Environmental impacts of emerging carbon capture technologies for industrial decarbonisation

Chief Scientist’s Group report

October 2025

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Dr Robert Bradburne
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Executive summary

Carbon Capture Technologies (CCT) and industrial decarbonisation are an important part of the Government's Net Zero Strategy. CCT are a group of engineered processes used to remove carbon dioxide (CO_2) from industrial flue gases to prevent its release into the atmosphere. The captured CO_2 can either be utilised or stored underground, thereby mitigating the continued use of fossil fuels for heat and power in the absence of other options. Government funding to boost development of UK capacity in CCT across these applications by 2030 amounts to £20 - 30 billion over the remainder of this decade.

In 2022, the Department for Business, Energy, and Industrial Strategy (BEIS) published a review of next generation CCT, which focussed on the potential performance of these technologies rather than their wider environmental impact. Using this earlier report as a starting point, this study collates and reviews evidence on the potential environmental and health impacts of emerging systems and novel applications of CCT from the published scientific literature covering January 2020 to March 2024. In addition, this study reviews the emerging trends and technologies since the BEIS study, and whether the implementation of these technologies may differ across industrial sectors.

Innovations in CCT for Industrial Decarbonisation

Many options have been proposed for CCT, although few of these have been commercialised. Most research on CCT technologies is centred around conceptualisation, laboratory-scale, and pilot-scale. Many technologies have yet to consider the engineering, environmental, and cost challenges associated with scaling-up to commercial readiness.

There are several common factors driving innovation in CCT. The main influences on the speed of uptake are capital cost, energy penalty, and the ability to retrofit to existing industrial infrastructure. However, several additional drivers have been identified including a move to less-hazardous technologies (environmental and operational) and systems that are more robust to cope with operational conditions and other hazards within flue gases. The former appears particularly relevant to amine-based CCT, where concerns about amines and their breakdown products have been reported for many years.

Trends for Sector-by-Sector CCT

Although the power sector is often seen by researchers to be at the forefront of efforts to reduce CO_2 emissions from fossil fuels, other industries such as the cement, iron and steel, and petrochemical sectors make significant contributions to global emissions. Three options for decarbonisation were identified across a wide range of industrial sectors:

- Source control, which includes energy substitution and improved efficiency
- Process optimisation to improve manufacturing efficiency
- CCT deployment

It was considered that different industrial sectors are likely to be more or less reliant on one or more of these options. Although some energy intensive industries will achieve decarbonisation only by coupling their energy use with efforts made by the power sector.

Other key drivers for differences in the implementation of CCT between different industries were found to include: the characteristics and composition of the flue gas (and most notably the CO_2 concentration), the balance of capital and operational costs for deployment of CCT, and other practical factors such as the degree to which sources within a plant can be readily combined for treatment. Several research studies noted that pre-combustion offers lower operating costs and potential reductions in harmful emissions, but at the expense of much higher capital costs and challenges with retrofitting.

According to the studies reviewed, the sectors with the most developments at 0.2 Mt CO_2 pa and above are power (coal, gas, and oil), chemicals (biofuels and fertilisers), and oil and gas refining.

Environmental Impacts of CCT

There is a limited amount of information on the wider environmental impacts of CCT reported in the literature beyond considerations of the energy penalty (the amount of additional energy needed to run the CCT plant at a given capture rate) and water use. Mostly, this reflects a lack of operational experience and reporting, with most research focusing on conceptual/modelled designs and bench-scale experiments. While life-cycle analysis is undertaken to compare several CCT options in different industrial situations, the standardised methods for reporting outcomes such as chemical toxicity often limit the detail provided to a single index or chemical standard. In many cases, the only emission of interest is CO_2 itself.

Environmental impacts in this review were grouped in this review into four areas:

- Mitigation of CO_2 emissions – capture efficiency and the energy penalty
- Resource use – principally water
- Environmental emissions – mainly to air and water
- Waste management – solid and liquid wastes

In some areas, reducing the environmental impact is aligned with reducing costs (a major driver for innovation), and are subject to considerable interest as a result. For example, reductions in the energy penalty or improvements in the capture efficiency through process design or integration with low carbon energy sources was commonly reported. Impacts that either depend on operational experience or are not associated with significant cost reductions such as waste management were rarely considered. Many studies at bench- or even pilot-scale failed to consider the emissions or waste management challenges associated with scaling-up for commercial use.

Capture efficiency is widely reported for different technologies, although most of the evidence comes from pilot-scale studies. Efficiencies are often greater than 80% with limited variation between industrial sectors (reflecting a lack of data). In the case of amine-based systems, where operational experience is available, the capture efficiency achieved in practice is lower than that promised by designers due to teething problems with continuous plant operation.

Similarly, energy penalties were also found in the available literature for some, but not all, CCT. In general, post-combustion options have the highest penalties, and pre-combustion options the lowest. Some technologies appear well-suited to specific industries, for example, the implementation of calcium looping in the cement sector. This is especially true where the products of a CCT plant can be utilised within the production process or where energy management is seen as complimentary.

Issues for resource use identified in the scientific literature almost exclusively focus on the need for water, either for processing/transporting (such as a solvent carrier) or cooling. It is clear that the demand and availability of water represents a significant challenge for many CCT processes, especially post-combustion plants.

Reducing emissions is identified as a design goal for several innovations in amine-based capture systems where the hazard from emissions has been previously identified. Amine emissions remain a challenge for current systems, but several options including new solvent blends and better engineering have been proposed to address it. If the time gap between hazard identification and design innovation for amine-based systems is reflected in other CCT development pathways, then it is perhaps unsurprising that so little research attention has been paid to it to date. Some CCT options in development were identified within the literature as posing a lower environmental risk than current amine-based technologies, but one reason for this was considered to be the lack of operational experience with these alternative technologies at full-scale.

Recommendations

The main issue to emerge from this review was the lack of available information on the wider environmental impacts of different technologies and the broad lack of prioritisation of such issues within design goals. The following recommendations are aimed at addressing this:

- Early engagement with researchers to raise awareness of wider environmental impacts in the evaluation and design of innovative CCT
- Review implementation of related technologies in other industrial sectors to examine the potential to read across to CCT for a range of operational issues, for example, how waste management has worked for membranes used by other industries
- Engage with regulators and operators in other countries, where plants have been operating at either demonstration or commercial scales, to better understand emission and waste management issues for a range of technologies

Introduction

This report collates and reviews evidence on the potential environmental and health impacts of emerging systems and novel applications of carbon capture technologies (CCT) for industrial decarbonisation. CCT are a group of engineered processes used to remove carbon dioxide (CO_2) from industrial flue gases to prevent its release into the atmosphere. The captured CO_2 can either be utilised or stored underground, thereby mitigating the continued use of fossil fuels for heat and power in the absence of other options.[1]

CCT systems and industrial decarbonisation are an important part of the Government's Net Zero Strategy (BEIS 2021a). It has potential uses in production of low carbon power (DESNZ 2023), industrial decarbonisation (BEIS 2021b), and in greenhouse gas removals (UKRI 2021) such as direct air carbon capture and storage (DACCS). Government funding to boost development of UK capacity in CCT across these applications by 2030 amounts to £20 - 30 billion over the remainder of this decade.

Many industrial applications of CCT are subject to the Environmental Permitting Regulations 2016 (as amended), where the Environment Agency is the principal environmental regulator (in England) for larger and more complex installations. In assessing the suitability of permit applications and of future monitoring and management arrangements, we need to consider the potential operational emissions (mainly to air and water) and waste management activities at these sites. While our technical knowledge of amine-based solvents has risen sharply in recent years, lesser-known alternatives are now moving rapidly from bench-scale into pilot-scale and demonstration schemes. Knowledge of the potential environmental impacts of these technologies is vital to our strategic planning for future regulatory demands.

Methodology

In 2022, the Department for Business, Energy, and Industrial Strategy (BEIS) published a review of next generation CCT (BEIS 2022), which focussed on the potential performance of these technologies rather than their wider environmental impact. The report identified CCT with the potential to be deployed at scale (around 1 kT CO_2 per day or 0.35 MT CO_2 per year) by 2030, along with less well-developed technologies that were more likely to be deployed at scale from 2035. Other technologies at the research stage were recorded, but

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[1] The whole process of carbon capture is known as carbon capture and storage (CCS) or carbon capture utilisation and storage (CCUS), but this report focuses only on the technologies used to capture CO_2.

it was considered unlikely that they would be scaled-up before 2035. A summary of the definitions used by the report and its key findings are shown in Table 1.

Using BEIS (2022) as a starting point, we undertook a Quick Scoping Review of the published scientific literature from January 2020 to March 2024 (Collins et al. 2015). Further details on the search methodology are set out in Appendix 1. The review identified nearly 700 articles using Scopus, which included more than 100 published in the first quarter of 2024. Further references were identified in following up the initial review – especially when chasing down descriptions of process fundamentals (often described in older articles).

In addition to identifying emerging trends and technologies since the BEIS study, the primary aim of our review was to collate and review the evidence on the potential environmental and health impacts of these novel CCT systems. The review also examined whether the implementation of these technologies may differ across industrial sectors because of the nature and scale of the processes involved (such as differences in flue gas volumes, carbon dioxide loadings, and other physical-chemical characteristics).

Table 1: Next generation CCT according to developmental status (BEIS 2022)

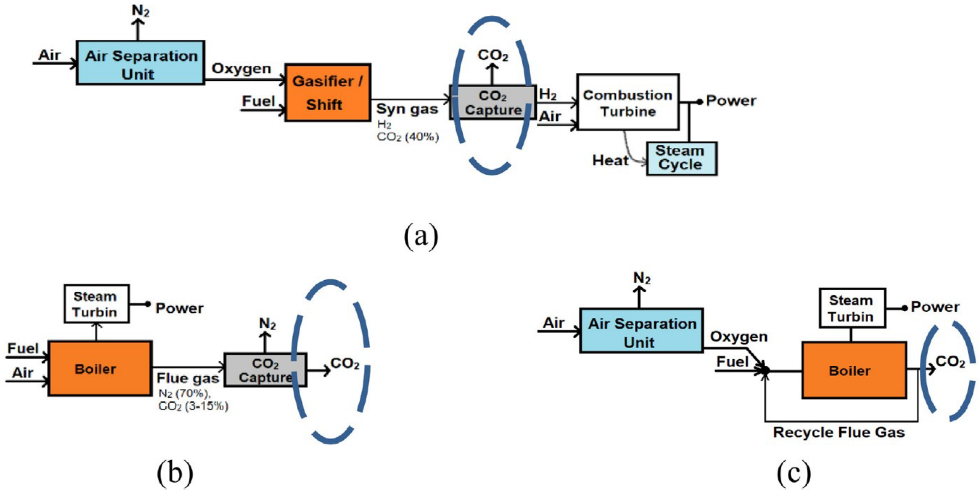
Developmental Status	Number	Technology Types
Demonstration stage. Likely to be deployable at a scale in the order of 1 kT CO_2 per day by 2030. At Technology Readiness Level 8 or higher.	5	All post-combustion systems using amine-based solvents
Development stage. May be deployable at a scale in the order of 1 kT CO_2 per day by 2035. Broadly consistent with Technology Readiness Levels 5 to 8.	17	A range of technologies including non-amine-based solvents, solid sorbents, membranes, fuel cell technology, cryogenics, calcium looping, and oxy-combustion processes.
Research stage. Broadly consistent with Technology Readiness Levels 1 to 4.	76	A mix of novel solvents (n=28) and sorbents (n=18), membranes (n=22), and others (n=8)

Overview of Emerging Technologies

Carbon Capture technologies (CCT) are a group of engineered processes used to remove carbon dioxide (CO_2) from industrial gases. Most often this is flue gas (sometimes called exhaust gas or stack gas), which is the hot gas released by industrial combustion of fossil fuels and contains the reaction products of fuel and air. Combustion processes are mainly used for electricity generation, but they are also used in a wide range of other industrial applications including heating and drying, and for generating steam in boilers to operate equipment and to provide mechanical power using gas turbines. Captured CO_2 can be compressed for either long-term geological storage or utilisation by others such as the food industry.

Three main approaches to CCT are frequently set out in the available literature, as shown in Figure 1 (Ganeshan et al. 2023, Larki et al. 2023, Rajabloo et al. 2023). In **pre-combustion**, CO_2 is captured and removed prior to the combustion process. For example, CO_2 may be isolated from the syngas produced from biomass and coal gasification before the fuel is burned (Gautam and Mondal 2023). Partial oxidation or steam reforming of the carbonaceous fuel at very high pressures in a gasifier results in an enriched mixture of carbon monoxide (CO) and hydrogen (H_2). After impurities such as ash have been removed, the CO is converted to CO_2 in a water gas shift reactor and separated from the H_2 gas, which is then used as a fuel for the power turbine. Pre-combustion capture produces a more concentrated CO_2 stream (around 45% by volume), while requiring less space for equipment, and reducing costs and water consumption (Gautam and Mondal 2023). However, take up has been limited because pre-combustion systems cannot be retrofitted to many facilities. Global uptake was reported as slow because integrated gasification combined cycle (IGCC) power plants were more costly to construct than other power plants (Gautam and Mondal 2023, Joel and Isa 2023). In **post-combustion**, CO_2 is captured from the combustion flue gas, where it is present at much lower concentrations (between 4 and 18% by volume). This was considered the most common approach proposed for industrial decarbonisation by reviewers with the potential to be more easily retrofitted to a wide range of facilities and plant designs. Its major drawback was considered to be the lower CO_2 levels in the flue gas making capture and recovery processes less efficient and more energy intensive (Gautam and Mondal 2023). In **oxy-fuel combustion**, a special case of the post-combustion approach using either an air separation unit to pretreat and oxygenate the combustion gases or a chemical oxidising agent, the flue gas consists of a highly enriched CO_2 stream (approximately 80 – 98% by volume) and water. In this latter process, the water is condensed and removed leaving a pure CO_2 stream. While capture efficiency was considered high (nearly 100%), there was a significant energy cost reported for air separation to produce the enriched oxygen for the process (Gautam and Mondal 2023).

Figure 1: Simple schematics of (a) pre-combustion, (b) post-combustion, and (c) oxy-combustion CCT.



(a)

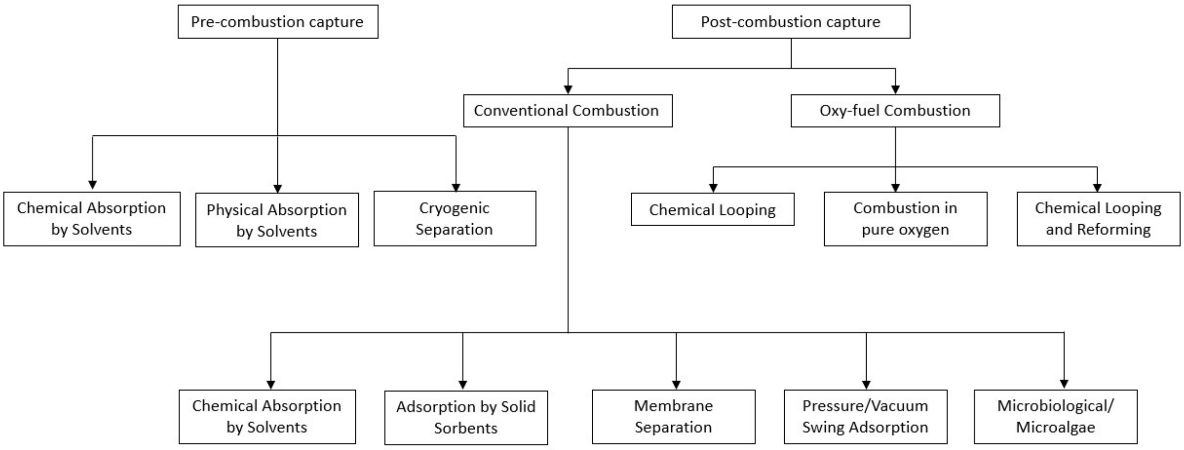
(b)

(c)

Reprinted from RAJABLOO T., VALEE J., MARENNE Y., COPPENS L., DE CEUNINCK W., 2023. Carbon capture and utilization for industrial applications. ENERGY REPORTS, 9, pp. 111-116, with permission from Elsevier.

Within these three main approaches, a range of CCT systems were identified (including Ganeshan et al. 2023, Gautam and Mondal 2023, Larki et al. 2023, Peu et al. 2023, Shahbaz et al. 2021) and have been summarised in Figure 2. These systems are described in more detail in subsequent sections. While discussed individually, some research studies proposed solutions that integrated two or more of these options (Soepyan et al. 2024).

Figure 2: CSS options for industrial plants.



Adapted with permission from SHAHBAZ M., ALNOUSS A., GHIAT I., MCKAY G., MACKEY H., ELKHALIFA S., AL-NASARI T., 2021. A comprehensive review of biomass based thermochemical conversion technologies integrated with CO_2

capture and utilisation within BECCS networks. RESOURCES, CONSERVATION & RECYCLING, 173, art. no. 105734, with permission from Elsevier.

According to Yagmur Goren et al. (2024), there were around 40 commercial CCT facilities operating around the globe in 2023, with an annual capture capacity of 45 Mt CO_2 pa, and around 500 projects at various stages of development. Many systems were based on chemical absorption using amine solvents.

Absorption by Solvents

Solvent absorption, a pre- and post-combustion option for conventional combustion plants, was considered by most researcher studies to be one of the most mature technologies (Shahbaz et al. 2021, Gautam and Mondal 2023, Kammerer et al. 2023, Rezaei et al. 2023). Solvents include solids, liquids, and hybrid forms. Allangawi et al. (2023) observed that liquids were considered the most economical for gas streams with a lower CO_2 content because of their higher selectively, while solids were considered more cost-effective at higher CO_2 concentrations in the flue gas. Solids in general were noted as compact, having a high absorption speed and greater CO_2 binding capacity per unit volume than liquid solutions (Kammerer et al. 2023).

Solvents separate CO_2 from other gases by either physical or chemical mechanisms (Kammerer et al. 2023). Once the CO_2 has been separated, the absorption process is reversed to recover a concentrated stream of CO_2 and to regenerate the solvent.

Allangawi et al. (2023) suggested that the ideal properties of a solvent for carbon capture were low manufacturing cost, a high absorption rate and a high capacity for absorbing CO_2, a low regeneration energy requirement (salts formed from capture must be unstable at regeneration temperature and pressure), non-corrosive and good handling characteristics, and a high chemical and thermal stability. However, the authors considered that no ideal solvent was currently available, and most researchers were still trying to find one. Low toxicity was not specifically highlighted.

An overview of the main options available at demonstration or commercial scale are summarised in the following sections. A final section under each category describes systems that are not yet at demonstration scale according to the scientific literature reviewed, but they are generally considered to be areas of active research.

Chemical Absorption Solvents

In this group of technologies, a chemical reaction takes place between the solvent and CO_2 (Kammerer et al. 2023, Shahbaz et al. 2021). Energy is required to reverse the reaction, producing a high purity (>99%) CO_2 stream. Most systems work broadly in the same way as illustrated by an amine-based system in Figure 4. In the absorber, contact between the flue gas and solvent leads to absorption of CO_2 by the solvent. The CO_2

depleted exhaust gas is subsequently treated (such as to remove other impurities and entrained solvent) and discharged. The enriched CO_2 solvent moves to the stripper, where CO_2 is released from the solvent, cleaned and captured, and the solvent is then regenerated/recycled and returned to the absorber. Amine-based chemical absorption using a liquid solvent was considered by most reviewers to be the most commonly used commercial process in post-combustion CCT.

