.[69] Subsequently, design and construction of a c.150 tpd CO_2 capture pilot plant at a 70% capture level is being implemented with 2021 funding from the US DOE NETL at the Wyoming Integrated Test Centre.[70] MTR have also planned testing at TCM in 2021.[71]

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
Oxy-Combustion				
NET Power	Allam-Fetvedt Cycle	Improved efficiency relative to conventional gas fired power generation with post combustion capture. Generates low carbon electricity. Produces industrial gas co-products (argon and nitrogen). Capable of water-free production. No emissions.[72]	Process performance not yet proven at a large scale, scale-up required prior to commercial application. Not yet demonstrated sustained reliable operation of the test plant.	NET Power's 50 MWth test facility in La Porte, Texas, USA was commissioned in March 2018 and has achieved more than 1,000 operating hours.[73] AECOM estimates that ~225 tpd of CO_2 could be captured by this facility based on an LHV of 50 MJ/kg and a 95% capture level of produced CO_2. NET Power are looking to develop a 300 MWth plant. AECOM estimates that ~1,350 tpd of CO_2 could be captured by this facility on the same basis. Starting in Q2 2020, they have been conducting a Pre-FEED study for installation at a generic UK location.[72]
Clean Energy Systems (CES)	Platelet oxy-fuel combustor process	Generates low carbon electricity. Higher turbine efficiencies. Compatible with a wide range of gaseous or liquid fuels. Ability to recover up to 100% of CO_2 produced in the combustor. No emissions. Water producer.[74]	Process performance not yet proven at a large scale, scale-up required prior to commercial application. Not yet demonstrated sustained reliable operation of the test plant.	CES have a 5 MWe Pilot at Kimberlina Coal and Biomass fuelled Power Plant in California, USA, which is claimed to be CCS ready and producing 1,500 Mscfd of CO_2 (~78 tpd CO_2).[75,76] The Mendotta BECCS project is planned to capture 300,000 tpa (~800 tpd) CO_2 using CES technology. FEED was expected to begin March 2021 with a final investment decision in 2022.[77]
Cryogenics				
Air Liquide	PSA plus cryogenic CO_2 separation and purification hybrid process	Uses only electrical power (no steam or thermal energy required) Integrates CO_2 liquefaction and purification into the separation process. Individual process steps based on established technologies. Improved hydrogen production rate when capturing CO_2 from hydrogen units.	Individual process steps working together in one integrated process not yet demonstrated at a large scale on flue gas, required prior to commercial application. Focus on hydrogen applications may mean post combustion capture is less advanced.	Each of the processing steps (compression, dehydration, PSA, cryogenic separation, expansion) have commercial applications, but the combined process has not been demonstrated.[78] An independent third-party assessment in July 2021 rated the technology at TRL-6.[79] Air Liquide has a contract to provide a design package for a 2,400 tpd capture facility for two hydrogen production units at Zeeland Refinery in Vlissingen, the Netherlands using the CryoCap FG technology. The contract was awarded June 2021.[81]

Providers	Overview	Stated Advantages	Challenges	Demonstration Status
Calcium Looping				
Endesa	Post combustion CO_2 capture process based on a carbonation-calcination cycle.	Low efficiency penalty Low-cost sorbent (limestone) Resilient to contaminants in input gas Purge material has high CaO content and can be used in cement production	Scale-up and demonstration of long term sustained operation Sorbent degradation through repeated cycling Process is conducted at high temperatures so a use for the heat is required to prevent a high energy penalty.	A 1.7MWt (up to 50tpd CO_2 capture) pilot project was constructed that captured CO_2 from a side stream of flue gasses from the 50MWe, La Pereda, coal power plant in Spain. Before finishing in May 2013, the project operated for around 380 hours in CO_2 capture mode and reportedly achieved capture efficiencies up to 95%[80]. The project was used to support the conceptual design of a larger, 20MWth project. The Endesa website states that they are looking to extend the project at La Pereda by developing other projects at the site.
Direct Separation Reactor				
Calix	A process modification for lime and cement manufacture to aid capture by producing a more concentrated stream of CO_2, refered to as LEILAC. Powdered limestone is indirectly heated in a tubular reactor such that the CO_2 released during calcination can be directly captured.	Low capital cost Low energy penalty Applicable in the lime and cement sector where other capture technologies can be challenging to apply. Plans for application in iron and steel sector	Demonstration of long term sustained operation Achieving high levels of calcination at high plant throughputs	Low Emissions Intensity Lime and Cement (LEILAC) 1 is a 25,000 tpa (~75 tpd) CO_2 Capture pilot plant operating at Heidelber Cement's Lixhe plant in Belgium. It started up in 2019 and is reportedly a success, although performance data is not publicly available.[36] LEILAC 2 will be a larger demonstration unit located at Heidelberg Cement's plant in Hannover, Germany. Planned capacity is 100,000 tpa (~300 tpd) CO_2 Capture, which represents 20% of the cement plant's capacity. It is currently in the engineering phase with construction scheduled to start at the end of 2022.[37]

5. Research Stage Technologies

Research stage technologies are those that current TRL makes them unlikely to be deployable by 2035. The majority have only been demonstrated at lab and bench scales or small-scale pilots. It is possible that among these technologies a small number could go on to see rapid advancement over the next few years and thus become leading commercial technologies. As these less readily deployable technologies are not the primary focus of this study only a high-level assessment of their development and potential has been conducted.

Most research stage technologies can be grouped into the three core technology types: membranes, solvents and sorbents. Projects in these technology groups are developing more advanced versions of those technologies seen in the demonstration and development categories, often through advances in materials and application methods to improve performance efficiency and reduce cost. In addition, other technology options are being developed that fit outside these groups of technologies. These technologies include enzyme catalysed capture, cryogenic capture, chemical looping and oxy-combustion cycles.

5.1 Solvents

Key challenges and development areas for solvent technologies are[83]:

- Improving absorption capacity
- Improving absorption rate
- Reducing the solvent cost
- Reducing the energy requirement for regeneration
- Improving solvent stability and reducing degradation
- Reducing solvent induced corrosion to allow use of lower cost materials
- Reducing the solvent environmental impact

Table 11 presents a summary of research stage solvent technology projects and their development status.