Alkali-based systems

One of the most important examples of an alkali-based system described in the literature is the Benson and Field (BenField) process, originally developed for the synthesis of liquid fuel from coal (Borhani et al. 2015, Kammerer et al. 2023). It is applied at commercial scale in hundreds of plants worldwide for the selective removal of hydrogen sulphide (H_2S) and CO_2 from ammonia synthesis gas, crude H_2, natural gas, and town gas.

Alkali-based solvent systems have theoretically at least lower regeneration energy costs than amine-based systems (see below) because of the more favourable thermodynamics of the absorption reaction. However, Rezaei et al. (2023) noted that these reactions are kinetically slower, which results in larger absorption and stripper towers. Various additives may be used to promote and speed up the reaction, some of which may be emitted from the stack, and/or released in solid and liquid wastes (see below).

In the absorber, the flue gas passes through a hot aqueous solution of potassium carbonate (K_2CO_3), which also potentially contains a promoter and a corrosion inhibitor (Borhani et al. 2015). Borhani et al. (2015) suggested that plants typically operated at pressures between 3,000 and 6,000 kPa and at a temperate of around 100 - 140˚C. The high operating temperature is maintained throughout the system and maximises the solubility of K_2CO_3 in the solvent solution. The fundamental absorption reaction is shown below (Borhani et al. 2015, Kammerer et al. 2023):

$$CO_2 + H_2O + K_2CO_3 \rightleftharpoons 2KHCO_3$$

In the stripper, which operates at a lower pressure of around 80 kPa, the reaction is reversed, releasing the CO_2 and regenerating the K_2CO_3 (Borhani et al. 2015). This regeneration results from the reduction in operating pressure in the stripper as absorption/desorption is driven by the partial pressure of CO_2 in the gas phase.

The typical concentration of K_2CO_3 in the solution was reported to be around 30% by weight (Borhani et al. 2015). Due to the highly corrosive solution used in the absorber, an inhibitor such as vanadium pentoxide is usually added to protect the steel surfaces of the operating plant. Promoters are also added to speed up the slow reaction including the use of various amines (see also amine-based systems) and inorganic compounds such as arsenic trioxide, vanadic acid, and arsenious acid (Borhani et al. 2015). Amines such as piperazine (PZ) were also shown to be an effective promoter to increase CO_2 capture (Kammerer et al. 2023, Khan and Kim 2024), as well as biological enzymes such as carbonic anhydrase (Borhani et al. 2015).

Other alkali-based salts were also mentioned in the literature including potassium, sodium, and calcium hydroxide, and amino acids (Gautam and Mondal 2023). Amino acids, which contained both amine and carboxylic acid groups, also formed salts with potassium hydroxide and ammonia, and were considered a potential alternative to carbonate salts (Gautam and Mondal 2023).

Amine-based systems

Amines are considered to fulfil many of the ideal solvent characteristics (Allangawi et al. 2023), being relatively cheap to manufacture, as well as absorbing CO_2 at relatively low temperatures (40 - 75˚C) and at atmospheric pressures (Gautam and Mondal 2023). Amine-based carbon capture systems are viewed as one of the most mature technologies (Shahbaz et al. 2021, Gautam and Mondal 2023, Rezaei et al. 2023, Wu et al. 2024). They were originally developed for the clean-up of natural gas (Wheatley et al. 2019), but they were also used in fertilizer and soda ash manufacturing (Dziejarski et al. 2023). Amine-based post-combustion systems were the most common option reported at demonstration scale in the UK (BEIS 2022). Rezaei et al. (2023) suggested that amine-based systems were at Technology Readiness Level (TRL) 8 – 9. Vinjarapu et al. (2024) reported numerous pilot schemes operating around the world using amine-based systems, including coal-fired, gas-fired, and energy from waste power plants.

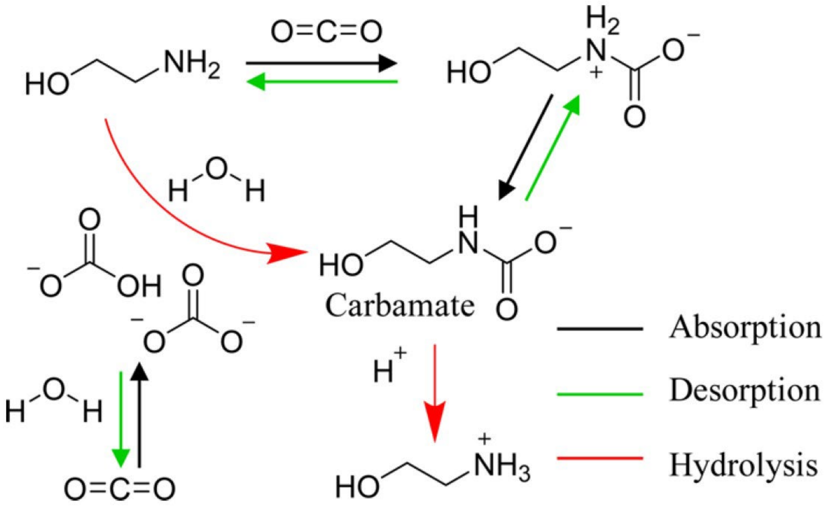
Amine-based systems strip out CO_2 from other gases through a series of reversible chemical reactions (Shahbaz et al. 2021). Monoethanolamine (MEA) was the primary solvent used by earlier systems, where the complex reactions occurred in aqueous solution (usually at a concentration between 20 – 30% by weight). Secondary alkanolamines had also been used, mainly diethanolamine (DEA), diethylene glycol amine (DGA), and di-2-propanolamine or DIPA (Wu et al. 2024). Compared with MEA, secondary alkanolamines have a higher boiling point, lower degradation losses, and a similar absorption capacity. A tertiary alkanolamine such as N-methyldiethanolamine (MDEA) has a higher CO_2 solubility and thermal stability under medium and high pressures. Wu et al. (2024) noted that in terms of absorption capacity, the general trend for amines was primary amine < space-site barrier amine < secondary amine < tertiary amine < diamine. It was also noted by the same authors that amines with the highest carrying capacity had the slowest reaction rates. Wen et al. (2024) suggested this often led to the use of a blend of primary and tertiary amines with the former used as an activator to speed up reaction rates.

Although the exact capture mechanism is not yet established (Lv et al. 2015), the most likely route of CO_2 absorption for MEA is thought to be mediated by the formation of a zwitterion (an ionised molecule containing both a positive and negative charged functional group) and the generation of a carbamate complex (see Figure 3). The reaction pathways vary due to CO_2 loading in the solution, which itself depends on its concentration in the flue gas. The CO_2 is recovered by heating the spent solvent, which releases it from the carbamate complex and regenerates the MEA. Shahbaz et al. (2021) concluded that MEA had proven to be the most efficient amine solvent in commercial use, achieving more than 90% CO_2 removal rates.

While not inherently corrosive to steel and other construction metals, amine solutions become more aggressive after absorption of acidic gases because of a complex mixture of various ions acting as oxidising and reducing agents (Wu et al. 2024). For example, the main source of corrosion in a water-MEA mixture was considered to be the formation of the bicarbonate anion (HCO_3^-). As a result, a range of corrosion inhibitors have been added to the solvent solution including sodium sulphate, copper carbonate, sulfoxide, sodium sulphide, and various hydrocarbons.

Other technical challenges with aqueous amine scrubbers, identified in the available literature, included their water demand, poor oxidative stability in the presence of oxygen and their oxidative degradation in the presence of other chemicals in the flue gas such as sulphur and nitrogen oxides (Forse and Milner 2021, Rezaei et al. 2023, Wu et al. 2024). In addition to oxidative degradation, amines also thermally degraded at the high temperatures found in the strippers (100 - 140˚C) and heat exchangers with increased risk of degradation at higher CO_2 loading rates (Gautam and Mondal 2023). In a study cited by Wu et al. (2024), DEA was reported to have the highest degradation losses (up to 50%) under test conditions, while 2-amino-2-methylpropanol (AMP) was the most resistant. Adding ethanol to the amine-water mix was reported to inhibit amine degradation. Vinjarapu et al. (2024) outlined the operation of an amine-based CCT at pilot-scale for an energy-from-waste plant in Copenhagen. They noted the need to treat the off gas from the stripper to remove entrained MEA with a water wash followed by an acid wash (using 0.1 M sulphuric acid).

Figure 3: Potential mechanism for the capture of CO_2 by MEA.



Reprinted with permission from LV B., GUO B., ZHOU Z., JING B., 2015. Mechanisms of CO2 Capture into Monoethanolamine Solution with Different CO2 Loading during the Absorption/Desorption Processes. ENVIRONMENTAL SCIENCE & TECHNOLOGY, 49, 10728−10735. Copyright 2015 American Chemical Society.

Wu et al. (2024) reviewed the recent literature to identify the most popular approaches taken to optimise the existing amine-based systems. Although focused on the use of alkanolamines, many of the innovations are broadly applicable to other amines. The key methods investigated and employed were (Karami et al. 2024, Wu et al. 2024):

- Development of new absorbents with higher and faster CO_2 absorption rates and capacities, and low regeneration energy consumption,
- Analysis of the material, temperature, and energy distribution within the process using thermodynamic methods to finetune the whole capture operating system,
- Optimisation of the existing approach, for example, by changing the absorbent feed mechanism to achieve more efficient capture, and
- Introduction of energy-saving equipment such as heat pumps or by coupling the process with solar power or other low carbon energy sources to improve efficiency.

Much of the technical developments in amine-based systems seek to overcome issues with MEA including optimisation of the existing process to reduce or offset the energy cost, increase the rate of absorption (which decreases the size of the absorber), and finding alternative solvents with better overall characteristics (Allangawi et al. 2023, Karami et al. 2024, Liu et al. 2024b, Shahbaz et al. 2021, Wu et al. 2024, Zeng et al. 2024). Catalysts have been proposed to increase absorption rate such as nanoporous crosslinked polymers based on benzene, polystyrene, and carbazole (Karami et al. 2024) and to improve the performance of regenerated solvents such as through the use of tungsten trioxide (Barzagli and Mani 2021). Other novel amines evaluated at scale include piperazine (Dziejarski et al. 2023, Leung et al. 2014). Sharma et al. (2020) highlighted several pilot studies, where adding a heat stable form of carbonic anhydrase to an existing solvent system such as MEA, MDEA, and PZ resulted in enhanced solution uptake of CO_2.

As a less energy intensive alternative to thermal regeneration of the solvent, electrochemical processes have been investigated at bench scale (Hassan et al. 2024). Of the main processes researched, electrochemically mediated amine regeneration (EMAR) is possibly the most advanced with extended lab-based trials (up to 100 hours of continuous operation). Hassan et al. (2024) demonstrated a bench-scale system using copper electrodes and a copper / sodium sulphate electrolyte.

Another reported innovation to reduce energy costs involves changes to the carrier (which in most reported systems to date is water). Wu et al. (2024) reported that alcohol had been added to the amine-water solution in some novel systems, which greatly improved the CO_2 desorption rate in the stripper. There was also a general trend to evaluate other carrier organic solvents (Wu et al. 2024). Allangawi et al. (2023) noted that some researchers had opted for a non-aqueous carrier for the amine such as 2-methoxyethanol or 2-ethoxyethanol, which again reduced the energy cost of regeneration because these organic liquids had a lower heat capacity than water. The mixing of alkanolamines with ionic liquids was also proposed, which due to their low vapour pressure and volatility, lowered the risk of solvent loss and other harmful transformations. Wen et al. (2024) investigated use of amino acid based ionic liquids at bench-scale, where the amine functional groups were used as activators to improve CO_2 solubility. Some researchers highlighted that due to their much higher viscosities, use of ionic liquids led to slower mass transfers (Wu et al. 2024). However, Madugula et al. (2024) modelled the use of amine and ionic liquid blends, showing that the blended solvent had a much lower viscosity compared to the pure ionic liquid. Shavalieva et al. (2021) highlighted the potential of phase-change solvents, where the separation was triggered by either a change in temperature or reaction with CO_2. The phases formed were CO_2-rich and CO_2-lean, the latter recycled back to the absorber. Liquid-liquid phase separation was the more active research area because of its potential to be retrofitted to existing amine-based systems. Aqueous based solvents included dipropylamine, butane diamine, and solutions of amino acid salts such as sodium glycinate, potassium taurate, and potassium alanate. Zhang et al. (2019) noted that deployment of phase-change solvents reduced the energy needed for separation and recovery of CO_2 by up to 30% compared with an MEA-based system.

Another innovation reported in the literature was the blending together of one or more amines to enhance CO_2 capture (Allangawi et al. 2023, Gautam and Mondal 2023, Wen et al. 2024, Wu et al. 2024), although these systems were often considered costly and highly corrosive. Blending takes advantage of different reaction pathways between amines and CO_2 (Wheatley et al. 2019). While the most important reaction pathway for MEA and similar primary amines is via the carbamate complex, a bicarbonate mediated reaction occurs simultaneously, although at a much slower rate. While the slower reaction has one significant disadvantage (the need to increase the size of the absorber column), the bicarbonate pathway also has a number of advantages over the carbamate route including a one-to-one reaction stoichiometry (one amine molecule captures one CO_2 molecule) and a lower complex stability.[2] As a result, the bicarbonate pathway produces higher concentrations of captured CO_2 and requires less energy to release the CO_2 and regenerate the amine. Using a tertiary amine such as MDEA or a molecule with steric hindrance to carbamate formation such as AMP increases the contribution from the bicarbonate pathway. Blending involves simultaneously exploiting the fast and slow absorption pathways to produce a more efficient capture effect (Wheatley et al. 2019). Gautam and Mondal (2023) reported that an investigation of 40 different amine blends revealed that CO_2 absorption capacity with increasing alkalinity (pKa) was primarily influenced by the tertiary amine component in biphasic solvent systems. Liu et al. (2024d) also investigated the blending of amine-based solvents with physical absorption solvents such as polyethylene glycol dimethyl ether (see also Physical Absorption Solvents) to reduce the energy burden associated with solvent regeneration.

Engineering related system improvements were also reported in the literature including innovations in thermal equipment and mass and energy process flows (Hosseinifard et al. 2024, Julio et al. 2023, Wu et al. 2024, Zeng et al. 2024). Researchers have been examining the temperature and energy distribution of the whole system through exergy

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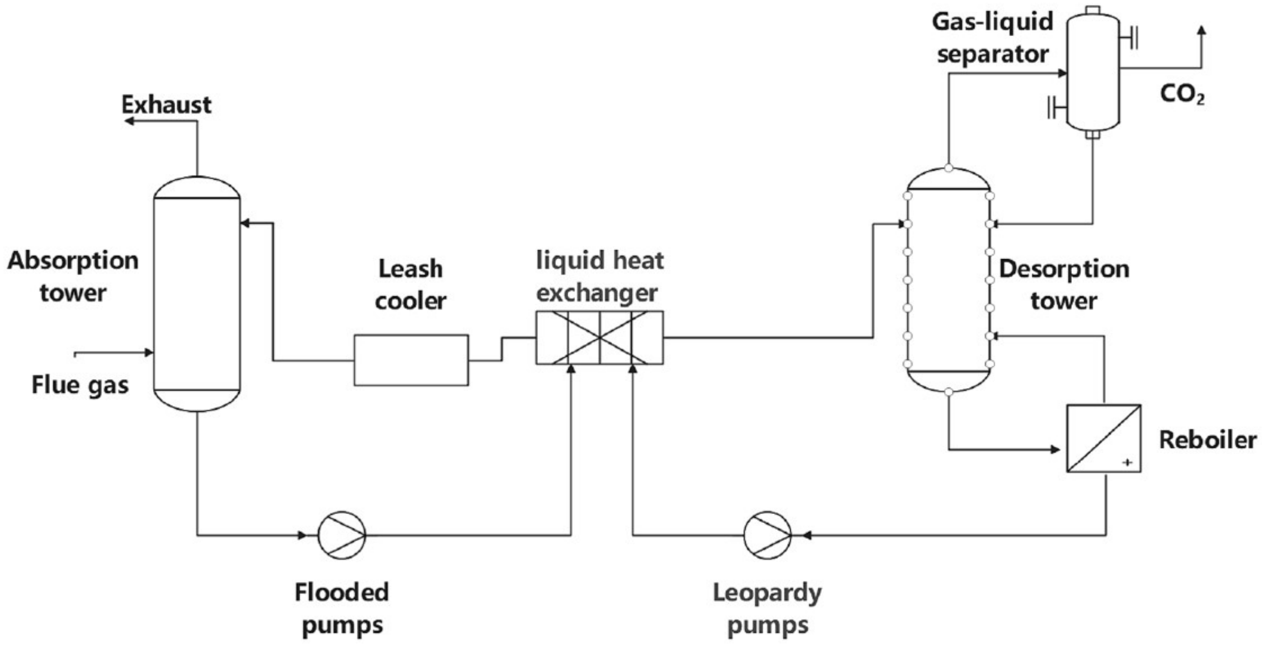
[2] Via the carbamate pathway, two moles of amine were required to capture every one mole of CO_2 (Wheatley et al. 2019).

analysis, pinch point analysis and other methods, to identify and optimise operational parameters.

Joel and Isa (2023) described process intensification as “*Any engineering development that leads to a substantially smaller, cleaner, safer and more energy efficient technology*.” They pointed to process intensification in three areas for post-combustion CCT: (a) reducing equipment size, (b) simplifying tasks by combining multiple processes within a single piece of equipment, and (c) reducing equipment size by reducing its scale and structure. Several pieces of current equipment and future developments have been discussed in the literature for both air – liquid contactors (such as mop fans), air – solid contactors (such as rotating packed and zigzag beds), as well as new sonication-based processes (Shukla et al. 2023).

The main components of an amine-based CCT plant include the absorption tower (the absorber), the desorption tower (the stripper), the cross-heat exchanger, the lean liquid cooler, the gas-liquid separator, the lean (rich) liquid pump, and the reboiler (Wu et al. 2024). Current system designs use a cyclic arrangement between absorber and stripper, where heating and cooling is required (see Figure 4). Solvent rich in CO_2 exits the absorber and needs heating prior to entry to the stripper, while conversely the rejuvenated lean solvent exiting the stripper requires cooling before it re-enters the absorber. In terms of mass flow, flue gases enter the absorber at the bottom and exit as exhaust gas at the top. Saturated solvent exits the bottom of the absorber and is pumped through the heat exchanger to the top of the stripper and lean solvent is recycled from the bottom. The distribution of heat throughout the system, greatly affects the capture and regeneration efficiency of the solvent (Wu et al. 2024). The energy needed for heating and cooling, and the mass transfer of liquids throughout the cycle, comes from the power plant, and therefore reduces the efficiency of power generation. Innovations have been investigating if this system could be optimised to operate the plant more energy efficiently.

Figure 4: Main components of an amine-based CCT system.