Table 11 Research stage solvent technology projects summary[87]

Project	Application Type	Participant	Development status
Novel Electrochemical Regeneration of Amine Solvents	Post-Combustion	Massachusetts Institute of Technology	Active, 1 MWe
Slipstream Demonstration Using Advanced Solvents, Heat Integration, and Membrane Separation	Post-Combustion	University of Kentucky	Active, 0.7 MWe
Biphasic CO_2 Absorption with Liquid-Liquid Phase Separation	Post-Combustion	University of Illinois at Urbana-Champaign	Active, Lab
Piperazine Solvent with Flash Regeneration	Post-Combustion	University of Texas	Active, 0.5 MWe
Microencapsulated CO_2 Capture Materials	Post-Combustion	University of Notre Dame	Active, Lab
Phase-Changing Absorbent	Post-Combustion	GE Global Research	Active, Bench-Scale, Simulated Flue Gas
CO_2-Binding Organic Liquid Solvents	Post-Combustion	Pacific Northwest National Laboratory	Active, Lab
Aminosilicone Solvent	Post-Combustion	GE Global Research	Active, 10 MWe
Ammonia- and Potassium Carbonate-Based Mixed-Salt Solvent	Post-Combustion	SRI International, Baker Hughes and University of Illinois	Active, Bench-Scale, Simulated Flue Gas.
Waste Heat Integration	Post-Combustion	Southern Company Services, Inc.	Active, Pilot-Scale, Actual Flue Gas

Project	Application Type	Participant	Development status
Slipstream Novel Amine-Based Post-Combustion Process	Post-Combustion	Linde LLC	Completed, 1.5 MWe
Carbonic Anhydrase Catalyzed Advanced Carbonate and Non-Volatile Salt Solution (“Solvents”)	Post-Combustion	Akermin, Inc.	Completed, Bench-Scale, Actual Flue Gas
Carbon Absorber Retrofit Equipment	Post-Combustion	Neumann Systems Group	Completed, 0.5 MWe
Novel Absorption/ Stripper Process	Post-Combustion	William Marsh Rice University	Completed, Bench-Scale, Simulated Flue Gas
Gas-Pressurized Stripping	Post-Combustion	Carbon Capture Scientific	Completed, Bench-Scale, Real Flue Gas
Solvent + Enzyme and Vacuum Regeneration Technology	Post-Combustion	Novozymes North America, Inc.	Completed, Bench-Scale, Simulated Flue Gas
Optimized Solvent Formulation	Post-Combustion	Babcock & Wilcox	Completed, Bench-Scale, Simulated and Actual Flue Gas
Hot Carbonate Absorption with Crystallization-Enabled High-Pressure Stripping	Post-Combustion	University of Illinois at Urbana-Champaign	Completed, Lab
Chemical Additives for CO_2 Capture	Post-Combustion	Lawrence Berkeley National Laboratory	Completed, Bench-Scale, Simulated Flue Gas
Self-concentrating Amine Absorbent	Post-Combustion	3H Company, LLC	Completed, Lab
Ionic Liquids	Post-Combustion	University of Notre Dame	Completed, Lab
Novel Integrated Vacuum Carbonate Process	Post-Combustion	Illinois State Geological Survey	Completed, Lab
POSTCAP Capture and Sequestration	Post-Combustion	Siemens Energy Inc.	2.5 MWe
Reversible Ionic Liquids	Post-Combustion	Georgia Tech Research Corporation	Completed, Lab
Phase Transitional Absorption	Post-Combustion	Hampton University	Completed, Lab
(Pre-Combustion) CO_2 Capture Using AC-ABC Process	Post-Combustion	SRI International	Completed, 0.15 MWe
Compact Carbon Capture (3C) – Rotating Absorber	Post-Combustion	Baker Hughes	Pilot
DMX Process – Single to Dual Phase Solvent	Post-Combustion	IFPEN/Axens	1500 hours of operation was achieved on a mini-pilot at IFPEN operating on synthetic blast furnace gas.[15] A 0.5 tph (~12 tpd) CO_2 capture pilot plant is to be built for the European H2020 3D project at ArcelorMittal’s site in Dunkirk.[84] Commissioning and start-up are scheduled for first half of 2022.[85]

5.2 Sorbents

Key challenges and development areas for sorbent technologies are[87]:

- Creating and designing tailored sorbent materials with desired attributes for specific applications
- Developing understanding of the molecular, microscopic and macroscopic structure levels and their relationship to the sorbent material properties
- Improving long-term reactivity, recyclability and robustness of the sorbent
- Optimising integration of the sorbent within the process

Table 12 presents a summary of research stage sorbent technology projects and their development status.

Table 12 Research stage sorbent technology projects summary[87]

Project	Application Type	Participant	Development status
Pressure Swing Adsorption Process with Novel Sorbent	Post-Combustion	Georgia Tech Research Corporation	Active, Lab
Porous Polymer Networks	Post-Combustion	Texas A&M University	Active, Lab
Novel Solid Sorbent	Post-Combustion	SRI International	Active, Bench-Scale, Actual Flue Gas
Fluidizable Solid Sorbents	Post-Combustion	Research Triangle Institute	Active, Lab
Advanced Aerogel Sorbents	Post-Combustion	Aspen Aerogels, Inc.	Completed, Bench-Scale, Simulated Flue Gas
Temperature Swing Adsorption with Structured Sorbent	Post-Combustion	NRG Energy, Inc.	-
Rapid Pressure Swing Adsorption	Post-Combustion	W. R. Grace and Co.	Completed, Bench-Scale, Simulated Flue Gas
Advanced Solid Sorbents and Processes for CO_2 Capture	Post-Combustion	RTI International	Completed, Bench-Scale, Simulated Flue Gas
Cross-Heat Exchanger for Sorbent-Based CO_2 Capture	Post-Combustion	ADA-ES, Inc.	Completed, Bench-Scale, Simulated Flue Gas
Low-Cost, High-Capacity Regenerable Sorbent	Post-Combustion	TDA Research, Inc.	Completed, Bench-Scale, Actual Flue Gas
Rapid Temperature Swing Adsorption	Post-Combustion	Georgia Tech Research Corporation	Completed, Bench-Scale, Simulated Flue Gas
Novel Adsorption Process	Post-Combustion	InnoSepra, LLC	Completed, Bench-Scale, Actual Flue Gas
Hybrid Sorption Using Solid Sorbents	Post-Combustion	University of North Dakota	Completed, Bench-Scale, Actual Flue Gas
Metal Monolithic Amine-Grafted Zeolites	Post-Combustion	University of Akron	Completed, 15 kW, Simulated Flue Gas
CO2 Removal from Flue Gas Using Microporous MOFs	Post-Combustion	UOP	Completed, Lab
A Dry Sorbent-Based Post-Combustion CO_2 Capture	Post-Combustion	RTI International	Completed, Bench-Scale, 1 tonne per day, Actual Flue Gas
High Capacity Regenerable Sorbent	Pre-Combustion	TDA Research, Inc.	Active, 0.1 MWe
Novel Concepts/ Integrated Temperature and Pressure Swing Carbon Capture System	Novel Concept, Pre-Combustion	Altex Technologies Corporation	Completed, Lab

5.3 Membranes

Key challenges and development areas for membrane technologies are[87]:

- Developing an understanding of the transport phenomena at the membrane interface in new materials (of particular interest are polymeric, carbon metallic, ceramic, dual-phase and composites) to improve their permeability and selectivity performance
- Fabrication of new designs and methods to produce membrane structures or modular units at large scale and reduced cost
- Improving membrane life and resistance to detrimental effects of contaminants in the gas feed

Table 13 presents a summary of research stage membrane technology projects and their development status.