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Wu et al. (2024) summarised a number of the options considered, which included analysis and modelling of energy and mass distribution within the CCT and between the CCT and the power plant. For example, increasing the concentration of the amine solution resulted in energy efficiencies because it reduced the volume of solvent in the system and allowed slower mass flow. Wu et al. (2024) noted that a 10% increase in MEA concentration from 30 – 40% by weight resulted in a 10% energy saving, but this proportional saving reduced with further increases in MEA concentration. Oxidative solvent degradation was also noted to increase as solvent concentration increased.

Engineering innovations in absorber towers have also been proposed to improve capture and energy efficiency (Wu et al. 2024). For example, packed towers were considered better than plate towers, although both designs were currently used, while a proposed spray tower design showed great promise. Parmar et al. (2024) investigated the impact on absorption and solvent evaporation from the presence of neighbouring droplets in the absorber to optimise spray performance. Wardhaugh et al. (2024) reported the development of a rotating liquid sheet contactor, where gas passed between multiple liquid sheets formed at the outlet of helical slots in a rotating central feed tube. It was suggested that flow rate and operating temperature in the absorber were also parameters that could be optimised for effective absorption (Wu et al. 2024). Research had shown that installing an inter-cooler at different stages in the tower and/or injecting flue gases and lean solvent at different levels ensured better process control of solvent temperature and minimised hot spots (Wu et al. 2024).

Most recent stripper designs are plate towers with a trade-off between capital costs and regeneration efficiency (the more plates, the greater the cost). Considering the cooling water circulation, reboiler heat load, separation accuracy, tower height, equipment specifications and other factors, the optimal theoretical plate number of a plate desorbing tower was considered by researchers to be 24 (Wu et al. 2024). Another key parameter was the temperature of the rich solvent entering the stripper. If the temperature difference of the rich solvent increased (or decreased) by 10%, energy consumption increased (or decreased) by 5% (Wu et al. 2024). The operating pressure in the stripper was also considered an important parameter since an elevated pressure raised the solvent boiling point and increased the CO_2 mass transfer rate from liquid to gas phase. When the operating pressure of the stripper was 220 kPa, the regenerative energy consumption value was minimised (Wu et al. 2024).

The main direction for research to improve stripper efficiency was reported to be optimisation of the heat source including direct steam desorption and heat pump technology (Wu et al. 2024). Direct steam injection into the stripper negated the need for the reboiler, while pinch analysis had shown that using a supercritical CO_2 recirculating heat pump to supply the heat for desorption effectively reduced the regeneration energy consumption. Alternative sources of energy for heating and cooling the solvent in both the absorber and the stripper were also being investigated including use of low carbon sources such as solar power (Wu et al. 2024).

Wu et al. (2024) noted that many of the proposed solvents and improved system designs were either at bench-scale or were mostly theoretical, respectively. They concluded that considerable work was still required to engineer and scale-up many of the innovations.

Calcium Looping

In the calcium looping method (Kammerer et al. 2023, Tan et al. 2024), solid sorbent (calcium oxide, often crushed limestone) circulates between two connected fluidised bed reactors (see Figure 5). Flue gas from combustion enters the carbonator and reacts with calcium oxide (CaO) to form calcium carbonate ($CaCO_3$):

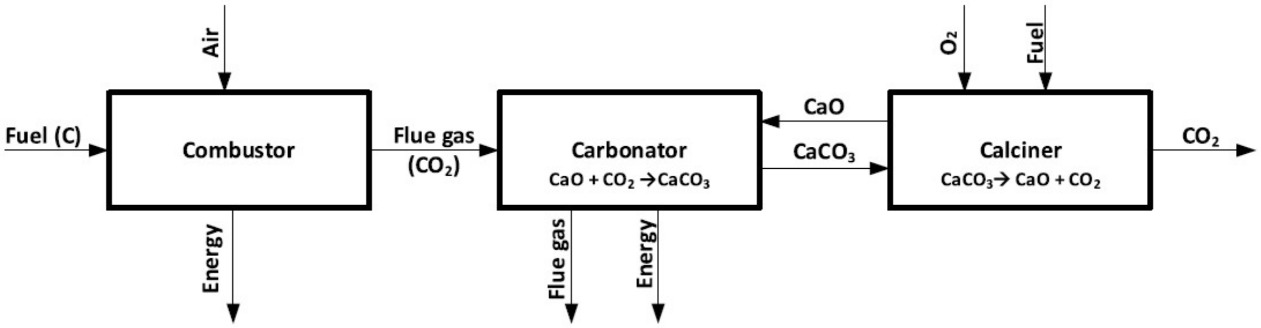
$$CaO + CO_2 \rightarrow CaCO_3$$

The $CaCO_3$ moves to the calciner, where it is heated to reverse the reaction and recover a pure stream of CO_2 (Kammerer et al. 2023):

$$CaCO_3 \rightarrow CaO + CO_2$$

Although the formation of calcium carbonate is an exothermic reaction, Kammerer et al. (2023) noted that the CO_2 reacts faster with the CaO if heated to around 580 to 700 °C. However, if the temperature is too high, the reaction stalls. In the calciner, the endothermic reverse reaction takes place at higher temperatures. Tan et al. (2024) summarised the experience from pilot-scale plants from around the world, noting that the typical operating temperatures were from 600 – 700 °C in the carbonator and from 800 – 1000 °C in the calciner. Although these temperatures had reported advantages over other solvent/sorbent systems in terms of a lower energy penalty (around 4 – 7%), Tan et al. (2024) noted that intense sintering resulted in the gradual collapse of the porous structure in the CaO, leading to reduced sorbent surface area and particle agglomeration.

Figure 5: Diagram of a calcium looping system.



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Sulphur dioxide (SO_2), a component of flue gas, reacts irreversibly with CaO to form the corresponding calcium sulphate (Kammerer et al. 2023), which reduces capture efficiency. In addition, other sintering processes caused by high steam and CO_2 pressure during calcination have been found to reduce the effectiveness of regenerated sorbent.

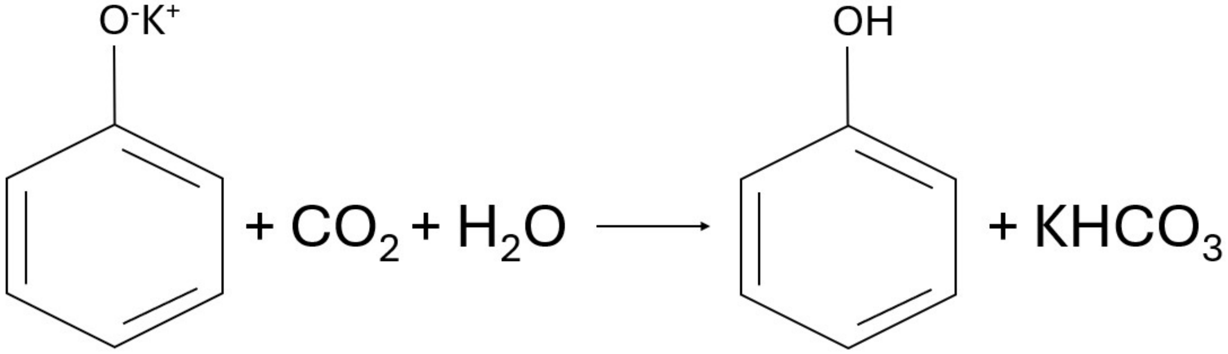
Tan et al. (2024) considered that calcium looping was at TRL 7 with a demonstration system operating at 20 MWt-hour at the Technische Universität Darmstadt in 2018. They noted that the flue gases entering these test systems contained around 12-15 % CO_2 by weight, although up to 35% CO_2 by weight was reported from a cement plant. Tan et al. (2024) stated that typical capture efficiencies were around 90% and higher. A key operational issue was reported to be the movement of materials between the carbonator and calciner including sustained transfer rate and the impact of particle compaction and abrasion. Innovations in calcium looping have focused on improving the CaO sorbent including the evaluation of different limestone sources, and the use of steam reactivation and/or thermal pretreatment to stabilise and activate the surface properties of the sorbent (Kammerer et al. 2023, Tan et al. 2024). Tan et al. (2024) also commented that indirect heating of the calciner was seen as advantageous because the more uniform and milder heating process extended the working life of the sorbent.

Carboxylic acid-based systems

In amine-based systems, capture occurs via both a carbamate and a bicarbonate pathway (see above). While there are considered many advantages to capture proceeding via the bicarbonate intermediate complex, the reaction is considerably slower and requires a much larger absorber column (Wheatley et al. 2019). Since many industrial amines are corrosive substances and form highly toxic breakdown products, Wheatley et al. (2019) concluded that other less hazardous reagents could potentially function as a Brønsted-Lowry base in the formation of HCO_3^- complexes.

Alkali metal salts of phenol (also called phenoxides) were considered for gas clean-up in the 1960s, ultimately losing out to amines (Wheatley et al. 2019). They were bases with a similar pKa range (around 9-11) to many amine-based solvents. The basic capture mechanism between a phenoxide and CO_2 is illustrated in Figure 6. Phenoxides are used alone or in combination with amines, where they complement capture via the faster carbamate pathway. Wheatley et al. (2019) noted that the presence of excess potassium phenoxide lowered the stochiometric limit for carbamate formation in an MEA aqueous solution, increasing overall capture rates via the bicarbonate pathway. One of the most significant advantages of CO_2 capture via HCO_3^- complexes was thought to be their lower stability, which required less heat energy for CO_2 release and solvent regeneration.

Figure 6: Hydration of CO_2 by potassium phenoxide.



Although phenoxides were inexpensive, Wheatley et al. (2019) noted that their potentially hazardous nature was “arguably” comparable with some amines. In 2019, a carboxylic acid-based system developed by C-Capture started a demonstration trial at the bioenergy carbon capture and storage (BECCS) power plant operated by Drax in Yorkshire. This system had “…*evolved from utilising phenoxide salts as capture agents to employing acid salts with a proprietary blend of modifying agents*” (University of Leeds 2021).

Ammonia

In ammonia (NH_3) scrubbing, CO_2 is passed through an aqueous ammonia solution (Kammerer et al. 2023), where it dissolves in the liquid and reacts with NH_3 to form ammonium bicarbonate via a carbamate complex ($NH_2CO_2NH_4$). The fundamental absorption reaction is shown below:

$CO_2(g) + NH_3(aq) + H_2O\ (l) \rightleftharpoons NH_4\text{-}HCO_3(aq)$

Ammonia solutions have been used to capture CO_2 and remove hydrogen sulphide (H_2S) from industrial gas streams for many years (Gautam and Mondal 2023). The chemical equilibrium depends on the temperature as well as reactant and product concentrations (Kammerer et al. 2023). At a low temperature (0–10 °C), the equilibrium shifts towards the righthand side of the equation, while at a higher temperature it moves to the lefthand side.

Therefore, a temperature >120 °C is used to reverse the reaction, releasing the CO_2 for compression and storage, and regenerating the solvent.

In a conventional system, capture happens at ambient temperature (25–40 ˚C), but in the more novel chilled process, ammonium carbonate and HCO_3^- precipitation occurs (Gautam and Mondal 2023). These products are then used by the fertiliser industry. Although, reducing the operating temperature in the absorber reduces NH_3 losses, it also reduces the CO_2 absorption rate.

The advantages of ammonia-based scrubbing were considered by reviewers to be a high CO_2 capture efficiency, low regeneration costs, high absorption capacity, and the ability to remove sulphur and nitrogen oxides, simultaneously, from the flue gas (Gautam and Mondal 2023, Kammerer et al. 2023). However, NH_3 slip, slow reaction rates, and high volatility were presented as challenges to its scaling up (Rezaei et al. 2023).

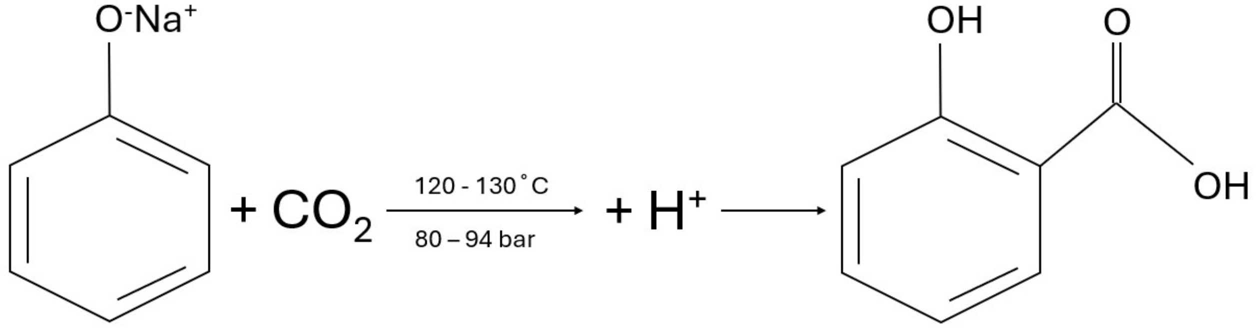
Other potential options under active research

On-going research for several other solvent systems was identified in the literature.

Carboxylation is related to the capture of CO_2 using carboxylic acids (see Carboxylic acid-based systems), but instead of regenerating the solvent and recovering the CO_2 for utilisation and storage, the products themselves are used as chemical feedstocks. Wheatley et al. (2019) noted that sodium and potassium phenoxide had been used as feedstocks to form aryl carboxylic acids via the Kolbe-Schmitt process (see Figure 7). This reaction is a source of numerous compounds in the chemical industry, most notably salicylic acid, although the overall scale in terms of CO_2 utilisation was considered small.

Several studies comprehensively reviewed the ongoing research to utilise carboxylation reactions within the chemicals industry, where CO_2 could be used as the feedstock (Faba et al. 2022, Rawat et al. 2023). Carboxylation produces carboxylic acids, which could potentially replace other feedstocks such as methane, formaldehyde, methyl halides, or CO in coupling reactions. Faba et al. (2022) considered that the ideal approach involved reactions at low temperatures and pressures, which could be achieved by enzymatic, biochemical, and chemical pathways.

Figure 7: The Kolbe–Schmitt reaction used by industry.

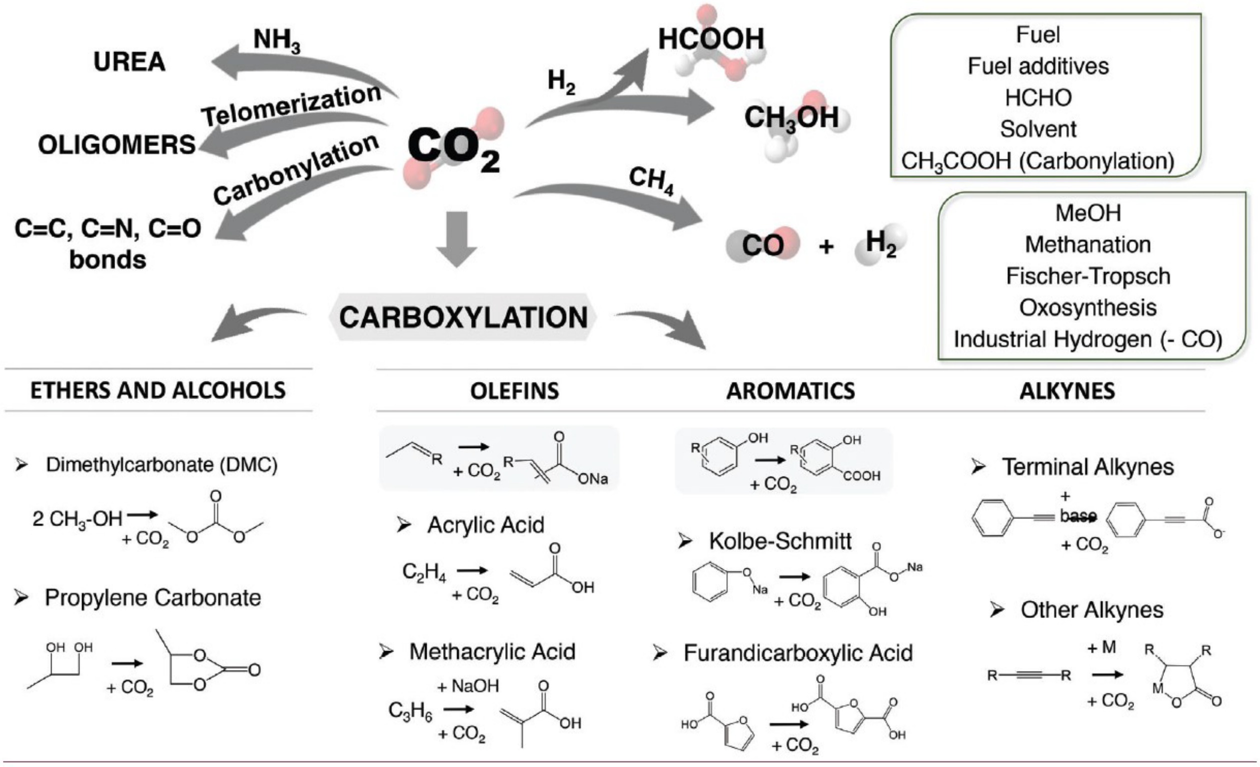


The challenge of working with CO_2 as a reagent was considered to be its thermodynamic stability and kinetic inertness (Faba et al. 2022, Rawat et al. 2023). Only a limited number of reactions had been used by the chemical industry (Wheatley et al. 2019). The main methods for activating CO_2 were identified as either liquids at low (negative) temperatures with organic metallic catalysts or higher temperatures with alkali salt precursors. Rawat et al. (2023) noted that traditionally either a Grignard reagent (a substance with the general formula R−Mg−X, where X is a halogen, Mg is magnesium, and R is an alkyl or aryl organic group) or an organolithium compound are required to initiate the reaction. However, they also commented that new porous materials and metal organic frameworks (MOFs) had shown that they could catalyse the carboxylation reaction (see also Adsorption by Solid Sorbents).

Faba et al. (2022) summarised the most promising approaches from the recent literature (see Figure 8), which included the production of monomers for more sustainable plastics. The authors noted that most of these processes were still at lab-scale and there were significant challenges to demonstrate that they could be scaled-up. Highlighting its potential, Zhang et al. (2024b) investigated the life cycle of producing upscaled plastic products from CO_2 captured using activated carbon from waste plastics. They modelled that utilising a low carbon energy source would make the products close to carbon neutral.

One especially active area of research is the development of technologies for the sustainable conversion of CO_2 to liquid fuels including methanol, ethanol, and dimethyl ether (Faba et al. 2022). CO_2 can be transformed directly into methanol using a catalyst such as copper, zinc, or aluminium oxide. However, the authors noted that the reaction kinetics decreased significantly in the presence of other flue gases such as CO and H_2, and the catalyst was inhibited by water. Faba et al. (2022) also commented that the commercial promise was limited by availability and cost of H_2.

Figure 8: Promising chemical routes for CO_2 utilisation via carboxylation.



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Enzymes, most notably carbonic anhydrase, had also been investigated for the chemical absorption of CO_2 from flue gases (Sharma et al. 2020, Molina-Fernández and Luis 2021). Carbonic anhydrase is a metalloenzyme and monomeric protein containing zinc or cadmium, which catalyses in aqueous solution the reversible conversion of CO_2 into HCO_3^- (Talekar et el. 2022). Although found in various forms in all living organisms, the most commonly used for CCT was derived from bovine sources (Molina-Fernández and Luis 2021). Carbonic anhydrase was used alone to rapidly convert CO_2 in gas-liquid phase absorption or in combination with other aqueous-based solvents like amines, where it acted as a promoter to speed up the rate limiting hydration of CO_2.