Table 13 Research stage membrane technology projects summary[87]

Project	Application Type	Participant	Development status
Selective Membranes for <1% CO_2 Sources	Post-Combustion	Ohio State University	Active, Lab
Subambient Temperature Membrane	Post-Combustion	American Air Liquide, Inc.	Active, 0.3 MWe
Inorganic/Polymer Composite Membrane	Post-Combustion	Ohio State University	Completed, Pilot-Scale, Actual Flue Gas
Composite Hollow Fibre Membranes	Post-Combustion	GE Global Research	Completed, Bench-Scale, Simulated Flue Gas
Low-Pressure Membrane Contactors (Mega-Module)	Post-Combustion	Membrane Technology and Research, Inc.	Completed, Bench-Scale, Simulated & Actual Flue Gas
Hollow-Fibre, Polymeric Membrane	Post-Combustion	RTI International	Completed, Bench-Scale, Simulated Flue Gas
Biomimetic Membrane	Post-Combustion	Carbozyme	Completed, Lab
Dual Functional, Silica-Based Membrane	Post-Combustion	University of New Mexico	Completed, Lab
Zeolite Membrane Reactor	Pre-Combustion	Arizona State University	Active, Bench-Scale, Actual Syngas
Mixed Matrix Membranes	Pre-Combustion	State University of New York, Buffalo	Active, Bench-Scale, Actual Syngas
PBI Polymer Membrane	Pre-Combustion	SRI International	Active, Bench-Scale, Actual Syngas
Two-Stage Membrane Separation: Carbon Molecular Sieve Membrane Reactor followed by Pd-Based Membrane	Pre-Combustion	Media and Process Technology, Inc.	Active, Bench-Scale, Actual Syngas
High-Temperature Polymer-Based Membrane	Pre-Combustion	Los Alamos National Laboratory	Completed, Bench-Scale, Simulated Syngas
Dual-Phase Ceramic-Carbonate Membrane Reactor	Pre-Combustion	Arizona State University	Completed, Lab
Pd-Alloys for Sulfur/Carbon Resistance	Pre-Combustion	Pall Corporation	Completed, Lab
Hydrogen-Selective Zeolite Membranes	Pre-Combustion	University of Minnesota	Completed, Bench-Scale, Simulated Syngas
Pressure-Swing Membrane Absorption Device and Process	Pre-Combustion	New Jersey Institute of Technology	Completed, Lab
Nanoporous, Superhydrophobic Membrane Contactor Process	Pre-Combustion	Gas Technology Institute	Completed, Bench-Scale, Simulated Syngas
Polymer Membrane Process Development	Pre-Combustion	Membrane Technology and Research, Inc.	Completed, Bench-Scale, Actual Syngas
Hybrid GO-PEEK Membrane Process	Novel Concept	Gas Technoogy Institute - GTI	Active, Lab

Project	Application Type	Participant	Development status
Novel Concepts/ICE Membrane for Post-Combustion CO_2 Capture	Novel Concept, Post-Combustion	Liquid Ion Solutions LLC	Active, Lab
Novel Concept/ Encapsulation of Solvents in Permeable Membrane for CO_2 Capture	Novel Concept	LLNL – Lawrence Livermore National Laboratory	Active, Lab

5.4 Other Technologies

Table 14 presents a summary of other research stage technology projects and their development status.

Table 14 Other research stage technology projects summary[87,88,89]

Project	Participant	Development status
Novel Concepts/ Cryogenic Carbon Capture Process	Sustainable Energy Solutions, LLC	Active, Bench-Scale, Actual Flue Gas
Supersonic Inertial CO_2 Extraction System	Orbital ATK Inc.	Active, Bench-Scale, Simulated Flue Gas
Better Enzymes for Carbon Capture	Codexis	Active, Lab-Scale
Calcium Looping	Technical University of Darmstadt, Germany	Active, 1 MWth, Scaling-Up to 20 MWth
Chemical Looping, $CaSO_4$	ALSTOM Windsor	Completed, 3 MWth
Industrial Waste Carbonation	OCO Technology (Formerly Carbon8)	OCO's containerised system uses an accelerated carbonation process. It currently offers small-scale CO_2 capture at 30,000 t over the lifetime of the plant.
Oxy-Fuelled Flash Calciner	Origen Power	Received funding from BEIS in 2019 for Oxy-Fuelled Flash Calciner Project; £249,000 towards the £356,000 project.
CO_2 to Polypropylene	Lanzatech	Lanzatech have a technology that convers gasses containing CO into hydrocarbon products using a fermentation process. The company recently announced intentions to develop a project that allows CO_2 to be used as a feedstock[86]. Details of the development status of the technology are limited.

5.5 Hybridisation

A developmental area of interest is the adoption of a hybridised approach, combining the different technology types with the aim of overcoming their individual challenges and gaining the benefits of each of the technologies. Examples of a hybrid approach include:

- Solvent-Membrane CO_2 Capture – An aqueous ammonium solvent is used in an absorber to remove CO_2 from a flue gas stream, the carbon-rich solution from the absorber is then passed through a membrane designed to selectively transport the bound carbon, enhancing its concentration on the permeate side.
- Sorbent-Membrane CO_2 Capture – A membrane is used to perform bulk CO_2 removal from a flue gas stream under mild vacuum, removing more than 50% of CO_2, then a second stage of sorbent CO_2 separation is performed to achieve ~90% capture.
- Membrane-Liquefaction (Cryogenic) CO_2 Capture – A membrane is used to pre-concentrate the CO_2 stream sent for liquefaction capture.

6. Technology Applications

Input gas streams to carbon capture facilities will have different physical properties and/or composition. This will give rise to different processing requirements due to factors such as pressure, temperature, contaminant species, and contaminant concentrations. CO_2 concentration is important when considering technology selection. However, even if a technology is applicable to one input gas stream within a certain CO_2 concentration range, it may not be applicable for another input gas stream with the same CO_2 concentration range due to differences in contaminant concentrations.

Typically, higher concentrations of CO_2 will aid capture and separation. However, there is always a possibility that another parameter of the higher concentration input gas may mitigate any benefit. For example, presence of a contaminant species that is highly reactive to a technology's solvent may cause extreme levels of degradation and render capture by its use impractical.

This section focusses on post combustion technologies that could be added to a range of existing processes. It does not consider alterations to industrial processes such as in the LEILAC process or the NET Power technology. These processes are limited in application to specific industries, with LEILAC technology being proposed for lime and cement manufacture and the NET Power technology being proposed for power generation.

6.1 Technology Application Matrix

A matrix of the applicability of each of the demonstration and development stage technologies to capture CO_2 from gas streams with different CO_2 concentrations is displayed in Table 15. Examples of typical industrial processes where these flue gas CO_2 concentrations are present are also provided.

The applicability of each technology to different flue gases has been judged based on the projects completed by the technology supplier. Most credit has been given for current and past operational projects, then pilot testing conducted, then funded future projects, and finally engineering judgement has been used to apply the ratings.

Where projects processing a particular input gas stream have not been identified for a technology this has been given a lower applicability ranking in the matrix created. In these cases, applicability for flue gasses with higher concentration CO_2 than the projects identified for the technology has been deemed more favourable than for lower concentration. This is because typically lower CO_2 concentrations will prove technically and economically more challenging to capture. In many cases it would be possible to apply a technology across a wide range of input gas streams, but cost could vary significantly.

Where a technology has been marked as 'Possibly Applicable' in the matrix it may still be well suited to that kind of input gas. Furthermore, it is possible that it could be better suited to a given input gas stream than other technologies that have been marked as 'Applicable' for that gas stream because they have developed projects that process similar gasses.

Table 15. Technology Application Matrix, based on known projects

Flue Gas CO_2 Concentration Category	Low 1-5%	Mid 5-10%	High 10-15%	Very High 15+%
Typical industrial processes where such a flue gas may be present	• CCGT • Aluminium • CHP • Glass (air/fuel furnace)	• Natural Gas Fired Boiler • Fired Heater • Oil Refining	• Oil-Fired Boiler • Coal-Fired Boiler • EfW • Biomass-Fired Boiler	• Iron & Steel Production • Cement/Lime Production • Hydrogen Production • Anaerobic Digestion
Demonstration Stage Technologies				
Mitsubishi Heavy Industry	🟡	🟡	🟢	🟡
Shell Cansolv	🟢	🟢	🟢	🟡
Fluor Econoamine FG Plus	🟢	🟢	🟢	🟡
Carbon Clean	🟠	🟢	🟢	🟢
Aker Carbon Capture	🟢	🟢	🟢	🟢
Development Stage Technologies				
BASF & Linde	🟠	🟠	🟢	🟡
C-Capture	🟢	🟢	🟢	🟡
CO_2 Capsol	🟠	🟠	🟢	🟡
CO_2 Solutions SAIPEM	🟠	🟢	🟢	🟡
Baker Hughes CAP	🟢	🟢	🟡	🟡
ION Clean Energy	🟡	🟡	🟢	🟡
RTI International	🟠	🟡	🟢	🟡
Kawasaki CO_2 Capture	🟠	🟠	🟢	🟡
Svante	🟠	🟢	🟡	🟡
TDA Research	🟠	🟠	🟢	🟡
FuelCell Energy	🟡	🟢	🟢	🟢
Membrane Technology and Research	🟠	🟠	🟢	
Air Liquide	🟠	🟠	🟠	🟢

Key

Applicable	🟢
Likely to be Applicable	🟡
Possibly Applicable	🟠

There are two important limitations to note in relation to the classification process applied. Firstly, classification has been based primarily on input gas CO_2 concentration. The CO_2 concentrations from some industrial flue gasses are likely to change over time due to reasons such as electrification of process heating or changes to the mixture of fuels fired in combustion appliances.

Secondly, analyses based on input gas contamination levels for different contaminants may have provided different results. Classification based on CO_2 concentration was selected because contamination levels vary between sites in any given industry and contamination can be controlled, at a cost, by pre-treatment technologies that could be incorporated into the carbon capture facility.

During the technology selection process for any potential carbon capture facility, it is important to fully understand the composition and physical properties of the output emission stream from the process generating the CO_2, and the effects on the proposed post-combustion capture process to de-risk future deployment. In addition, consideration should be given to any parameters that may change in the emission stream during the life of the capture plant. This can then be used when considering what combination of input gas pre-treatment and carbon capture technology would be most compatible with the site.

7. Opportunities and Barriers

This section contains a brief overview of opportunities and barriers relating to the development and deployment of carbon capture technologies. Opportunities and barriers common to all potential end users are discussed followed by an examination of sector specific issues. In addition to in-house knowledge of the industry, the information below was informed by an industry engagement workshop that took place on 30 September 2021.

7.1 Common Opportunities

With increasing concerns relating to the climate emergency there is a growing acceptance of the urgent need to reduce anthropogenic CO_2 emissions rapidly and substantially. This creates opportunities in relation to the development and deployment of carbon capture technologies in the UK. Some of the main opportunities common to most carbon capture projects are outlined below. The opportunities have been split into those applicable to carbon capture users and those applicable to carbon capture technology providers. The potential for these opportunities to be realised can be increased by encouraging collaboration between different companies and industries involved in the carbon capture sector.

7.1.1 For Carbon Capture Technology Users

Mitigation of risk associated with CO_2 emission costs – It is likely that the cost of emitting CO_2 in the future will increase. Consequently, being able to operate with lower CO_2 emissions may provide competitive advantage.

Licence to operate – Some industries may be prevented from operating in the future if CO_2 emissions are not prevented.

Corporate reputation – The implementation of projects that benefit the environment can enhance the reputation of companies.

Availability of investment – Public and private investment funds may be available for the development of carbon capture projects.

Early adoption advantages – There are advantages relating to the early adoption of any new technology.

CO_2 as a feedstock – In some processes there is the potential to use CO_2 as a feedstock.

7.1.2 For Carbon Capture Technology Providers

Market size – There is a substantial potential global market to successful developers of carbon capture technologies.

Availability of investment – Public and private investment funds may be available for the development of carbon capture technologies.

Incremental improvements – Carbon capture technology has had very limited deployment in many applications. Where existing CO_2 capture technology is deployed in new applications there will be scope for incremental technical improvements to the system which will lead to performance improvements and cost reductions.

New concepts – There are a wide variety of CO_2 capture concepts available, many of which are at the early stages of development. It is possible that an early-stage technology concept could offer cost and performance advantages over more established options.

Modularisation – The production of standardised modules that can be attached to existing processes is a concept being explored by technology suppliers. The use of standardised modules offers financial and technical advantages.