As many other enzymes, carbonic anhydrase is sensitive to solution conditions including pH and temperature, which can inhibit its industrial application (Sharma et al. 2020). However, studies had partially overcome these limitations by immobilising the enzyme on support materials including porous solids (silica, aluminium oxide, iron filings, and activated carbon) and nanoparticles (silica, titanium dioxide, amine functionalised iron oxide, and spun carbon nanofibres). Immobilisation resulted in reduced enzyme activity but often prolonged its stability and reusability (Molina-Fernández and Luis 2021). Contact between the solvent, the flue gas, and the immobilised enzyme was an important consideration in test systems. Initial designs had proposed a packed bed, where the fluids were pushed through beads to ensure good contact. However, results showed that the rates of enzyme activity were much lower than could be obtained from the free enzyme (Molina-Fernández and Luis 2021). Other options were put forward in the literature, which included spraying it directly into the absorber and/or scrubber. Molina-Fernández and Luis (2021) concluded that based on the current research evidence, use of enzymes to support chemical absorption seemed more promising than their use in membranes.

Ionic liquids are defined as a salt (consisting of a cation and an anion) in the liquid state under near ambient conditions (Allangawi et al. 2023).[3] The cation can be a metal such as sodium, but many applications use salts formed from imidazole or ammonium, while the anion is typically a halogenated borate or phosphate complex, or a large organic ligand like bis-trifluoromethanesulfonimide, trifluoromethanesulfonate or ethyl sulfate. In CCT, ionic liquids have been classified into three groups (Kammerer et al. 2023): room temperature ionic liquids (RTILs), task specific ionic liquids (TSILs), and supported ionic liquid membranes (SILMs). RTILs behave according to Henry's Law and absorb CO_2 via a physical mechanism (see Physical Absorption Solvents), while SILMs are considered a membrane technology (see Membrane Separation). TSILs behave like chemical solvents at low pressures (> 1,000 kPa) and can potentially absorb up to three times more CO_2 than RTILs (Kammerer et al. 2023). However, reversing the chemical absorption of CO_2 was reported to require higher energy input (Allangawi et al. 2023).

The main advantages of ionic liquids over other solvents were reported to be that they have extremely low vapour pressures, making them easier to handle and control emissions, and their relatively high thermal and chemical stability (Allangawi et al. 2023). In addition, the wide range of applicable cations and anions means that combinations can be optimised to reduce degradability, lower toxicity, and other operational factors (Zhang et al. 2024a). Addition of an amine group to constituents was suggested to significantly improve the CO_2 absorption properties (Kammerer et al. 2023). The main disadvantage identified was cost. Allangawi et al. (2023) reported that ionic liquids were typically between 10 and 20 times more expensive than other solvents.

Other solid sorbents have been investigated for use in carbon capture including metal oxides, **metal organic frameworks (MOF)**, and zeolites (Kammerer et al. 2023, Othman et al. 2024). MOF are porous and crystalline solids consisting of metal ions linked by hydrocarbons. Selectivity towards certain molecules, pore shape and size, absorption capacity, surface adsorption capacity, and kinetics can be tailored to a specific purpose. Researchers have investigated the use of embedded amines to increase CO_2 capture efficiency, as well as the use of water-dispersible nanocatalysts to reduce the energy

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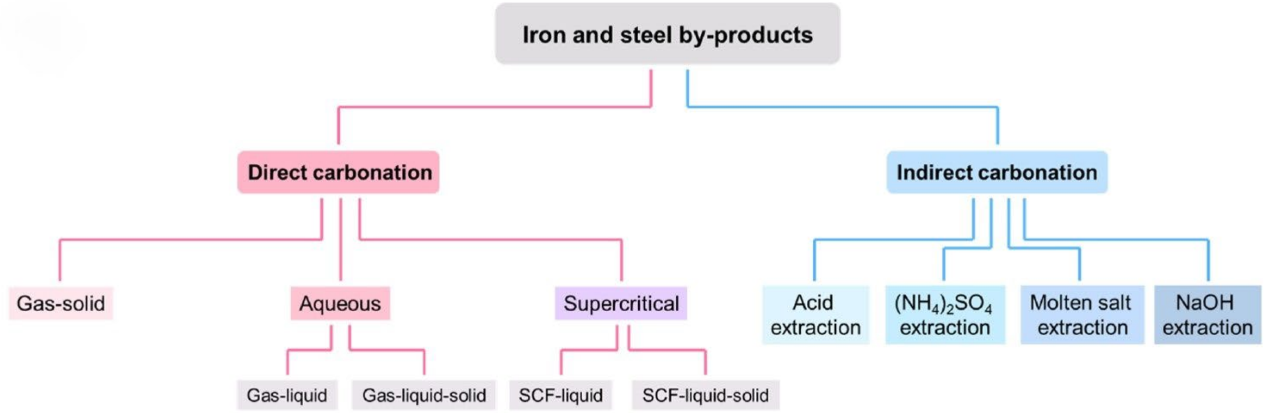
[3] Wilkes (2003) defined ionic liquids as salts that melt at temperatures below 100˚C. Despite their name, these salts can be in solid form at ambient temperatures and pressures, requiring hydration to form liquids.

required to release sorbed CO_2. MOF were reported to also be used for surface adsorption (see Adsorption by Solid Sorbents).

Figure 9: Methods for mineral carbonation of iron and steel wastes.



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Mineral carbonation is also a technique under investigation using low-cost wastes from the cement, paper, and iron and steel industries, that potentially combines carbon capture with the circular economy (Wang et al. 2024a). Uliasz-Bocheńczyk and Deja (2024) investigated the use of cement kiln dust (calcium oxide) for the capture of CO_2, which effectively involved carbonation without solid sorbent regeneration (see Calcium Looping). The treated carbonated material was available for recovery / reuse. Lyu et al. (2024) proposed a method to produce aggregates from flue gas desulphurisation ash, which combined a phase of air curing and a phase of CO_2 curing, to overcome cracking issues. De Oliveira Maciel et al. (2024) proposed using paper and pulp residues with the enzyme carbonic anhydrase to absorb CO_2 from flue gases at a paper mill. CO_2 was converted to HCO_3^- in aqueous solution, which could then be treated to produce mineral carbonate either on or off-site. The enzyme was added to enhance the hydration of CO_2 to form carbonic acid (H_2CO_3), which is often a rate limiting step in the reaction. In a review of wastes from the iron and steel sector, Wang et al. (2024a) considered a number of ways that materials such as steel slags could be used for carbon capture (see Figure 9). In addition to direct gas-solid carbonation (see Calcium Looping), aqueous systems were also under development that first dissolved the CO_2 in water to form H_2CO_3, which subsequently reacted with CaO and silica dioxide in the waste materials. Innovations in this area were summarised including use of acid and alkalis such as hydrochloric acid, sulphuric acid, ammonia and ammonium salts, and sodium hydroxide, to enhance aqueous solubility and extraction and indirect carbonation, and the use of supercritical CO_2 fluids. Although considered more expensive in terms of reagents, indirect carbonation was effective at lower temperatures and pressures. Wang et al. (2024a) reported that only a limited number of pilot-scale projects had been undertaken to date including at Aalto University in Finland using steel slag and ammonium chloride. The Finnish project had reported a 70% capture rate at room temperature with a residence time of around an hour.

Physical Absorption Solvents

Physical absorption solvents do not react with CO_2 (Dziejarski et al. 2023, Kammerer et al. 2023). They are based on the relationship between the concentration of a gas dissolved in a liquid and the partial pressure of the gas above the liquid (Henry's Law). CCT has been demonstrated commercially using Rectisol® (cold methanol) and Selexol® (a blend of polyethylene glycol dimethyl ethers) and the solvents have also been used in natural gas processing, coal gasification, ammonia production, and methanol synthesis. Physical absorption was considered by Kammerer et al. (2023) to be more efficient than chemical absorption where CO_2 was present at higher partial pressures, and therefore it had been largely developed as a pre-combustion option. Below a level of 15% CO_2 v/v, physical absorption was considered uneconomic (Dziejarski et al. 2023).

Three methods for separating the absorbed CO_2 and regenerating the solvent were identified in the literature (Dziejarski et al. 2023, Kozak-Jagieła et al. 2024):

- Pressure swing adsorption – sorbent is regenerated by pressure reduction.
- Temperature swing adsorption – sorbent is regenerated by temperature increase.
- Electric swing adsorption – sorbent is regenerated by a low-voltage electric current.

The energy costs were considered lower than for a comparable amine-based system. In addition, the solvents were reported to have a lower corrosivity (Dziejarski et al. 2023). See also Adsorption by Solid Sorbents for a further discussion of separation methods.

Purisol®

The Purisol® process was developed as a pre-combustion method to clean syngas (a mixture of CO and H_2) in gas turbines with integrated gasification (Kammerer et al. 2023). Using a mixture of N-methyl-2-pyrrolidone (NMP) and water, the absorber operates at low temperatures (typically between -40°C and -20°C) and at pressures as high as 70,000 kPa. Recovery of the CO_2 and regeneration of the solvent takes place by reducing the pressure, which boils out the solvent.

Rectisol®

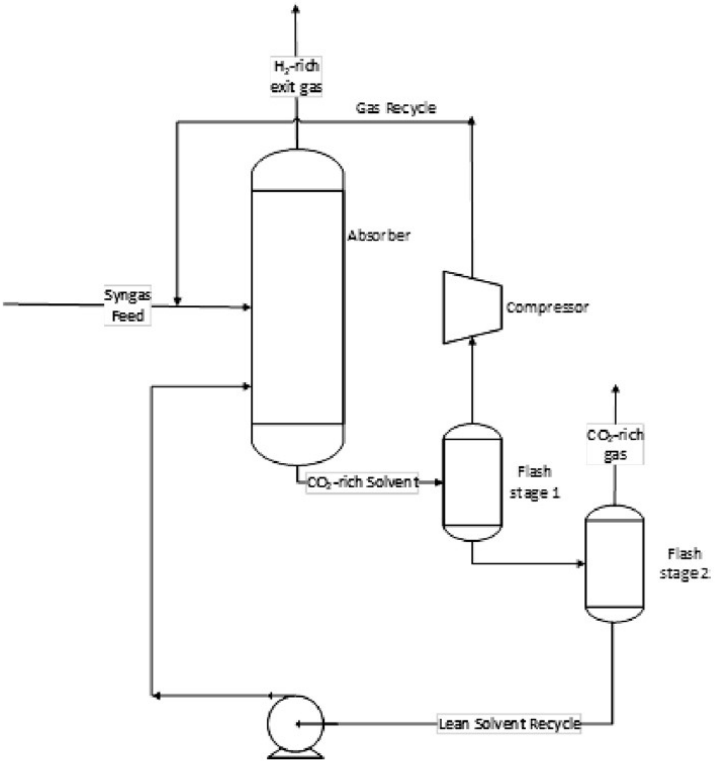
In the Rectisol® process (see Figure 10), the solvent methanol is used to remove CO_2 from syngas (Kammerer et al. 2023). The absorber is refrigerated to between -70°C and -10°C to limit solvent losses, while the stripper operates under a nitrogen (N_2) rich atmosphere and at a higher temperature. Absorption takes place at high pressures (around 20,000 kPa). While the focus of the original process was to separate H_2S, the purity of the CO_2 stream could be increased by using a selective membrane after separation.

Selexol®

The Selexol® uses the solvent polyethylene glycol dimethyl ether to remove CO_2 and sulphur compounds from pre-combustion gases (Dave et al. 2020, Kammerer et al. 2023). The process exploits the higher solubility of CO_2 in the organic solvent compared to other flue gases. Gases are pretreated to remove water and acid gases before they enter the absorber under pressure (> 20,000 kPa). Gas flows upwards, while the solvent flows downwards.

Kammerer et al. (2023) noted that the main advantage of the Selexol® system was that it required little or no energy because the process took place with and without cooling in the absorber. However, the process was not considered suitable for gases with a high hydrocarbon content and a low acid gas partial pressure. Kammerer et al. (2023) reported that it was being evaluated for use by the cement industry.

Figure 10: Illustration of the Rectisol® process.



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Other potential options under active research

On-going research for several other solvent systems was identified in the literature.

As noted previously (see Chemical Absorption Solvents), **ionic liquids** can also be used as physical absorption solvents. They rely on anionic and cationic structures to dissolve and absorb CO_2 through hydrogen bonding and Van der Waals forces (Zhang et al. 2024a). Anions are considered to play the important role in CO_2 absorption. While there were many reported operational advantages to use of ionic liquids (including a low regeneration cost), the capture capacity was generally considered small at low CO_2 partial pressures. Ionic liquids for physical absorption included large organic cations such as those based on imidazole combined with inorganic anions such as boron tetrafluoride or phosphorous hexafluoride (Zhang et al. 2024a). Recently reviewed innovations sought to boost the selectivity and capacity for CO_2 absorption by using substituted functional groups including amines to provide chemical specificity. Other identified operational difficulties with using ionic liquids included their viscosity and cost (Zhang et al. 2024a), leading to blending with either water or organic solvents such MEA.

De Vries et al. (2023) proposed the use of **photoacids** such as merocyanine for CO_2 capture. These are organic chemicals that release protons (hydrogen ions) under illumination. The authors suggested that such light-driven pH switches offered the ability to cyclically alter the pH of a solution, and this could be used to increase and decrease the solubility of a solvent for CO_2 (specifically, the HCO_3^- ion). The main advantage is a potentially much lower energy cost compared to temperature or pressure changes. However, the main challenges are the solubility and stability of existing photoacids in water. De Vries et al. (2023) sought to overcome these difficulties by using a binary solvent mixture of dimethyl sulfoxide (DMSO) and water instead of water alone with promising results in a series of bench-scale experiments.

Hydrate-based encapsulation is also considered an emerging technology for CO_2 capture and storage (Zhang et al. 2024f). The reported advantages of this method included large CO_2 storage capacity, moderate operating temperatures, continuous operation ability and low operation cost compared to other CCT. CO_2 hydrate forms under phase equilibrium conditions when CO_2 molecules are trapped within the cage-like crystal lattice formed by hydrogen-bonded water molecules at high pressures (around 4,400 kPa at 7˚C). However, the equilibrium pressure could be reduced with the use of additives such as tetrahydrofuran and tetra-n-butyl ammonium bromide (Zhang et al. 2024f). In order to speed up hydrate formation kinetics, surfactants and stirrers had been proposed, but these were reported to damage the stability of the crystal lattice. Zhang et al. (2024f) conducted bench-scale experiments to improve kinetics by splitting the bulk liquid into small capsules to maximise gas-liquid exchange rates. In this two-stage separation system, CO_2 and flue gases were cooled to form hydrate, which was then released as a pure stream of CO_2 on heating.

Adsorption by Solid Sorbents

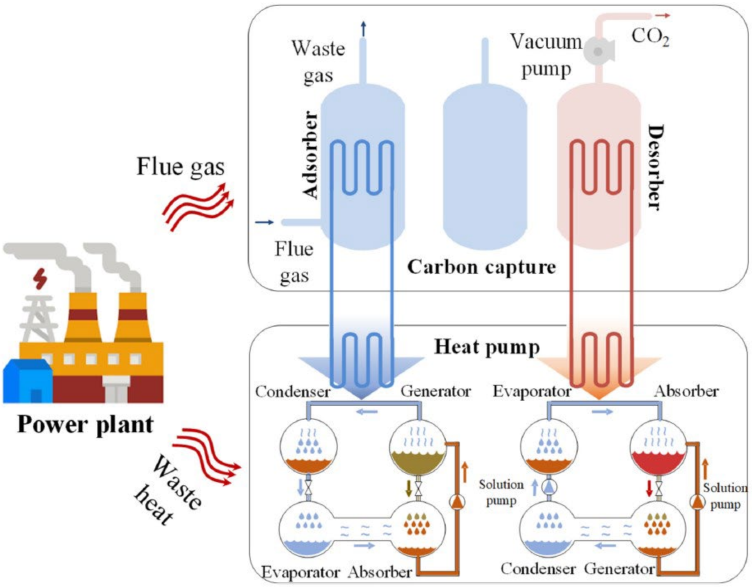
In an adsorption process, components in the gas phase attach to a solid surface by either physical attraction (such as Van der Waals forces) or chemical bonds (Kammerer et al. 2023, Singh et al. 2024). A high surface area to mass ratio was identified as a critical parameter, along with selectivity and capacity for CO_2, high solid stability, easy sorbent regeneration (a low heat of adsorption), and low-cost materials. Singh et al. (2024) noted that pore diameter was also important. Poor selectivity for CO_2 was seen as a major disadvantage for many existing sorbents, but a high adsorption capacity at low CO_2 partial pressures was considered an important advantage (Gautam and Mondal 2023). Rezaei et al. (2023) noted that high initial costs for emerging sorbents, along with high running costs (challenging operational maintenance and sorbent losses), may inhibit commercialisation of some systems and materials.

Adsorption systems are also categorised in the literature according to their regeneration method (see also Physical Absorption Solvents). The most commonly reported systems are pressure/vacuum swing adsorption and temperature swing adsorption, but other systems are under development such as electric swing and moisture swing adsorption (Liu et al. 2024c). Pressure swing adsorption is used for higher concentrations of CO_2, but temperature swing adsorption is recommended for lower concentrations (Gautam and Mondal 2023). Pressure swing adsorption had a number of reported advantages including a lower energy cost, a shorter cycle time, and the ability to integrate with other processes such as H_2 gas capture. However, engineering plant was considered to be more complicated, which had been considered a barrier to date to its wider utilisation. A combination of temperature and vacuum swing adsorption had shown promise for use with solid sorbents because the gentle regeneration conditions were less energy intensive. Proposed innovations included integrating the heating and cooling cycles (see Figure 11) to further offset energy costs (Liu et al. 2024c). In a proposed electric swing adsorption system, a low-voltage electric current was passed through the adsorbent bed, which consisted of hybrid materials like activated carbon and zeolite. While it was potentially much more energy efficient than other methods, integrating it with required cooling and drying of flue gases was a challenge for retrofitting it (Gautam and Mondal 2023).

Many novel solid sorbent systems have not yet reached demonstration-scale, and many materials have been synthesised and evaluated only in bench-scale studies using simplified systems (Kammerer et al. 2023, Othman et al. 2024). Rezaei et al. (2023) estimated that the TRL for many adsorption systems was between 5 and 7. Sahu et al. (2024) also noted that many of the current research materials had a low tolerance to humidity and other impurities in the flue gas, a low adsorption capacity and slow adsorption kinetics, and a high energy cost associated with regeneration. The quest to overcome these limitations is driving research and innovation (Gautam and Mondal 2023). Zhao et al. (2024) categorised solid adsorbents according to temperature (see Figure 12). In the context of industrial decarbonisation, the low and high temperature systems have received the greatest interest, although the intermediate temperature band was considered important for uses in H_2 production.

Porous organic polymers are a relatively new sorbent for CO_2, which offers the potential for high porosity, surface area, and selectivity (Sekizkardes et al. 2022). These polymers are stable because they are interlinked with strong covalent bonds. **Amine-functionalised polymers** improve the selectivity and capacity of these polymer materials to adsorb CO_2 in preference to non-polar gases such as N_2 by chemically binding with CO_2. Options for the production of amine-functionalised polymers include direct synthesis (amine functionality part of the monomer), amine grafting (amine bonds with polymer after polymerisation), and amine impregnation (amine additive, which do not bond to polymer). A wide range of different material types were reported to be under investigation, but they were considered expensive to manufacture and relatively untested for practical durability. Sekizkardes et al. (2022) noted that early experimental materials were derived from primary amines, which were known to degrade, and that future research would likely concentrate on more stable secondary and tertiary amine groups.

Figure 11: General concept for heat pump assisted solid adsorption.



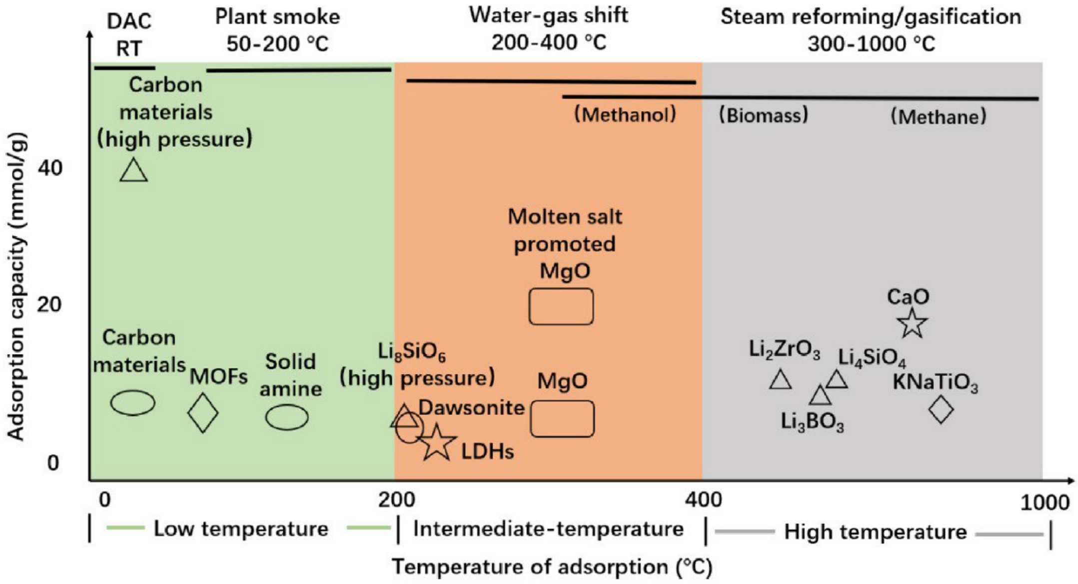
Reprinted from LIU W., JI Y., HUANG Y., ZHANG X.J., WANG T., FANG M.X., JIANG L., 2024c. Adsorption-based post-combustion carbon capture assisted by synergetic heating and cooling. RENEWABLE AND SUSTAINABLE ENERGY REVIEWS, 191, art. no. 114141, with permission from Elsevier.

Metal oxides activated with aluminium oxide modified with sodium hydroxide on a fixed bed have also been investigated for use in CCT, along with mesoporous alumina (Kammerer et al. 2023). The latter have a large surface area and a large porous volume, which are potential chemical and physical adsorption sites for CO_2. Magnesium oxide (MgO) is considered a promising solid sorbent for intermediate temperatures (Zhao et al. 2024). Metal oxides do not often achieve their theoretical capacity in practical applications because of surface formation of carbonate layers with innovations focused on improving their microporous structures. Sahu et al. (2024) investigated the theoretical potential for nanoparticles of transition metals to adsorb CO_2 under varying conditions of surface charge, the authors suggesting that this method showed promise.

Zeolites have been investigated for the physical adsorption of CO_2 in combination with either pressure or temperature swing regeneration (Kammerer et al. 2023). Zeolites can be produced synthetically or naturally and are microporous and crystalline silicate framework materials, which can incorporate metal cations to improve specificity for CO_2.

Adsorption using zeolites had been investigated at pressures exceeding 2,000 kPa, with adsorption capacity decreasing with increasing temperature (Kammerer et al. 2023). Heating could therefore be used to release CO_2 and regenerate the sorbent. Some natural zeolites contain impurities and have also been observed to absorb water, which reduces their effectiveness (Othman et al. 2024). More recent research has investigated whether synthetic zeolites could be made from wastes like coal residues (Liu et al. 2024a).

Figure 12: Applicable operating conditions for solid sorbents.



Reprinted from ZHAO C., WANG L., HUANG L., MUSYOKA N.M., XUE T., RABEAH J., WANG Q., 2024. Recent advances in intermediate-temperature CO2 capture: Materials, technologies and applications. JOURNAL OF ENERGY CHEMISTRY, 90, pp. 435-452, with permission from Elsevier.

Porous **carbon-based solid adsorbents** have been widely investigated for use in CCT and are proposed for some commercial applications (Othman et al. 2024, Singh et al. 2024). Examples include activated carbon, carbon nanofibres (CNF), carbon fabrics, carbon nanotubes (CNT), activated carbon nanofibres (ACNF) and graphene (Othman et al. 2024). **Activated carbon** has an extremely porous structure, high specific surface area and a relatively high packing density (Othman et al. 2024). The surface has been further activated by either chemical or physical treatment to enhance adsorption capacity and selectivity for CO_2 by controlling pore size and shape and the hydrophilic and hydrophobic tendencies of an activated surface (Ketabchi et al. 2023, Othman et al. 2024). Chemical activation methods have included doping with other materials such as those containing heteroatoms (nitrogen and sulphur) or metal oxides (copper oxide and magnesium oxide). Activated carbon could be manufactured at low cost from waste materials such as biomass bottom ash and lemon peel and is likely to be available in granular and powdered forms (Gorbounov et al. 2024, Ketabchi et al. 2023, Li et al. 2024, Othman et al. 2024, Weldekidan et al. 2024). Initial studies with a fixed bed, demonstrated rapid sorption and desorption kinetics (González et al. 2013). Ji et al. (2023) observed good CO_2 adsorption at bench-scale with biochar from coconut shells with the surface activated by potassium hydroxide and modified with the further addition of amines. **Graphene** is a two-dimensional carbon sheet in a honeycomb crystal lattice, which stacks in layers connected by weak Van der Waals forces. It has a high surface area, high mechanical strength, good thermal and chemical stability, and modifiable surface chemistry (Othman et al. 2024). **Electrospun carbon nanofibres** (CNF) have slit-shaped pores, which have been used in gas adsorption, separation, and storage applications. They have a high surface area, abundant microporosity, high hardness and density, and high manufacturing yield (Othman et al. 2024). With surface modifications, they are considered a good candidate for CO_2 adsorption. **Carbon nanotubules** (CNT) are composed of carbon atoms linked in hexagonal shapes with a cylindrical nanostructure. They have excellent electrical and thermal conductive properties and are very strong. In an experimental study, CO_2 uptake by CNF was similar to MOF, but much higher than zeolite (Othman et al. 2024). **Cellulose**, an abundant natural polymer, has also been proposed for use as a solid sorbent and as a carrier for other solid and liquid sorbents such as aerogels (Zhang et al. 2024e). Forms of cellulose under investigation included nanocellulose and cellulosic nanoparticles.

Microporous organically pillared layered silicates (MOPS) are another class of materials under active research for CO_2 capture (Kammerer et al. 2023, Othman et al. 2024). They are formed from sheets of clay silicates with the distance between sheets determined by complex metal organic cations. Although the basic sheets and pores spaces have a low affinity for CO_2, they could be made highly selectable through the functional addition of amine groups (Othman et al. 2024). Once captured, CO_2 could be flushed from the sorbent using an inert gas such as helium. The major disadvantages of silica and MOPS reported in the literature were their high energy consumption for regeneration, their high affinity to water, and the cost associated with functional modifications (Othman et al. 2024).

As well as being used for chemical absorption (see Chemical Absorption Solvents), **metal organic frameworks** (MOF) have also been investigated for gas adsorption (Garcia and Smit 2023, Othman et al. 2024, Yong et al. 2024). MOF are synthesised by combining organic ligands with metal nodes. These frameworks possess controllable pore sizes, excellent mechanical and thermal properties, chemical resistance to acids and alkalis, and a well-defined macromolecular structure (Othman et al. 2024). Over 90,000 MOF have already been synthesised by chemists with around 10,000 with a crystalline structure that is considered potentially suitable for CCT (Garcia and Smit 2023). With such a vast number of potential options, researchers have developed key performance indicators and thermodynamic models to optimise the selection of promising materials for the flue gas characteristics of different industrial sectors. MOF were considered suitable by reviewers for high pressure CO_2 storage due to their high surface area and micropore volume. Othman et al. (2024) noted they were also less stable to heat and water than zeolites and were difficult and costly to synthesise, Yong et al. (2024) reported on the synthesis of MOF by combining diamine with a propylene linker to significantly improve performance under humid conditions.

Other potential options under active research

Similar to carboxylation (see Absorption by Solvents), solid sorbents in conjunction with the reverse water gas shift reaction have been proposed as a step in the production of methanol, methane, and CO (Wang et al. 2024b and 2024c, Zhu et al. 2024). The reverse water gas shift reaction uses H_2 and CO_2 to form CO and water, which with additional H_2 forms syngas. Numerous potential solid sorbents have been proposed by researchers including calcium oxide, magnesium oxide, and transition metal oxides and silicates, as well as waste materials such as marble dust. After an initial adsorption phase, the concentrated CO_2 is mixed with H_2 to form syngas, which undergoes further reactions in the presence of a catalyst to form methanol and methane (Wang et al. 2024b). This reaction is often facilitated by a metal oxide or oxy-silicate catalyst with common transition metal oxides including nickel, iron, chromium, and cobalt. Researchers have also combined these reagents with promoters and supports such as aluminium, silicon, and titanium oxide.

Cryogenic Separation

In the cryogenic process, CO_2 is physically separated from other flue gas components by condensation, sublimation, or distillation (Font-Palma et al. 2021, Kammerer et al. 2023, Gautam and Mondal 2023). A precondition of this process is that the sublimation temperature of CO_2 is lower than that of other constituents (Madejski et al. 2022). Font-Palma et al. (2021) distinguished between conventional (liquid-vapour) and unconventional (solid-vapour) separation. The conventional approach has been demonstrated at field scale for the removal of CO_2 from natural gas, where it may be present at >70% by mass (Kammerer et al. 2023).

Gautam and Mondal (2023) noted that this method has a low water requirement, uses cheap and non-corrosive chemicals, and handles large gas volumes. Rezaei et al. (2023) also concluded that it may be more easily retrofitted because the only energy source required is electricity. In addition, the production of liquid CO_2 offers practical and cost advantages for transport, storage and utilisation (Gautam and Mondal 2023). However, the requirement for flue gas pre-treatment and the high energy costs associated with cooling the flue gas are considered to be major disadvantages for the conventional approach (Font-Palma et al. 2021) and mean that it is only commercially economic at CO_2 concentrations >90% (i.e. under some pre-combustion conditions). Therefore, researchers are investigating ways to reduce the overall costs and broaden its application (Madejski et al. 2022). Unconventional approaches using vapour-solid separation were considered an attractive option by Font-Palma et al. (2021) because studies had shown a 50% reduction in the energy requirements to achieve separation. Several technologies have been considered including the use of heat exchangers, direct cryogenic liquid contact, and packed beds of cooled surfaces. However, many of these unconventional separation methods are only at the initial stages of development (Font-Palma et al. 2021).

In conventional systems, Zhang et al. (2024d) proposed combining cryogenic separation with liquid air energy storage (LAES) using a model simulation to reduce energy consumption. Gautam and Mondal (2023) also highlighted the issue of ice formation from moisture within the flue gas, which had been reported to block pipelines during field-scale operation. Therefore, a cryogenic plant would also require pre-treatment investment to dry the flue gases for some applications.

Membrane Separation

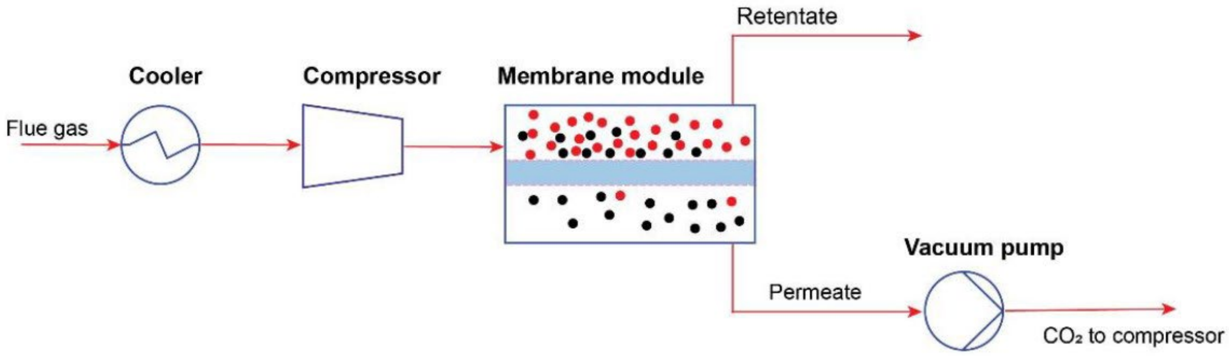
Acting like a sieve, membranes can be used to separate gases, according to their molecular size (Gautam and Mondal 2023, Kammerer et al. 2023, Kamolov et al. 2023, Madejski et al. 2022, Olabi et al. 2023). Figure 13 shows a basic membrane system (Kamolov et al. 2023). The driving force for separation is the concentration gradient across the membrane, which in theory at least, requires no energy input (Madejski et al. 2022). However, this is likely to be a challenge for post-combustion use because of low CO_2 levels in the flue gas. Therefore, it necessitates the need for a highly selective membrane.

The separation characteristics of a membrane are determined by its permeability and surface chemistry. Their ability for selection between two gases such as CO_2/N_2 is based on the Robeson line (Robeson 2008), which is a compromise between the selectivity (ability to separate two molecules) and the permeance (flow through the membrane) of a membrane (Costa et al. 2024). The ideal characteristics of a membrane for CO_2 capture suggested by researchers included a high thermal stability (up to 400˚C), a high mechanical stability (up to 6,500 kPa), a high resistance to ageing and plasticisation, a high carbon to nitrogen selectivity, and a high CO_2 permeability (Powell and Qiao 2006, Olabi et al. 2023). In addition, the membranes should be cheap to manufacture and low cost to maintain. There are broadly three types of membrane materials reported in the literature: organic (polymeric) membranes, inorganic membranes, and mixed/hybrid materials (Kamolov et al. 2023).

Membrane technology is considered to be mature in some areas such as the oil and gas industry, where membranes are already used for dehydration or to separately recover CO_2 during natural gas processing (Rezaei et al. 2023). It had also been developed for pre- and post-combustion process for industrial decarbonisation (Gautam and Mondal 2023), but many of the newer membrane materials were developed and modelled only at bench-scale. Membrane systems could be applied in pre-, post-, and oxy-combustion configurations. In pre-combustion, the focus is on the separation of CO_2 from H_2, and in post-combustion, it is on separation of CO_2 from N_2 (Olabi et al. 2023). Rezaei et al. (2023) considered that most membrane systems for post-combustion CO_2 capture were at TRL 2 – 6. Reported advantages of membrane technologies included a small footprint, easy scaling, integration into existing technologies, low operating costs, and low energy consumption (Kamolov et al. 2023). However, Rezaei et al. (2023) noted that the permeability and selectivity of currently available membranes are lower than needed for full-scale deployment, resulting in a requirement for very large membrane surface areas that would incur high capital expenditure. Reported disadvantages included high membrane material costs, high energy requirements for vacuum to drive separation and CO_2 compression, and limited CO_2 purity. Operational performance could potentially be impacted by fouling, the accumulation of ash and other gases, and by the corrosive effect of other flue gases such as sulphur and nitrogen oxides, requiring cleaning and/or membrane replacement (Olabi et al. 2023, Rezaei et al. 2023). Gowd et al. (2023) commented that a membrane-based CCT applied to a 550MW coal-fired power station would consume around 162 kWh to capture 1 tonne of CO_2.

Polymeric membranes are co-polymers of hard and soft blocks (Kammerer et al. 2023), which combine high separation and high permeability characteristics. Examples from the literature included polyacetylene, polycarbonates, polyetherimides, polyaniline, polyethylene oxide, polysulphones, and polyvinylamines. Polymeric membranes for CCT are currently being scaled up from pilot- to demonstration-scale (Kamolov et al. 2023). One advantage of co-polymers is that an effective and costly polymer could be combined with a cheaper monomer to reduce overall costs. The main drawbacks are considered to be plasticisation and swelling by water (Kamolov et al. 2023). Polyimides had been the most researched to date (Kammerer et al. 2023) because of their good gas transport and physical characteristics, simple production methods, and potential structural variability and selectivity. One promising area of research is the use of facilitated transport membranes (Kamolov et al. 2023), where CO_2 is attached to a reactive carrier, which offers much higher selectivity and permeability. Chen and Ho (2024) reported that polymeric membranes containing mobile and fixed amines and amino acids have showed promise in separating CO_2/N_2 mixtures. CO_2 is moved across the membrane through reversible reactions with the amine carriers. They reported that although overall CO_2 transport was governed by diffusion, their experimental results indicated that at lower CO_2 partial pressures, carbamate products were predominantly responsible for CO_2 transport, while an increase in CO_2 partial pressure led to a greater contribution from bicarbonate products.

Figure 13: A diagram of basic membrane technology for CO_2 capture.



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Inorganic membranes have been developed, which include ceramic, metal, glass, and zeolite-based materials (Kamolov et al. 2023). They offer better chemical and thermal stability than polymeric membranes at a higher cost and are better suited for higher operating temperatures and harsher overall conditions. Cost is considered the major barrier to their commercialisation, and many systems have only been evaluated at bench-scale (Kamolov et al. 2023). Microporous inorganic membranes have a lower permeability, but a higher selectivity for CO_2 versus N_2, while mesoporous membranes have a higher permeability and a lower selectivity (Kamolov et al. 2023). Dense membranes have the highest selectivity and lowest permeability. **Ceramic membranes** consist of a double layer, a thick large-pore base and a gas tight thin non-porous ceramic – carbonate top layer (Kammerer et al. 2023). It is the top layer that ensures selective CO_2 permeation. Permeability could be maximised by configuring the microstructure within the ceramic support material. Zhang et al. (2024c) investigated at bench-scale the use of a ceramic membrane to enhance liquid dispersion and maximise contact rather than act as a filter.

In trying to address the trade-off between selectivity and permeability, researchers have focused on **hybrid membranes**, which could be produced to improve selectivity by combining co-polymers with porous nanofillers such as metal organic frameworks (MOF), zeolites, and porous carbon-silicon nanocomposites (Kammerer et al. 2023, Kamolov et al. 2023). These hybrid membranes are selectable by adjusting their porosity and surface chemistry. Hybrid membrane materials have mostly been tested at bench-scale only. Shan et al. (2024) pointed out several difficulties with the use of MOF in polymer membranes including chemical stability to water vapour and other flue gases. Only a limited number of MOF had been evaluated under industrial conditions for up to 100 hours and stable performance (over 1,000 hours) had been reported only under dry conditions. Shan et al. (2024) concluded that research on MOF membranes should focus on controlling interactions between MOF and the membrane and increasing production efficiency.