7.2 Common Barriers

Cost of emitting CO_2 – The cost of capturing, transporting and storing CO_2 is currently greater than the cost of emitting it to atmosphere in most situations.

Policy and incentives - Clear policy and a robust, long term, system of taxes and incentives will be required to make carbon capture project economically attractive and allow financeable business models to be developed. Work in this area is ongoing but there are multiple challenges associated with development of the required policy and incentives schemes.

CO_2 infrastructure – There is currently a lack of infrastructure for the transportation and storage of CO_2 in the UK. The carbon capture clusters proposed for some industrial hubs in the UK have the potential to serve these areas and be extended. However, in much of the country there are no plans for the development of CO_2 transportation infrastructure in the short to medium term.

CO_2 storage risk – Storage of large quantities of CO_2 could create large financial liabilities. Organisations involved in this industry would need to be both capable of, and willing to, assume that liability.

Carbon capture chain risk – For a carbon capture plant to be of value it requires a source of CO_2, a means of transporting CO_2 to a storage site and a functioning storage site. These elements of the chain may be owned and operated by different companies. If any one of these elements is unavailable, or becomes unavailable during the life of the project, then this is a risk to the carbon capture project. The risks created by reliance on other parts of a chain of equipment create additional costs for a project and may discourage investment.

Alternative decarbonisation options – Lower cost decarbonisation options may be a barrier to carbon capture deployment in some settings. Examples of potential alternative decarbonisation options include demand reduction, product substitution, electrification, efficiency improvements and fuel switching. The availability of lower cost decarbonisation options is industry and site specific.

Permitting and regulation – carbon capture is a new industry so there are areas of environmental permitting and regulation that require to be developed. A balance is required between the sometimes-competing priorities of encouraging the development of carbon capture projects, protecting the environment from potentially harmful emissions (other than CO_2), encouraging the deployment of new technologies and allowing the intellectual property of technology developers to be protected. In addition, any differences in approach between the devolved administrations in the UK have the potential to add complication to requirements.

Planning – Obtaining the required planning permission for a carbon capture facility may be a barrier at some sites. Carbon capture plants are large process plants with impacts relating to appearance, emissions, noise, traffic, safety and environmental hazards and other potential impacts. For retrofit projects there may also be physical constraints in relation to the space available adjacent to the existing process plant.

Technology risk – Carbon capture plants can be complex and expensive and many technologies have not been demonstrated in a commercial setting.

Scale-up – Scaling up new technologies to a large scale can be an expensive, time consuming and high-risk process with no guarantee of success. A balance is required between achieving rapid scale-up, to benefit from economies of scale, and avoiding excessive technical risk associated with rapid scale-up.

Availability of funding – There is a limited amount of funding available for the development of new technologies.

Health, safety and the environment – The construction of a carbon capture plant will introduce new hazards to a site that require to be mitigated.

Public Perception – The development of carbon capture projects has the potential to benefit corporate reputation. However, public perception also has the potential to be a barrier to development if carbon capture is perceived as high risk and a method of prolonging the continued operation of polluting industries or distracting attention from less politically favourable decarbonisation options, such as demand reduction. To overcome this barrier both appropriate use of carbon capture and management of public perception are required.

7.3 Industry Specific Opportunities and Barriers

Table 16 details industry specific opportunities and barriers relating to the deployment of carbon capture technology.

Table 16. Industry Specific Opportunities and Barriers

Industry	Opportunities	Barriers
Energy from waste	• Potential for net negative CO_2 emissions due to biogenic content of feedstock • Consistent high load operation • Experience of complex flue gas treatment • Improved public perception • Limited other options for residual waste treatment	• The potential impact of residual contaminant carryover from existing flue gas treatment processes. • Dispersed location of sites
CHP and gas fired power generation	• Relatively low level of contamination in flue gas • High volumes of CO_2 produced at one source	• Competing technologies for low carbon electricity generation • Possible intermittent operation • Low CO_2 concentrations
Biomass Power generation	• Potential for net negative CO_2 emissions due to biogenic content of feedstock	• Limited availability of sustainable feedstock
Cement and lime	• High volumes of CO_2 produced at one source • Limited other ways of substantially reducing CO_2 emissions • Potential to export low CO_2 product • Potential for net negative CO_2 emissions if feedstock with biogenic content is used.	• Dispersed location of sites • The potential impact of residual contaminant carryover from existing flue gas treatment processes.
Glass	• Limited other ways of substantially reducing CO_2 emissions. Particularly for large sites that cannot source enough good quality recycled glass to replace carbonate feedstock • Potential to export low CO_2 product	• Dispersed location of sites • The potential impact of residual contaminant carryover from existing flue gas treatment processes.
Oil and gas	• Experience of gas handling, including CO_2 capture technologies • Access to storage sites • High volumes of CO_2 produced at one source	• Multiple emission streams at some sites • May be perceived negatively as a way of allowing the continued use of fossil fuels
Iron, steel and non-ferrous metals	• High volumes of CO_2 produced at one source • Potential to export low CO_2 product	• Other potential decarbonisation options available
Chemicals	• Some emission streams with high CO_2 concentration (eg in fertiliser production) • Potential to export low CO_2 products • Potential to use CO_2 in product manufacture	• Different challenges for different industry subsectors. For example, intermittent operation, contamination, scale or geographic location.
Anaerobic digestion	• Potential for net negative CO_2 emissions due to biogenic content of feedstock • Relatively high CO_2 concentration in biogas • Established processes for CO_2 extraction for when biogas is upgraded to biomethane	• Relatively small scale • Dispersed location of sites
Brewing and distilling	• Potential for negative CO_2 emissions • High concentration CO_2 produced • Established CO_2 capture and sales	• Dispersed location of sites • Relatively small scale

8. Industry Engagement Workshop

This section summarises findings from the ‘Next Generation Carbon Capture Technology’ industry engagement workshop held on 30 September 2021. The workshop was managed by AECOM, hosted by the UK Carbon Capture and Storage Research Centre (UK CCSRC), with technical input from Jon Gibbins of the University of Sheffield and BEIS.

The purpose of the workshop was to engage with representatives from a range of industry sectors. As well as stimulating enthusiasm, the workshop facilitated open discussion and promoted opportunities for collaboration in relation to next generation carbon capture technologies. Participants were encouraged to share their views on opportunities and barriers relating to the development and deployment of carbon capture technologies. Feedback on opportunities and barriers is contained in the WP 2 report (that will be published by BEIS in May 2022), all other feedback from the workshop is reported in this document.

Following an introductory presentation by AECOM the workshop had two interactive sessions. During the interactive parts of the workshop information was gathered from participants by asking multiple choice questions and collecting comments made anonymously on different subjects. While all responses were made anonymously, attendees were asked to provide an indication of the industry sector that they were affiliated with. The X-Leap software platform was used to anonymise and facilitate the interactive part of the workshop.