A **membrane contactor** works with solvent-based absorption and promotes contact between two non-miscible phases and is considered by some reviewers a membrane separation technology (Fattah et al. 2023, Kammerer et al. 2023, Kamolov et al. 2023). In this instance, the membrane itself does not select for one or more components in the mixture, rather the driving force for separation is differences in CO_2 solubility and behaviour between the two non-miscible phases. Many of the most promising designs are being scaled up from bench- to pilot-scale (Kamolov et al. 2023). An example of the proposed use of a membrane contactor, such as a hollow fibre membrane contactor (HFMC), was in conventional amine-based chemical absorption, where its use increased the efficiency of sorption and desorption processes and reduced the necessary size of the absorber and stripper (Kammerer et al. 2023). In this system, CO_2 in the flue gas contacts the liquid solvent at the apertures of the membrane in the absorber and is transferred across the interface (Fattah et al. 2023). The greater contact surface area across the membrane increases the CO_2 mass transfer rate. In the stripper, a porous membrane operates in reverse, transferring the CO_2 from the liquid to the gas phase using a vacuum pump and steam. Membrane contactors require a high gas permeability, a high chemical and physical stability, and should be cost-effective to produce and maintain (Kammerer et al. 2023, Kamolov et al. 2023). The most commonly reported materials in contact membranes included polymers such as polyetherimide, polysulphones, polyethersulphones, polyethylene, polypropylene, polytetrafluoroethene, and polyvinylidene (Fattah et al. 2023). Modification of these base polymers through the introduction of organic and inorganic additives, surface treatment and coating, and blending with other polymers has been proposed to enhance performance. Solvent choice is also critical to make membrane contactors competitive at an industrial scale (Fattah et al. 2023). Liquid solvents should have a high CO_2 absorption capacity, low regeneration energy cost, fast absorption kinetics and efficiency, good physical and chemical compatibility with the membrane materials, low viscosity, high surface tension to reduce membrane wetting, and low toxicity. Various absorbents such as cyclic amines, primary, secondary, and tertiary amines, amino acids, ionic liquids, and inorganic solvents have been evaluated (see also Absorption by Solvents).

Other potential options under active research

Enzymes have been studied for their potential role in Chemical Absorption Solvents (see earlier section), but they have also been investigated for use in membrane-based technologies (Molina-Fernández and Luis 2021). Early systems were proposed for stripping out CO_2 for workers in confined spaces. They used a porous membrane filled with an aqueous solution of carbonic anhydrase, held in place by capillary forces (Molina-Fernández and Luis 2021). Although highly permeable, these systems lose fluid through pressure differences across the membrane and via evaporation. Other liquid supports have also been investigated including ionic liquids and eutectic solvents, along with protection for the liquid membrane itself using a sandwich structure and aerogels forces. Molina-Fernández and Luis (2021) concluded that based on current research, use of enzymes to support chemical absorption seemed more promising than their use in membranes.

Electrical chemical cells using membranes have also been investigated at bench-scale (Song et al. 2024). Bipolar membranes have been shown to desorb and compress CO_2 from alkaline solvents (see Absorption by Solvents) through a pH swing process. Using copper and silver electrodes, Song et al. (2024) demonstrated the reduction of carbonate and HCO_3^- anions to ethylene in aqueous solution.

Microbiological and Microalgae Methods

Several researchers have proposed using microorganisms for removal of CO_2 from industrial flue gases (Bhatia et al. 2019, Gautam and Mondal 2023). Bhatia et al. (2019) identified several microbes that can capture CO_2 such as Acetabacterium woodii, Clostridium aceticum, Clostridium kluyveri, Clostridium ljungdahlii, Chlorella vulgaris, Rhodococcus erythropolis, Ralstonia eutropha, Synechococcus elongatus, and Rhodobacter sphaeroides. Potential mechanisms for capture include hydration of CO_2 to HCO_3^- by carbonic anhydrase (an enzyme), the reduction of CO_2 to methane via nitrogenase, and the biologically mediated conversion of CO_2 to formate and methanol. Microbial mediated fermentation is an important source of biofuels (Bhatia et al. 2019).

In many cases, microbial based capture and transformation reactions rely on one or more biological enzymes to mediate the reactions. These enzymes are often fragile and difficult to stabilise in the high temperature conditions of a flue gas (Bhatia et al. 2019). In addition, some mechanisms require multiple enzymes, which can make control of the reactions difficult and costly. Inert matrices and supports for carbonic anhydrase is an area of active research highlighted by Bhatia et al. (2019) using many of the materials proposed for solid sorbents and membrane technologies. Methane from the reduction of CO_2 can be achieved via ATP dependent nitrogenase, although it requires a genetically modified organism because natural nitrogenase is unable to do it. Bhatia et al. (2019) identified several systems mediated by light, which provides the necessary energy for the biological transformation.

Another example reported in the scientific literature is the use of microalgae, which in the presence of sunlight converted CO_2 to glucose (Gautam and Mondal 2023):

$6H_2O+6CO_2 + \text{light} \rightarrow C_6H_{12}O_6 +6O_2$

These reported systems are considered largely theoretical or applied only at bench-scale. In principle, microorganisms like algae take up CO_2 either as a gas or in the form of the HCO_3^- ion from solution, where it is processed by enzymes in the cell membranes. These organisms have a high capacity to absorb CO_2. In various studies, their cultivation was controlled by temperature, pH (between 7 and 8.4 was considered optimum), light, and nutrient availability (Gautam and Mondal 2023). Outputs from microalgae uptake have the potential to be used as biofuels. Research studies have also combined microorganisms with nanoparticle photocatalysts to produce electricity.

Oxy-fuel Combustion

Oxy-fuel combustion is a post-combustion CCT (Kammerer et al. 2023). In various configurations, it has been operated in pilot-scale power plants in the 25 – 1,000 kW-hr range and in kilns for cement production (De Vos et al. 2020). Research into chemical looping was increasingly focused on its use in the production of chemicals including H_2 (De Vos et al. 2020).

Combustion in Oxygen

This process relies on the main combustion process taking place in an atmosphere of pure oxygen rather than air and has been proposed / piloted at coal-fired power plants (Kammerer et al. 2023, Madejski et al. 2022). A simple schematic for the process is shown in Figure 14. The main advantage of this approach is reported to be that the flue gases are composed primarily of CO_2 and water vapour (Shahbaz et al. 2021). Leung et al. (2014) stated that CO_2 levels in the flue gas ranged from 80 – 98% based on the fuel source. Water vapour in the flue gas is cooled, condensed, and separated with the dried gas further treated to remove impurities such as sulphur oxides (Kammerer et al. 2023). The principal challenge with this technology was considered to be the energy required to separate the oxygen from air for the combustion process (Shahbaz et al. 2021). Leung et al. (2014) suggested that the air separation unit may require up to 7% more energy when compared to a conventional power plant without CCT.

Chemical Looping Combustion (CLC)

Conceptually similar to **combustion with oxygen** (see above), in CLC (De Vos et al. 2020, Kammerer et al. 2023, Leung et al. 2014), the fuel is not combusted directly with air, but with an oxygen-carrier (usually a metal oxide). The reported advantage of this process over combustion with oxygen is that energy intensive air separation is not required. De Vos et al. (2020) noted that a number of pilot-scale power plants (output in the 25 to 1000 kW-hr range) had been built over the past decade at universities and research institutes. More recent developments have also focused on its application in the production of H_2 and CO.

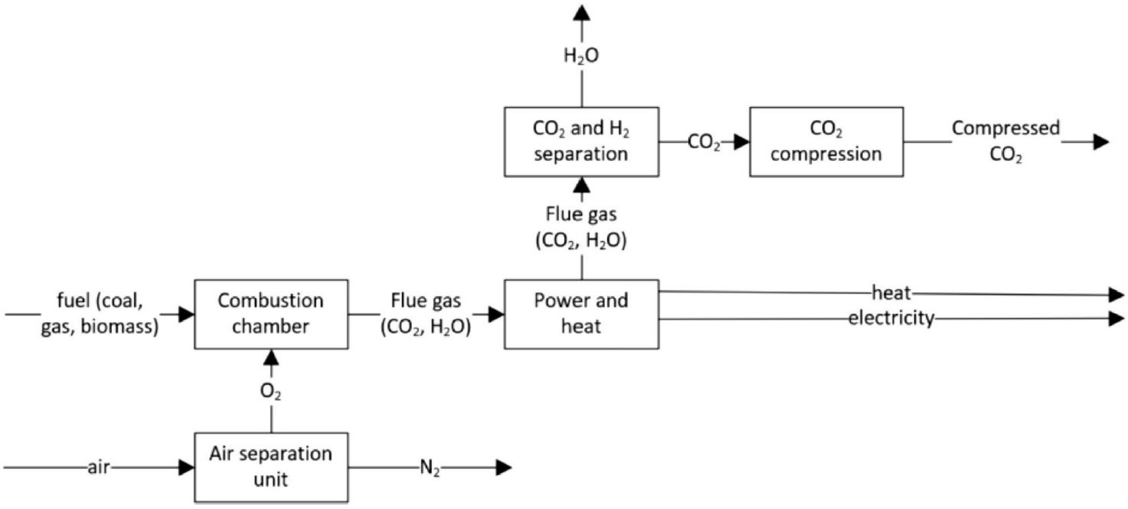
The idealised CLC system consists of two connected reactors, an air reactor and a fuel reactor (Madejski et al. 2022). In the air reactor, the oxygen-carrier such as a metal or metal oxide of iron, manganese, nickel or copper, reacts with oxygen in air to form a compound with a higher oxidation state (that is, it takes on additional lattice oxygen within its solid structure). For example, the reactions involving elemental manganese and iron oxide are shown below:

$2Mn + O_2 \rightarrow 2MnO$

$6FeO + O_2 \rightarrow 2Fe_3O_4$

The oxygen-carriers are transported to the fuel reactor, where they react with fuel such as coal, natural gas, and syngas to produce heat energy. As the oxygen-carrier is reduced (loses oxygen), the fuel is oxidised to CO_2 and water (De Vos et al. 2020). Water vapour in the flue gas from the fuel reactor is cooled, condensed, and separated with the dried gas further treated to remove impurities such as sulphur oxides (Kammerer et al. 2023). The regenerated oxygen-carrier is returned to the air reactor to begin the cycle again.

Figure 14: Illustration of a combustion with oxygen system.



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and Applications in Modern Energy Technologies. ENERGIES 2022, 15, 887 – 902. Copyright 2022 MDPI Journals.

Since the effectiveness of CLC depends on intimate contact between air, fuel, and the oxygen-carrier, reactor design and the transport of the oxygen-carrier between reactors is considered critical (De Vos et al. 2020). The most commonly reported research design was a fluidised-bed system as shown in Figure 15 (De Vos et al. 2020, Kammerer et al. 2023). Other reactor types include a packed bed (alternating air and fuel gases through a stationary layer) and a rotating bed reactor that continually turns between the different reacting gases.

Oxygen-carriers are the materials, which transfer oxygen from the air to the fuel in CLC, and their chemical and mechanical performance are considered key (De Vos et al. 2020). Therefore, this is an intensely active area of research with De Vos et al. (2020) finding more than 600 potential oxygen-carriers in the available literature.

The ideal properties of an oxygen-carrier were listed as (De Vos et al. 2020):

- A high oxygen transport capacity
- Favourable thermodynamic and kinetic properties for fuel and air conversions (considering reactor operating conditions and residence times)
- Chemical and thermal stability and limited sensitivity to impurities such as hydrogen sulphide (>5,000–10,000 hours on stream for engineered materials and >2,000 hours for ores)
- Good mechanical resistance to attrition and fragmentation within a reactor bed
- Negligible agglomeration under process conditions
- Low cost
- Negligible hazards to human health and the wider environment

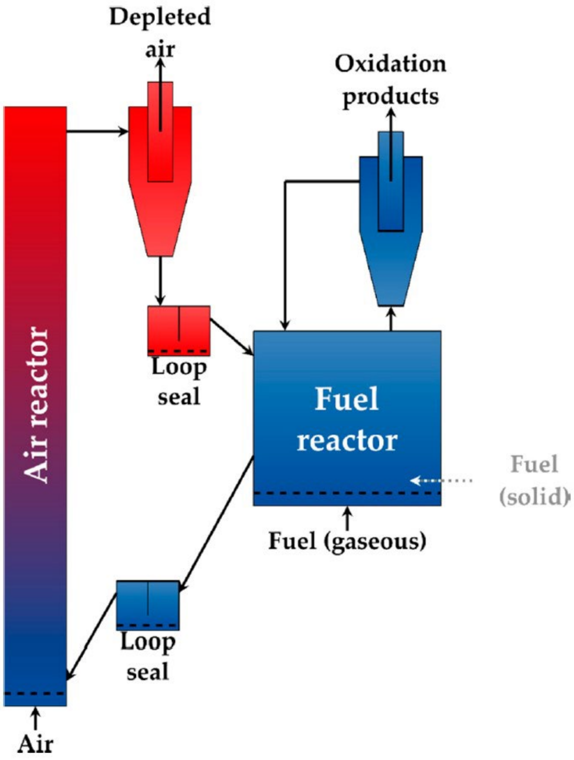
Early systems used nickel-based compounds as the oxygen-carrier, but in addition to being sensitive to sulphur impurities in the fuels, they were considered to pose a health and environmental hazard (De Vos et al. 2020). Iron has since emerged as a promising alternative because of its lower cost, reduced hazard, thermodynamic properties, and high oxygen-carrying capacity.

Metals and metal oxides are considered the active component in the oxygen-carrier, but other chemicals, called the inert support, are also used to enhance and maintain long-term performance (De Vos et al. 2020). These supports increase the surface area for reaction, improve mechanical properties, and/or enhance thermal stability. Frequently used supports in research reported in the literature included aluminium oxide, magnesium aluminium oxide, silicon dioxide, titanium dioxide, kaolin, zirconium dioxide, perovskites, and cerium dioxide (De Vos et al. 2020). Careful pairing of active agent and inert support is required because of solid-state interactions that can inhibit overall performance.

In addition to increasing oxygen carrying capacity and extending operational lifetimes, it was suggested by De Vos et al. (2020) that future research on oxygen-carriers and inert supports should focus on performance at higher operating pressures and developing effective process catalysts to work with low-cost materials.

Novel applications of CLC are also being investigated including energy from organic wastes. Domingos et al. (2024) evaluated using CLC for bioenergy from pig slurry with a small-scale reactor (0.5 kWt-hour). The process used a copper-based oxygen carrier supported on magnetic manganese-iron spinel. The study reported high combustion efficiencies (95-98%), high carbon capture efficiencies (82%-99%), and negligible tar residues in the flue gases. Most nitrogen present as ammonia or nitrogen oxides (93%-96%) was converted to N_2.

Figure 15: Simple schematic of a CLC system using a fluidised bed.



Reprinted with permission from DE VOS Y., JACOBS M., VAN DER VOORT P., VAN DRIESSCHE I., SNIJKERS F., VERBERCKMOES A., 2020. Development of Stable Oxygen Carrier Materials for Chemical Looping Processes—A Review. CATALYSTS, 10, 926-989. Copyright 2020 MDPI Journals.

Trends for Sector-by-Sector CCT

Power plants are the largest global source of industrially emitted CO_2 (Peu et al. 2023, Jing et al. 2024). In the UK, around 11% of total CO_2e emissions came from electricity generation in 2023 according to provisional data (DESNZ 2024). Other industries such as cement, iron and steel, oil, and petrochemicals are responsible for around 22% of global

CO_2 emissions (Rajabloo et al. 2023). According to provisional figures from the UK, oil refining and other extraction and production was responsible for 8% of emissions in 2023, while wider industrial emissions including iron and steel totalled 14% (DESNZ 2024).

Several researchers have outlined the options for decarbonisation available across a range of industrial sectors (Ganzer and Mac Dowell 2023, Jing et al. 2024):

- Source control, which includes energy substitution and energy efficiency improvements such as improved insulation.
- Process optimisation, which includes improving the efficiency of manufacturing processes such as using catalysts, combining technologies, and cogeneration.
- CCT, which includes a wide range of options to capture CO_2 emissions for storage and utilisation.

Ganzer and Mac Dowell (2023) noted that some wider industrial processes may be reliant on efficiencies and use of CCT in the power sector to achieve emission reductions because alternatives may be more energy intensive. This was seen as a critical coupling of the power sector with other industries.

The most favourable CCT options produce CO_2 streams of high purity, which are considered to be more suitable for compression, transport, and storage (Rajabloo et al. 2023). Many of the systems already operating at commercial-scale are based on the removal of these pure streams from either natural gas, syngas, or from fermentation during biofuel production (Al-Sakkari et al. 2023). Pre-combustion was noted by several authors to have lower operating costs than either post-combustion or oxy-combustion, however, capital expenditure was much higher (Podder et al. 2023, Jing et al. 2024). While it is considered a viable option for newer installations (Rajabloo et al. 2023), pre-combustion systems are not easy to retrofit, and such options are reportedly at a very low TRL. The main issue for retrofitting pre-combustion systems is thought to be the burn characteristics of H_2 as a fuel compared to other fossil fuels such as methane. In many cases, this required replacement of existing kilns or boilers and results in additional abatement costs for emissions such as nitrogen oxides.

In general, 70%–80% of the total cost of post-combustion CCT comes from the capturing stage, which depends on the partial pressure of CO_2, storage scale, energy costs, and technology innovation (Rajabloo et al. 2023). Many post-combustion systems could be retrofitted to existing plant, reducing the required capital expenditure (Jing et al. 2024). In the case of oxy-combustion and chemical looping, oxygen purification is considered necessary, and most conventional plants would require a dual fluidised bed system. Identified factors that reportedly increased the cost of its retrofitting included purifying of CO_2 from the flue gas and the removal of any hazardous co-contaminants such as sulphur and nitrogen oxides (Rajabloo et al. 2023). Jing et al. (2024) concluded that oxy–fuel combustion is currently not economically viable, and considerably more research is required before it could be applied.

Influence of Flue Gas Characteristics

The physical and chemical characteristics of the flue gas are considered by reviewers to play an important role in the selection of CCT for different industrial sectors (Jing et al. 2024). Factors that influenced the choice include operating temperature at the outlet, CO_2 concentration in the flue gas, and the presence of other gaseous and particulate components.

Jing et al. (2024) classified flue gases according to CO_2 concentration as high and low concentration gases. Industries with high concentration gases such as oil refineries have the advantage of capturing CO_2 without the need for enrichment, potentially lowering the capture cost. Low-concentration sources, such as steel and cement plants, require CO_2 enrichment and for these industries it is therefore a crucial area of research.

Where information on the composition of flue gases has been reported in the reviewed literature, this has been summarised for each industrial sector in the following sections.

Cement and Lime Industry

Few studies were identified in the literature for the historical uptake of CCT by the cement industry. Simoni et al. (2022) noted that despite intensive research efforts and development, CCT cannot be commercially applied in the lime sector yet due to their limited efficiency and the associated capital and operational costs. Commercial and demonstration-scale examples for the cement industry from the available literature are summarised in Table 2.