The workshop was well attended with 135 participants attending in total. Participants included representatives from all the anticipated industries. There were consistently high levels of engagement from attendees, with up to 80 responses in each X-Leap question and over 100 comments made during the opportunities and barriers open discussion. This high level of participation from a variety of sectors resulted in a wide range of opinions being expressed and meant that valuable information was obtained.

Some key messages from the workshop were:

- Carbon capture was seen by most participants as having greater potential to decarbonise than either fuel switching or process modification. Although, it should be noted that these results were obtained from attendees of an event relating to carbon capture, so attendees may be more likely to view it positively as a decarbonisation approach.
- Solvent-based technologies with improvements were seen as being the most promising next generation carbon capture technology.
- Most attendees anticipated deployment of carbon capture, and other decarbonisation technologies, by 2030.
- The majority of participants anticipated carbon capture technologies being capable of capturing more than 90% of total emissions from their plant.
- ‘False starts’ in the carbon capture industry have been a source of frustration and have the potential to undermine investor confidence.

The questions asked during the workshop were intended to provide insight into the current thoughts and opinions of different industrial sectors on a range of issues relating to the deployment of carbon capture technology. Participants were presented with simple multiple-choice answers to a range of questions to allow them to express their opinions. The answers to many of the questions asked were more complex than could be covered by multiple choice answers and will depend on a wide range of interrelated factors. Furthermore, questions may have been interpreted differently by different participants which may have affected their answers. This should be taken into consideration when drawing any conclusions from the results obtained.

The inputs provided by participants represent the anonymously expressed opinions of the individuals who attended the workshop, and for some industry sectors there were only a small number of attendees. Therefore, the results obtained do not necessarily represent the wider views of the industries concerned.

8.1 Interactive Session Results

8.1.1 Potential to Decarbonise

The question asked to participants in this section was ‘Please select and rank the approaches that have the greatest decarbonisation potential for your sector.’ Three options were given and were to be ranked in order, with the top approach being the option with the greatest potential. There were 80 responses to this question and the average (mean) ranking for each approach is given in Figure 3. A breakdown of the results by sector is given in Figure 3. The ‘petro-chem, fertilisers and fine chemicals’ sector was omitted from this graph because no responses were obtained.

Figure 3. Breakdown of decarbonisation approach ranking results by industry sector.

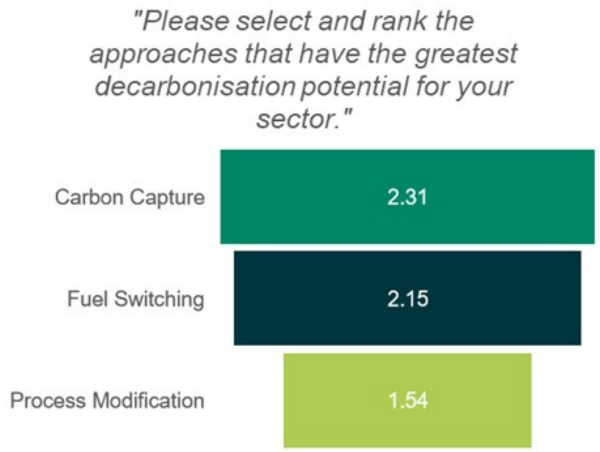
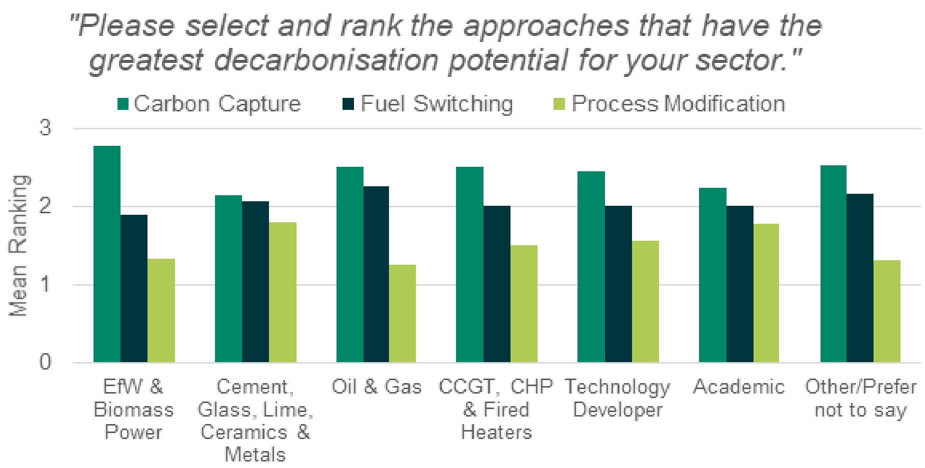


Figure 4. Decarbonisation approach ranking results.



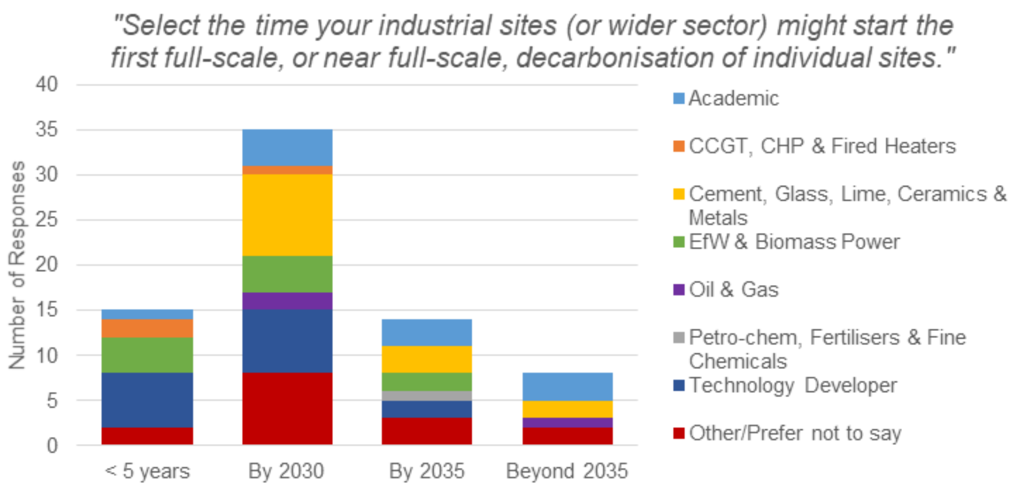
Key observations from the results obtained from this question are:

- In all industry sectors, carbon capture was considered to have more decarbonisation potential than fuel switching or process modifications. Although, it should be noted that these results were obtained from attendees of an event relating to carbon capture, so attendees may be more likely to view it positively as a decarbonisation approach.
- Carbon capture was viewed particularly favourably in the EfW sector. This may be due to the limited alternatives for decarbonisation in this sector.
- In the cement, glass, lime, ceramics and metals sector there was a more even split between responses on which decarbonisation option offered the greatest potential. This may reflect a greater availability of options in relation to fuel switching, or process modifications, compared to other industries.