Table 2. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Heidelberg Materials Brevik plant, Brevik, Norway Cement production	Post-combustion CO_2 capture using amine-based chemical absorption and compressed for transport (around 0.4Mt CO_2 pa)	Jing et al. 2024
Lafarge Holcim's Portland Cement Plant in Colorado, USA	Solid adsorption and release using the Veloxotherm^{TM} (around 2Mt CO_2 pa)	Plaza et al. 2020

Cement production is responsible for around 7% of global CO_2 emissions, which primarily originates from the calcination reaction (Hågg et al. 2017, Jing et al. 2024). In the calciner, lime reacts with the hot flue gas from the kiln, releasing processed CO_2 (Leeson et al.

2017).[4] The calcined feed enters the kiln, the other major source of CO_2 in cement manufacture, where it is converted to clinker. Approximately 60% of emissions comes from calcination and 40% from fuel combustion for the kiln. Laveglia et al. (2023) estimated calcination emissions were around 0.79 tCO_2 per t CaO. The importance of CO_2 emissions from non-combustion sources was noted by Williams et al. (2024), who suggested from an energy analysis that fuel substitution alone would reduce emissions from a cement plant by only 27%. Laveglia et al. (2023) suggested that such non-combustion emissions can only be avoided with use of CCT.

Researchers did not consider pre-combustion CCT a viable alternative in decarbonisation of the cement industry (Hågg et al. 2017, Jing et al. 2024). Simoni et al. (2022) reported average compositions of flue gases from lime and cement kilns of 20% CO_2, 63% N_2, 8% O_2, and 7% water. However, Hughes et al. (2024) noted that CO_2 levels in flue gases are significantly reduced by the impact of false air ingress – a standard industry practice that reduces CO_2 levels in the kiln. Flue gas flow rates and CO_2 inflow concentrations are noted to be highly variable (Jing et al. 2024), depending on factors such as the use of a cement mill. When the mill is not running, gas flow falls, and CO_2 concentrations increase. Jing et al. (2024) summarised the typical characteristics of the flue gas from the cement mill as: 20 – 30% CO_2, 68% N_2, 2% oxygen, a high outlet temperature (120 - 150˚C), and a high dust loading. In a pilot-study at the Norcem cement plant in Brevik, Norway, the flue gases from the cement kiln were reported to have a typical composition of 18% CO_2, 8% O_2, 18% water, up to 130 mg/m^3 sulphur oxides, between 180 and 250 mg/m^3 nitrogen oxides, and from 5 – 10 mg/m^3 dust (Bjerge and Brevik 2014, Knudsen et al. 2014). At the same facility, Hågg et al. (2017) noted the presence of sulphur oxides at times when the lime scrubbers were out of service, as well as residual nitrogen oxides at levels higher than those normally found in the power industry.

Researchers have reviewed the potential effectiveness of several CCT options in the cement and lime industry (Jing et al. 2024, Simoni et al. 2023). Laveglia et al. (2023) modelled several CCT options using life-cycle analysis. They concluded that under a best-case scenario, CCT would be able to absorb 100% of the emissions from the calciner, but emission reductions would only be achieved by thermal recovery to reduce kiln energy consumption. Bjerge and Brevik (2014) summarised the technologies being investigated at pilot-scale at the Brevik Test Centre at the Norcem cement plant, which included amine-based solvent absorption, calcium looping, and an unspecified solid sorbent that relied on temperature swing to achieve capture.

The easiest solutions to retrofit are considered to be amine- and ammonia-based chemical absorption, and solid absorption using calcium looping (Jaffar et al. 2023, Jing et al. 2024).

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[4] These are processed CO_2 sources and not combustion or flue gas streams (Bains et al. 2017).

These are also the most mature options (TRLs 7 – 8). Amine-based systems were noted by several researchers to have high energy costs, especially for first generation systems using MEA (Leeson et al. 2017, Plaza et al. 2020). Amine degradation and equipment corrosion also presents a challenge because of the higher operating temperature and impurities in the flue gas. Simoni et al. (2022) highlighted that amine-based solvents such as MEA require that the flue gases from the lime industry are pretreated to remove impurities such as sulphur oxides, nitrogen oxides, and particulate matter. Not only are these pre-treatments necessary to reduce corrosion and degradation, but they also compete with CO_2 capture and impacted the capture rate. Direct Contact Cooling (DCC) was also recommended (Jaffar et al. 2023, Plaza et al. 2020) to prevent solvent losses by lowering the inlet temperature of the flue gas and to remove excess water. While these pre-treatments are effective at reducing impurities, they incur extra cost. Ammonia-based solvents were noted as more resistant to thermal and chemical degradation (Jing et al. 2024, Leeson et al. 2017, Plaza et al. 2020), and the by-products from the removal of sulphur oxides could be sold as a fertiliser (ammonium sulphate). However, ammonia slip was identified as a significant issue, requiring gases to be cooled by DCC (an extra energy and cost burden). Plaza et al. (2020) also reported on a pilot study of an alkali-based solvent system using sodium hydroxide at a cement plant in Texas. The sodium carbonate formed was considered a useful by-product. Most of the energy costs reported by the study came from use of an electrolyser to produce the sodium hydroxide from brine.

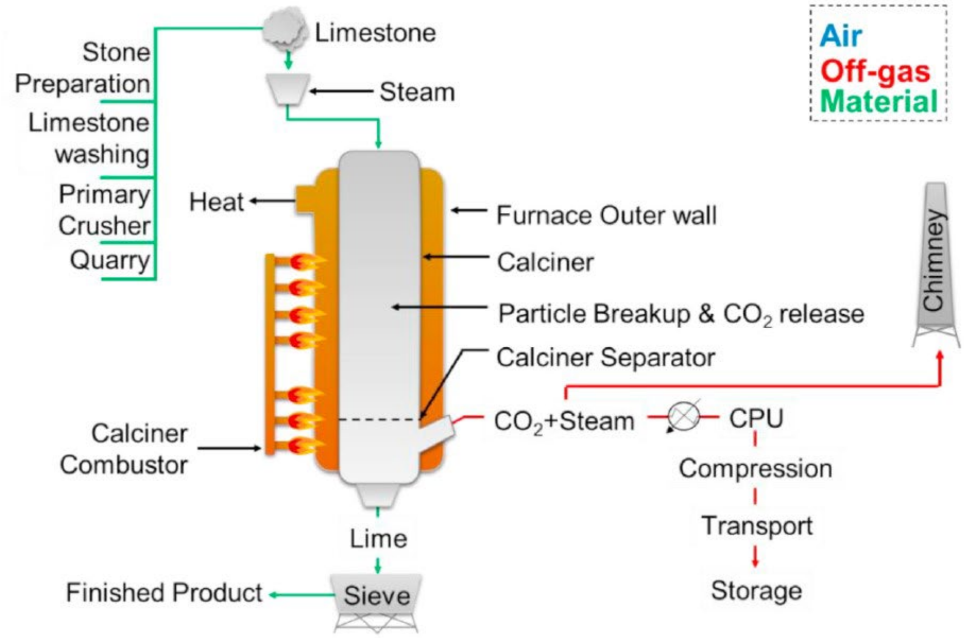
Calcium looping was considered to have many advantages including synergies with the calcination process (Greco-Coppi et al. 2024), but the operational problem of grain sintering, which reduced capture efficiency and increased particulate losses from the system, needed to be addressed (Jing et al. 2024). Simoni et al. (2022) also reported pilot plant experiences that suggested that capture efficiency dropped at higher sulphur oxide concentrations in the flue gases. Calcium looping was considered the best option for implementation in a Portuguese cement plant following an economic and environmental analysis, compared with post-combustion amine absorption and oxy-fuel CCT (Bacatelo et al. 2023). Greco-Coppi et al. (2024) noted that calcium looping implementation in the cement industry avoided the higher energy and economic costs of other post-combustion CCT. However, one of the high cost components of a conventional oxy-fired looping process is considered the air-separation unit (Greco-Coppi et al. 2024, Simoni et al. 2022, Yin et al. 2024). Greco-Coppi et al. (2024) modelled various configurations for indirectly heated calcium (carbonate) looping for heat recovery to offset energy requirements, by utilising waste heat from the combustion plant in various forms such as steam, solid heat carriers, and through a network of heat pipes that directly connected the calciner and the combustor. In an energy and economic analysis of these options, the choice of fuel was considered a critical factor with the optimised system using middle-calorific solid recovered fuel (SRF). Yin et al. (2024) investigated integration of various configurations of indirectly heated calcium looping into an existing cement plant, concluding that the most cost-effective was tail-end integration (taking the flue gas from the pre-heaters). Although full integration, combining indirect heating with the pre-calciner, resulted in the largest reductions in CO_2 emissions, the engineering and capital expenditure was considered applicable only to new-build plant and not existing locations. Ferrario et al. (2023)

proposed an alternative system where the heat energy required by the calciner was supplied by solar power.

Simoni et al. (2022) and Plaza et al. (2020) also identified the separation of the combustion and calcination reactions within the cement or lime kiln as a promising innovation. Also called Low Emissions Intensity Lime and Cement (LEILAC), the process has been piloted at the Heidelberg Cement facility in Lixhe, Belgium. Figure 16 presents an overview of the LEILAC process. Raw materials enter at the top of the reactor and calcined products exit at the bottom, while CO_2 rises in a counter-flow against the raw materials, allowing for the recovery of thermal energy. Cooled CO_2 exits at the top of the reactor, which is indirectly heated, requiring combustion gases to be treated separately.

Oxy-fuel combustion is considered by some researchers to require extensive equipment modification and a high capital expenditure (Bacatelo et al. 2023, Jing et al. 2024, Simoni et al. 2022). However, Costa et al. (2024) conceptualised that an oxy-fuel system could be used to enrich CO_2 in the flue gas (>70%), enabling more efficient post-combustion removal by cryogenic separation. Simoni et al. (2022) noted that for new build plants, there may be significant cost advantages through use of smaller and more efficient kiln designs.

Figure 16: The Low Emissions Intensity Lime and Cement process.



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Jing et al. (2024) concluded that while much easier to retrofit, membrane separation was considered to have higher energy and operational costs (the membranes being more easily damaged by sulphur and nitrogen oxides, and dust). In contrast, Ganzer and Mac Dowell (2023) identified membrane technologies as a potential option for cement plants, citing a pilot study at the Norcem Cement plant at Brevik in Norway (Hågg et al. 2017). Plaza et al. (2020) noted that the higher concentrations of CO_2 in the flue gases were especially advantageous to membrane technologies, although capture rates were typically around 60 – 70% in laboratory- and pilot-scale studies. In the pilot study at Brevik (Hågg et al. 2017), polyvinylamine based hollow fibre fixed-site-carrier membrane modules (up to 18 m^2) were installed at the site. Operational challenges included the presence of oxygen in the combustion gas as CO_2/O_2 selectivity by the membrane was much lower than its separation of CO_2/N_2. It was concluded by the authors that the membrane had maintained its performance despite the hard conditions resulting from the presence of sulphur oxides. The capture rate was not reported from the single-stage study, the purity of the separated gas was >70% CO_2. Nevertheless, the membrane capture efficiency was described as low, and the membrane modules suffered from water condensation and corrosion issues (Plaza et al. 2020). Hughes et al. (2024) modelled the economic and capture performance of a membrane-based CCT in a cement plant, noting that the practice of false air ingress in the kiln significantly reduced effectiveness and increased cost. Only when this practice was omitted from the analysis was a membrane system comparable with an amine-based absorption system. The modelling also noted that increasing the membrane selectivity for $CO_2:N_2$ from 25 to 60 significantly reduced predicted operational cost, but that further advances including a permeance beyond 1,000 Gas Permeation Unit (GPU) had only an incremental impact.

While solid adsorption had not been evaluated in the lime industry, Simoni et al. (2022) identified several pilot studies at cement plants including the LaFarge Holcim facility in British Columbia. Jaffar et al. (2023) highlighted that the modular nature of some processes, determined by the size of the fluidised bed, would require the operation of several modules in parallel for continuous operation. A system to exploit heat recovery from the kiln to produce steam was selected for demonstration at the LaFarge Holcim facility in Colorado, USA (Plaza et al. 2020). The Veloxotherm^{TM} Rotary Adsorption Machine splits the flue gas that enters the bottom of the unit into CO_2-rich and CO_2-depleted streams. It was reported by the developers to be sorbent agnostic (Plaza et al. 2020), and candidate physical solid sorbents included carbon materials, zeolites, alumino-phosphates (AlPOs), alumino-silico-phosphates (SAPOs), silica-alkoxylated polyethyleneimine, and MOFs (Jaffar et al. 2023, Plaza et al. 2020). Pressure-swing desorption using a vacuum was reportedly preferred for CO_2 capture and recovery because the flue gases from the cement plant are at atmospheric pressure (Plaza et al. 2020). A system using polyethyleneimine, loaded on silica, was piloted at the Norcem cement plant at Brevik between 2014 – 2017 (Plaza et al. 2020). A multistage fluidized bed was used to continuously circulate the sorbent between the absorber and the regenerator. The flue gas was cooled and the condensate knocked out to minimise impact of contamination on the sorbent. Tests showed that sorbent exposure to 100 ppm of sulphur dioxide reduced its CO_2 capacity by 30%. A capture rate of 80 – 90% was reported, but energy consumption (without any heat recovery) was considered a concern

(Plaza et al. 2020). Jaffar et al. (2023) modelled a similar system for a cement plant in the UK and showed that economic costs and capture rates were comparable with an amine-based system using MEA.

Chemicals Industry

Commercial and demonstration-scale examples from the available literature are summarised in Table 3. According to Jing et al. (2024), the chemicals industry is the world's largest energy consumer, accounting for approximately 5% of total global industrial CO_2 emissions. It has been heavily reliant on coal, oil, and gas as both fuel and feedstock. Approximately 25% of the industries' carbon emissions are attributed to chemical reactions and processing, while 75% originated from fuel combustion (Jing et al. 2024). Fritzeen et al. (2023) noted that almost half the reduction in emissions from CCT projected for the chemical sector are the result of upstream mitigations by the power and heat industry. Feedstock switching to biogenic sources accounted for up to 30% of the predicted emission reductions across the sector. Kloo et al. (2024) reviewed a number of industry and non-industry roadmaps for industry decarbonisation. These roadmaps showed a high degree of variability and industry uncertainty. Many decarbonisation options were proposed including switching feedstocks and use of renewable fuels and energy. CCT was proposed for both utilisation and storage of CO_2, although in many roadmaps its contribution to reducing emissions was <20%. In an integrated assessment model for the global organic chemicals industry that included the whole lifecycle of plastics, Fritzeen et al. (2023) concluded that the only scenario that delivers net-negative emissions by 2070 combined greater use of biogenic feedstocks with a continued reliance on landfilling of waste plastic, versus recycling or incineration.

Chemicals production involves high process integration and complex pipelines (Jing et al. 2024), meaning that multiple emission sources are present across an industrial plant. Ganzer and Mac Dowell (2023) noted that production of feedstocks including ethylene, ethylene oxide, bioethanol, and ammonia, result in high purity processed CO_2 gas streams as by-products, and that these outputs represent 'low-hanging fruit' for industrial decarbonisation. Ganeshan et al. (2023) identified four operational production facilities worldwide for bioethanol with a capture capacity of greater than 0.2 Mt CO_2 pa (see Table 3). Jing et al. (2024) noted that small modular capture units using amine-based solvents could address the logistical challenge of multiple capture points across a facility. Their small footprint, low cost, and easy installation would allow them to integrate within the constraints of existing plant processes and structures. Hu et al. (2023) modelled the effectiveness of an amine-based CCT unit to manage the flue gases from a thermal cracking unit used in ethylene production. The composition of the modelled flue gas was 4% CO_2, 14% O_2, 80% N_2, and 3% water. The authors noted that its energy efficiency could be improved by using excess heat energy from the cracking unit. As noted previously (see Carboxylation under Chemical Absorption Solvents), researchers have also proposed using waste plastics and captured CO_2 products as alternative feedstocks for chemical production in the future. Solarte-Toro and Alzate (2023) highlighted that CCT for utilization as a feedstock may be an important consideration for the sustainability of biorefineries.

Table 3. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Alco Energy, Rotterdam Bioethanol production	Captured CO_2 from fermentation (no method specified), compressed for use in greenhouses (around 0.4Mt CO_2 pa)	Ganeshan et al. 2023
Arkalon CO_2 Compression Facility, Texas, USA Bioethanol production	Captured CO_2 from fermentation (no method specified) and compressed for transport (around 0.3Mt CO_2 pa)	Ganeshan et al. 2023 Gautam and Modal 2023
Coffeyville Gasification Plant, Kansas, USA Fertiliser manufacture	Pre-combustion separation of CO_2 from coke gasifier using amine-based absorption (around 1Mt CO_2 pa)	Al-Sakkari et al. 2024
Enid Fertiliser, Koch Nitrogen Plant, Oklahoma, USA Fertiliser manufacture	Pre-combustion separation of CO_2 from natural gas (no method specified)	Gautam and Modal 2023
Illinois Industrial CCT, Illinois, USA Bioethanol production	Captured CO_2 from fermentation by amine-based solvents and compressed for transport (around 1Mt CO_2 pa)	Ganeshan et al. 2023 Gautam and Modal 2023
Nutrien Redwater Nitrogen Plant, Alberta, Canada Fertiliser manufacture	Pre-combustion separation of CO_2 from syngas using the Rectisol® method for physical absorption (around 0.6 Mt CO_2 pa)	Al-Sakkari et al. 2024
Occidental Petroleum Corporation and White Energy, Hereford and Plainview, Texas,	No details available (around 0.6Mt CO_2 pa)	Ganeshan et al. 2023

Example	CCT Description	Reference
Bioethanol production		
PCS Nitrogen, Louisiana, USA Fertiliser manufacture	Pre-combustion separation of CO_2 (no method specified)	Gautam and Modal 2023
Wabash Valley Resources, Indiana, USA Fertiliser manufacture	Pre-combustion separation of CO_2 from syngas for ammonia production using the Rectisol® method for physical absorption (around 2 Mt CO_2 pa)	Jing et al. 2024

Metals Industry

There has been limited historical uptake of CCT by the metals industry. Ganzer and Mac Dowell (2023) observed that there was a "noticeable paucity of pilot plants" for novel processes and CCT. Commercial and demonstration-scale examples from the available literature are summarised in Table 4.

The iron and steel industry is a significant contributor to greenhouse gas emissions, responsible for 14.2% of greenhouse gas emissions from manufacturing and 2.4% of total UK greenhouse gas emissions (Keep et al. 2023). Jing et al. (2024) highlighted that secondary steel from scrap metal offers significant emission reductions because it requires only 25% of the energy needed for production from iron ore. In an analysis of the techno-economic pathways for the Chinese iron and steel sector, Huang et al. (2023) observed that switching to scrap-electric arc furnace production and increasing the share of renewables in electrification reduced projected emissions from this sector by 52% in 2060. Promoting material efficiency, energy efficiency, natural gas, and bioenergy were considered key near-term measures since they accounted for 37% of emission reduction. Application of CCT and H_2 were predicted to reduce emissions by only 11%, but that these margins were likely to be indispensable in the long-term.