8.1.2 Time to Commercial Deployment

Participants were asked to 'Select the time your industrial sites (or wider sector) might start the first full-scale, or near full-scale, decarbonisation of individual sites.' Only one answer was to be selected. There were 72 responses, and the total results are given in Figure 5.

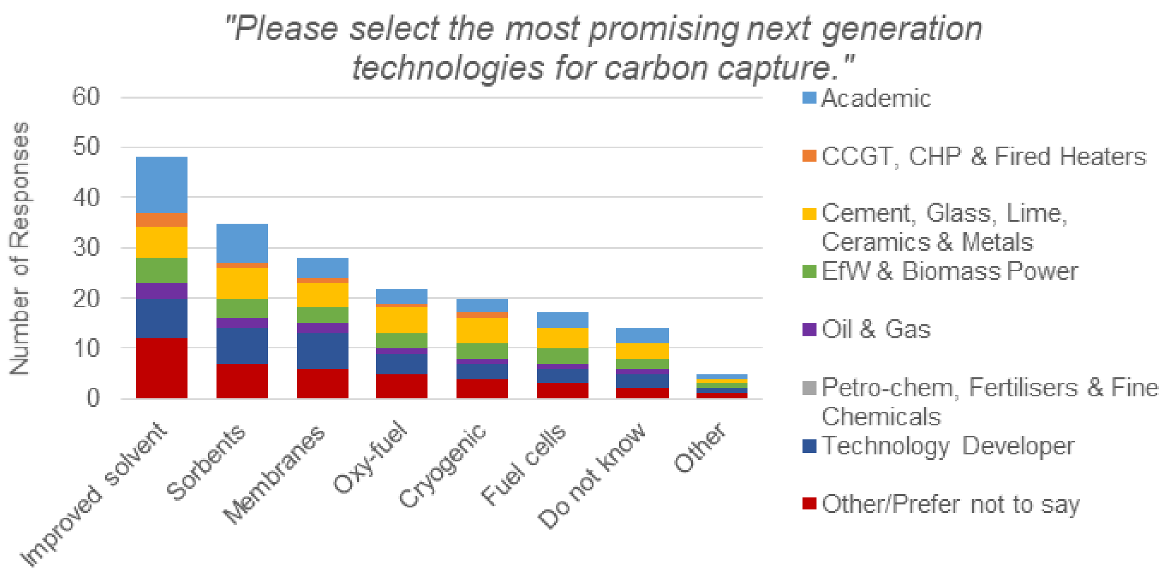
Figure 5. Time to commercial deployment results by sector.



8.1.3 Most Promising Next Generation Technologies

Participants were asked to 'Please select the most promising next generation technologies for carbon capture.' and given the option to select up to four answers. There were 189 answers selected in total from 77 respondents. A breakdown of the results by sector is given in Figure 6.

Figure 6. Most promising next generation technology results by sector.



8.1.4 Carbon Capture Deployment

There were five questions asked in this section regarding expected time and scale of carbon capture deployment. For each question, one answer could be selected and there were between 35 and 40 respondents to each question. The results from these questions are displayed in Figures 7 to 11.

Figure 7. Carbon capture technology deployment scale results by sector.

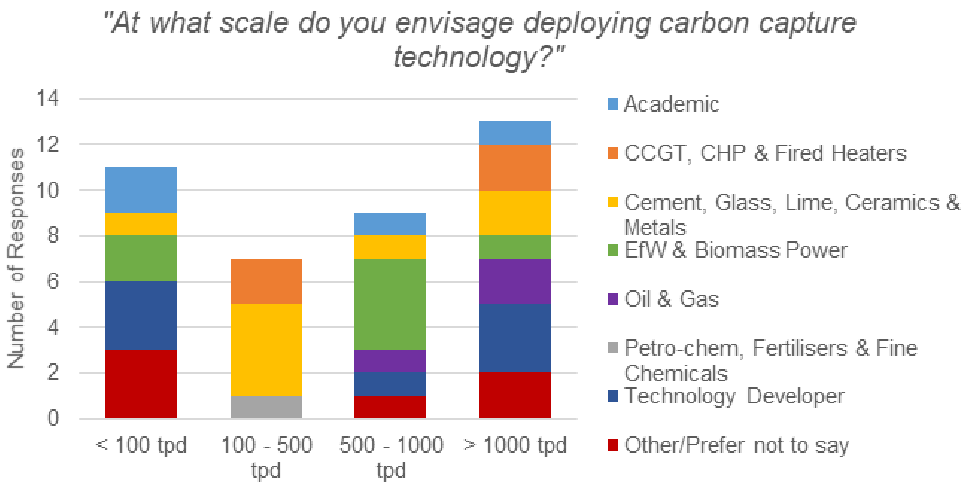


Figure 8. Carbon capture deployment timeline results by sector.

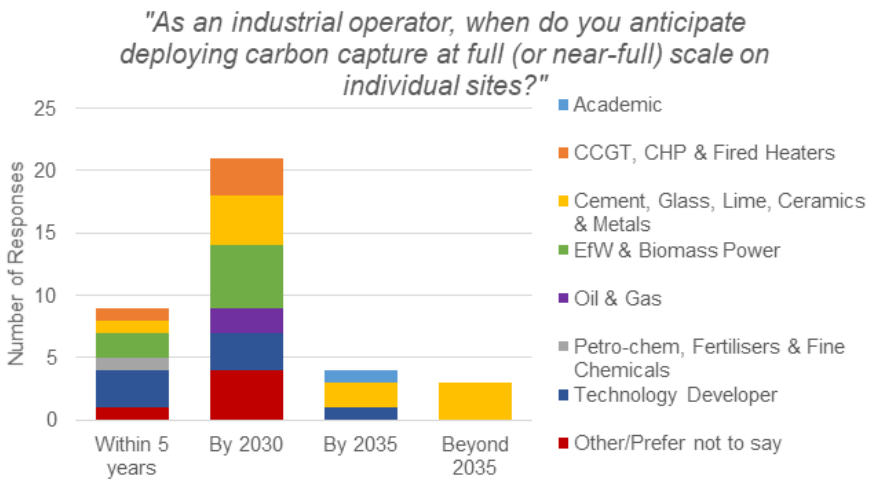


Figure 9. Carbon capture technology demonstration scale results by sector.

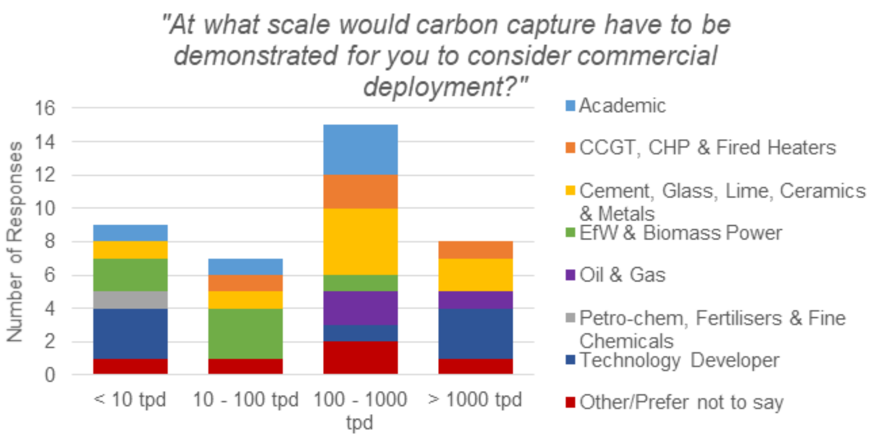


Figure 10. Carbon capture demonstration time results by sector.

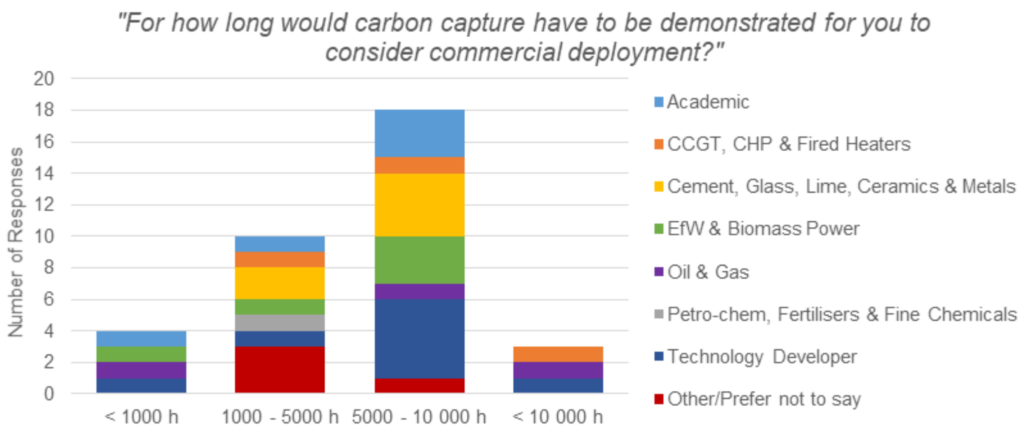
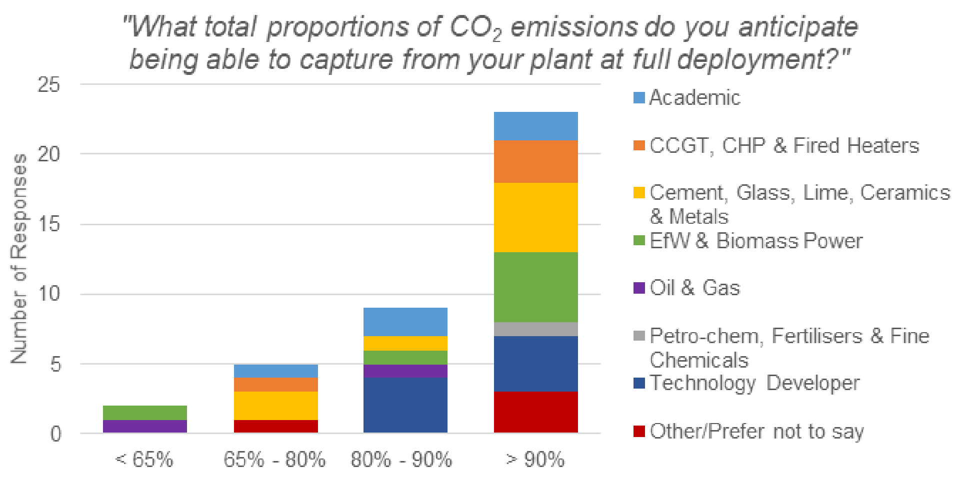


Figure 11. Anticipated CO_2 emissions captured results by industry sector.



9. Abbreviations

Abbreviation	Meaning
3D	3 Dimensional
AFC	Allam-Fetvedt Cycle
BAT	Best Available Technology
BECCS	Bioenergy with Carbon Capture and Storage
BEIS	UK Government Department of Business, Energy & Industrial Strategy
CAP	Chilled Ammonia Process
CAPEX	Capital Expenditure
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat & Power
CES	Clean Energy Systems
CO_2	Carbon Dioxide
CRI	Commercial Readiness Index
DOE	US Department of Energy
EfW	Energy from Waste
EPC	Engineering, Procurement & Construction
EOR	Enhanced Oil Recovery
EU	European Union
FEED	Front End Engineering Design
FID	Final Investment Decision
GCCSI	Global CCS Institute
HSE	Health, Safety & Environment
IEAGHG	International Energy Agency Green House Gas R&D Programme
IP	Intellectual Property
KCC	Kawasaki CO_2 Capture
KEPCO	Kansai Electric Power Company
LEILAC	Low Emissions Intensity Lime and Cement
LHV	Lower Heating Value
MCFC	Molten Carbonate Fuel Cell
MEA	Monoethanolamine
MHI	Mitsubishi Heavy Industries
Mscfd	Thousands of Standard Cubic Feet per Day
MTR	Membrane Technology and Research
MW	Mega Watts
MWe	Mega Watts Electrical
MWth	Mega Watts Thermal
NCCC	US National Carbon Capture Center
NETL	National Energy Technology Laboratory (of US Department of Energy)
NOK	Norwegian Krone
NZIP	Net Zero Innovation Portfolio
O&M	Operating & Maintenance
OPEX	Operating Expenditure
PCC	Post Combustion Capture

PSA	Pressure Swing Adsorption
RFCC	Refinery Residue Fluid Catalytic Cracker
TCM	Technology Centre Mongstad
tpd	Tonnes per Day
tpa	Tonnes per Annum
TRL	Technology Readiness Level
TSA	Temperature Swing Adsorption
UK	United Kingdom of Great Britain and Northern Ireland
UPLC-MS	Ultra-Performance Liquid Chromatography - Mass Spectrometer
US / USA	United States of America

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