The blast furnace is where most research has been focused (Leeson et al. 2017), where the flue gases are reported to contain up to 15% CO_2 by volume (Keys et al. 2019). Yang et al. (2023) described the typical properties of the flue gas from a blast furnace as 51% N_2, 22% CO, 24% CO_2, 3% H_2, and a temperature and pressure of 60˚C and 116 kPa, respectively. In a techno-economic analysis, researchers concluded that significant reductions in CO_2 emissions could be achieved by moving away from blast furnace/basic oxygen furnace production to direct reduced iron-electric arc furnace with CCT or direct reduced iron-electric arc furnace (DRI-EAF) with H_2 fuel (Benavides et al. 2024, Trinca et al. 2023, Zhang et al. 2023). Use of CCT with a traditional blast furnace was not considered as effective because of its multiple CO_2 emission points in the process, raising costs and complexity. Perpiñán et al. (2023) and Yang et al. (2023) disagreed.

Keys et al. (2019) identified the multiple emission sources at the coal-fired blast furnace operated by Tata Steel in the Netherlands. They attributed more than 50% of emissions to power generation, which is used within the various production processes. Other significant emission sources were the blast furnaces, the coking plant, and downstream steelmaking processes. Yang et al. (2023) described the typical properties of the flue gas from a coking plant as 4% N_2, 10% CO, 6% CO_2, 56% H_2, 24% volatile hydrocarbons, and a temperature and pressure of 60˚C and 108 kPa, respectively. Most primary options for decarbonisation considered by Keys et al. focused on modifying the process to reduce the amount of CO_2 emissions rather than on CCT. For example, in a top gas recycling blast furnace (TGR-BF), reducing agents in the off gas from the furnace (CO and H_2) are recycled to reduce the demand for coke, lowering emissions from the coking plant. Perpiñán et al. (2023) proposed using renewable H_2 to reduce the need for coke, combining this with a conventional amines-based CCT. Tata Steel were testing the HIsarna system at a plant in India, which used a higher temperature design to eliminate pre-processing of iron ore and coal through direct injection of these materials into the furnace, eliminating emissions from the pelleting and sintering plants. While a hydrogen-based system would offer even greater emission reductions in the longer term, there remain a number of technical and economic challenges to its implementation (Benavides et al. 2024, Jing et al. 2024, Shahabuddin et al. 2023). For example, some carbon is still required to give steel its hardness and strength, and there are difficulties in infusing H_2 safely at high temperatures. Furnaces must be equipped with indirect heating elements and novel coking technology to refine stronger and more reactive coke (Jing et al. 2024). Initial economic projections suggest that the introduction of H_2 would only be cost effective if technological costs are reduced and additional incentives provided. Hybrid systems that partially substituted H_2 for coke into the blast furnace process have been demonstrated in Japan (Jing et al. 2024).

An example of the DIR-EAF with CCT is operated in Abu Dhabi by Emirates Steel (Benavides et al. 2024, Al-Sakkari et al. 2024). It was reported to achieve a capture efficiency of >90%, which required further purification of the outlet stream from the capture plant (amine-based solvent) using a physical adsorption system to separate out H_2 and other hydrocarbon compounds for use as a fuel. Since the process was set up to selectively separate CO_2 from the system, there was minimal capital cost increase to the base plant.

Table 4. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Emirates Steel Industries, Abu Dhabi, United Arab Emirates Iron and steel production	Pre-combustion separation of CO_2 from natural gas, which is used to form syngas to replace coke in production, using an amine-based absorption process (around 0.8 Mt CO_2 pa)	Al-Sakkari et al. 2024

Research studies have reviewed the potential CCT options in the iron and steel industry and their effectiveness (Carbone et al. 2023, Jing et al. 2024, Keys et al. 2019, Leeson et al. 2017, Trinca et al. 2023). While many of the CCT options proposed for the power sector are considered broadly applicable, the multiple points for emissions control is considered an added complexity. Keys et al. (2019) noted that unlike the power sector, CCT in steelmaking does not readily fall directly into the standard classification system (pre-combustion, post-combustion or oxyfuel combustion). They observed that CCT for steelmaking primarily concerns capturing emissions from the reduction of iron ore, rather than combustion or oxidation. Perpiñán et al. (2023) commented that in the iron and steel industry, amine scrubbing is widely considered one of the most effective and practical approaches for capturing flue gas emissions from the blast furnace. However, the energy penalty (the amount of additional energy needed to run the CCT plant at a given capture rate) is identified as a significant challenge. Yang et al. (2023) modelled the capture efficiency and energy balance associated with use of CCT based on MEA using several scenarios for offsetting the heat needed to regenerate the solvent. Most scenarios utilised waste heat as steam from other parts of the steel making process. Challenges were noted around the volume of flue gas generated by the blast furnace and the size of the CCT absorber and stripper needed to accommodate it. Energy demands were higher for the recovery of CO_2 from the coking plant because of the lower starting concentration in the flue gas. Heat exchangers were identified as the equipment with the largest capital cost. Re-use of steam offset the operational cost of the system.

Possible solutions to the multiple sources of emissions across the process have been proposed using chemical absorption solvents including individual source treatment, combining sources for treatment centrally, and a hybrid system where absorbers are fitted at individual sources, but the stripper is centrally located. Most demonstration projects identified by Jing et al. (2024) used amine-based chemical absorption including the only full-scale commercial plant in Abu Dhabi.

Researchers reported several CCT options had been trialled at iron and steel works including use of amine chemical solvents (such as methyl diethanolamine) and vacuum pressure swing absorption (VPSA and PSA) using physical solvents such as Selexol

(Leeson et al. 2017, Trinca et al. 2023, Yang et al. 2023). A modelling analysis by Trinca et al. (2023) concluded that CCT could contribute a further 40% reduction in CO_2 emissions in addition to replacing the conventional blast furnace with DIR-EAF.

Keys et al. (2019) summarised the main CCT options being considered by the European Union Ultra-low CO_2 Steelmaking (ULCOS) programme as amine-based chemical absorption, VPSA and PSA, and cryogenics. Initial conclusions from a TGR-BF pilot plant in Luleå, Sweden were that implementation of a VPSA CCT system had the advantage that CO_2 removal increased the concentration of reducing agents for recycling back into the furnace. In a TGR-BF system, the typical concentration of CO_2 in the flue gas is between 15 – 55% by volume. CCT implementation for the HIsarna process is considered more challenging because of the need for dust removal, heat recovery and de-sulphurisation processes, although the off gas contains up to 95% CO_2 and in some cases, this may be sufficient without additional processing (Keys et al. 2019).

Carbone et al. (2023) identified calcium looping as a promising CCT process for iron and steel manufacture because of its suitable for high energy intensive processes and high temperature heat recovery. In addition, the sorbent, CaO, and its products could potentially be recycled in the steel production process as a base additive in flux. Life cycle analysis using an end-of-pipe application of a CCT unit to a conventional blast furnace or electric arc furnace demonstrated a significant reduction in CO_2 emissions, even accounting for the extra energy/emissions associated with the calciner. Jing et al. (2024) described the use of steel slag as a promising solid absorption material. In this method, the carbon in slags is converted to carbonates by reaction with the flue gases.

Oil and Gas Industry

Oil and gas refineries feature a number of point sources for the release of flue gases containing CO_2 at different concentrations and flow rates (Leeson et al. 2017, Yao et al. 2018). Refining and other extraction and production was responsible for 8% of UK emissions in 2023, according to provisional figures (DESNZ 2024). These sources include unit processes such as catalyst regeneration, utility systems for the use and production of steam and H_2, and fired heaters associated with the individual unit processes across the facility. Ganzer and Mac Dowell (2023) noted that the main decarbonisation methods for refineries involve replacement of fossil fuels with low carbon alternatives for heat.

Commercial and demonstration-scale examples from the available literature are summarised in Table 5. Many of the active commercial projects since the 1970s involve the purification of natural gas and the use of recovered CO_2 for enhanced oil recovery (Al-Sakkari et al. 2024, Gautam and Modal 2023). CCT methods at these plants include solvent-based physical absorption, amine-based chemical absorption, membrane processing, and cryogenic separation methods.

Yao et al. (2018) investigated the potential emission reductions and cost for US refineries based on implementation of either pre-combustion/oxy-fuel combustion methods and post-combustion methods. These were evaluated within either a distributed or a centralised design. The findings from the study included: post-combustion methods offered the greatest potential for emissions reduction but were more costly than pre-combustion methods; and post-combustion CCT may not be cost-effective for smaller sources within the plant. Overall, CCT could help achieve a 60 – 70% reduction in CO_2 emissions across the sector. The researchers noted that "*Although the conclusion that large sources will be economical and small sources will be uneconomical is intuitively obvious because CC technology costs need economies of scale to be acceptable, the questions of "how small is too small for CC adoption" or "how large is suitable for a CC adoption" did not have clear answers prior to this study.*" (Yao et al. 2018, page 95).

Table 5. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Century Plant, Texas, USA Natural gas production	Pre-combustion cleanup of natural gas using membrane separation (around 8.4 Mt CO_2 pa)	Al-Sakkari et al. 2024
Core Energy Antrim Shale Gas Plant, Michigan, USA Natural gas production	Pre-combustion cleanup of natural gas using an amine-based absorption process (around 0.3 Mt CO_2 pa)	Al-Sakkari et al. 2024
Dakota Gasification Company, North Dakota, USA Coal-gasification for methane	Pre-combustion separation of CO_2 from syngas using the Rectisol® method for physical absorption or amines-based chemical absorption (around 3 Mt CO_2 pa)	Al-Sakkari et al. 2024 Podder et al. 2023
Glacier Gas Plant, Alberta, Canada Natural gas production	Pre-combustion separation of CO_2 from syngas using the Rectisol® method for physical absorption (around 0.2 Mt CO_2 pa)	Al-Sakkari et al. 2024
Gorgon CO_2 Injection, Barrow Island, Western Australia Natural gas production	Pre-combustion cleanup of natural gas using a potassium carbonate-based absorption process (around 4 Mt CO_2 pa)	Al-Sakkari et al. 2024
Mol Sanke Gas Processing Facilities, Molve, Croatia Natural gas production	Pre-combustion cleanup of natural gas using an amine-based absorption process (around 0.16 Mt CO_2 pa)	Al-Sakkari et al. 2024

Example	CCT Description	Reference
Shute Creek Gas Processing Plant, Wyoming, USA Natural gas production	Pre-combustion cleanup of natural gas using a cryogenic separation method (around 7 Mt CO_2 pa)	Jing et al. 2024
Sinopec Zhongyuan Refinery, He'Nan Province, China Catalyst regeneration process	Post-combustion separation of CO_2 from flue gas after sulphur and nitrogen oxide pretreatment using amine-based solvent (around 0.6 Mt CO_2 pa)	Al-Sakkari et al. 2024 Gautam and Modal 2023 Zhang et al. 2017
Sleipner Fields, Norway Natural gas production	Pre-combustion separation of CO_2 from syngas using the Rectisol® method for physical absorption (around 1 Mt CO_2 pa)	Al-Sakkari et al. 2024
Hawiyah Gas Plant, Saudi Arabia Natural gas production	Pre-combustion cleanup of natural gas using an amine-based absorption process (around 0.8 Mt CO_2 pa)	Al-Sakkari et al. 2024

Power Industry (Coal, Gas, and Oil)

Power plants are the largest global source of industrially emitted CO_2 (Peu et al. 2023, Jing et al. 2024). In the UK, around 11% of total CO_2e emissions came from electricity generation in 2023, according to provisional data (DESNZ 2024). While many countries including the UK and India see renewables and other low carbon options such as nuclear driving emission reductions across the whole sector, CCT will have an important role to play in dispatchable energy supply (Das et al. 2023, Wilkes et al. 2023). Dispatchable power includes small-scale plants (<50MW) as well as some larger plants that can be powered up and down quickly to stabilise the electricity grid and balance short-term differences in supply and demand (Wilkes et al. 2023). The power sector is also the most advanced in terms of application of CCT at full-scale with commercial and demonstration-scale examples from the available literature summarised in Table 6. In this section, reference is made to CCT applications for coal-fired power plants because they are still widely used internationally and their CCT experience may be relevant to the UK. However, it is recognised that most power stations in the UK run on natural gas or oil with the last coal-fired power station closing in late 2024.

Gowd et al. (2023) noted that the main factors influencing the speed of uptake across this sector were: capital cost, energy penalty, and ability to retrofit. They estimated that addition of post-combustion CCT to a 550 MW coal-fired power plant increased the capital cost for the facility by 17%. An example of a membrane-based CCT, which consumed around 162 kWh to capture 1 tCO_2, was estimated to decrease the efficiency of the same coal-fired power station by between 33 – 38%. In a techno-economic modelling analysis of coal- and gas-fired power plants in China, Shao et al. (2024) concluded that adoption of current CCT designs (using amine-based solvents) would result in a levelized cost increase in the price of electricity of between 10 – 14%, attributed to the energy penalty. They recommended a greater focus on reducing this penalty in future innovations. Wilkes et al. (2023) highlighted the issues for dispatchable power generation in the UK from units operating at <50 MW and the need for further research to develop economic options for CCT. Fitting current CCT options to these smaller units was considered cost-prohibitive – tripling the cost of energy supplied due to economies of scale and lower plant capacities. Kim et al. (2023) modelled the environmental emissions and economic cost of using low grade coal in a 500 MW coal-powered station in combination with pre- (oxy combustion) and post-combustion (MEA-based solvent absorption). Oxy-combustion was identified as the option with the lowest economic and environmental cost of the two systems reviewed.

Table 6. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Boundary Dam 3 Carbon Capture and Storage Facility, Saskatchewan, Canada Coal-combustion for power (115 megawatts)	Post-combustion separation of CO_2 from flue gas using amine-based chemical solvents (1Mt CO_2 pa)	Al-Sakkari et al. 2024 Giannaris et al. 2021 Stockwell 2024
Elk Hills Power Plant, California, USA Gas-combustion for power (550 megawatts)	Post-combustion separation of CO_2 from flue gas using amine-based chemical solvents (1.4 Mt CO_2 pa)	Jing et al. 2024
Guohua Jinjie Power Station, Shaanxi, China Coal-combustion for power (600 megawatts)	Post-combustion separation of CO_2 from flue gas using either an amine-based chemical solvent or physical adsorbent (between 0.1 – 6 Mt CO_2 pa)	Jing et al. 2024 Lu et al. 2023

Example	CCT Description	Reference
NET Power LLC Test Facility, Texas, USA Gas-combustion for power (50 megawatts)	Oxy-combustion system for CO_2 capture from flue gas (not known)	Podder et al. 2023
Petra Nova, Texas, USA Coal-combustion for power (280 megawatts)	Post-combustion separation of CO_2 from flue gas using an amine-based chemical solvent (up to 1.6 Mt CO_2 pa). Plant shutdown in 2020.	Stockwell 2024
Warriors Run Generating Station, Maryland, USA Coal-gasification for power combustion (200 megawatts)	Post-combustion separation of CO_2 from flue gas using amine-based chemical solvents (not known)	Podder et al. 2023

Wang et al. (2023) presented an economic model that CCT was unlikely to make a significant contribution to the low carbon transition in China at a power company level by 2050. They concluded that one possible reason for this was that the increased investment and operational costs of retrofitting CCT outweighed the savings from reduced emission costs. Novel methods have been conceptualised for new power plant configurations, which often include CCT. For example, Liu et al. (2024e) modelled a power system that utilised biomass combustion for district heating with further heat recovery using an organic Rankine Cycle unit followed by production and burning of biogas. CCT using an amine-based solvent was included in the design to capture any residual emissions from the trigeneration system.

Power plants have very different flue gas characteristics. Nedoma et al. (2023) noted that the average CO_2 content in natural gas-fired systems ranged from about 4% by volume for combined cycles and 7–8% by volume for power plants with gas-fired boilers. These lean CO_2 combustion gases pose economic challenges for CCT options like sorbent adsorption, which are more cost-effective at higher CO_2 levels, along with the technical challenges associated with higher levels of O_2 and water. In the case of coal-powered systems, the flue gases contain higher levels of reactive components like sulphur oxides, heavy metals, and particulate matter (Nedoma et al. 2023).

Most commercial and demonstration-scale CCT projects have used post-combustion carbon capture using an amine-based solvent system (see Table 6). Boundary Dam, a coal-fired plant in Saskatchewan, Canada, adopted the Shell CanSolv proprietary amine-solvent blend because the system was considered able to handle high sulphur oxide content from the coal used (Stockwell 2024). Also using an amine-based solvent system, the Petra Nova plant in Texas was reportedly moth-balled in 2020 because of a drop in the price of CO_2 made it uneconomical. Capture rates at these two plants were reported to be 57% and 81%, respectively (Stockwell 2024). At Boundary Dam, the CCT plant was operational only 80% of the time due to mechanical issues caused by wet coal and plugging/fouling, water cooling issues, and corrosion. Amine-degradation was a significant factor as a result of high flue gas temperatures and fly ash. At the Petra Nova plant, the reduced performance was caused by scaling on the compressor and leakages in the heat exchangers (Stockwell 2024). The reported energy penalties at these operational plants was between 14 and 20%, which is within the range of expected penalties reported by Vasudevan et al. (2016) across gas, oil, and coal-powered plants.

While techno-economic analysis has concluded that oxy-combustion designs are the most cost-effective to operate and have lower environmental impact than post-combustion approaches (Kim et al. 2023), they remain difficult to retrofit. Many CCT options have been investigated for conventionally-fuelled power stations, but most examples in the published literature are conceptual or modelled systems only. For example, Duan et al. (2016) modelled the energy efficiency and capture rate using a calcium looping system in a coal-fired power station. They found that a capture efficiency of 85% resulted in an energy penalty of 10%, with the amount of sorbent and its replenishment the critical factors. Increased capture efficiency and lower energy requirements either through the chemical processes used or offsetting heat recovery are some of the most investigated options to reduce the energy penalty. For example, Nedoma et al. (2023) proposed a sorbent-based system (zeolite columns) using vacuum swing adsorption (VSA) for a gas-fired power station. They reportedly overcame the challenges of moisture in the flue gas by incorporating heat re-use in a dehydration pre-treatment stage in the design. In terms of amine-based systems, Subramanian and Madejski (2023) investigated options to reduce the energy penalty including the type and blend of solvents used in combination with secondary heat exchange. Zhu et al. (2023) modified the challenges of retrofitting an amine-based system to a coal-fired power station by using direct air cooling to reduce water demand. They showed that the overall energy balance and responsiveness of energy dispatch posed a problem to implementation. Xi et al. (2023) modelled a stochastic scheduling system for balancing the needs of day to day dispatchable power as highlighted by Wilkes et al. (2023), which optimised power and capture requirements. Such an approach would require integration into control systems.

Bioenergy with carbon capture and storage (BECCS) has been proposed for the power sector by many researchers and policy makers. However, despite several CCT options reported as ready for commercialisation, Ganeshan et al. (2023) noted that there were no examples of a commercial plant operating at >0.2 Mt CO_2 pa.[5] Similar to the available literature on conventional systems, proposed systems are often conceptual and modelled only. Researchers have investigated the combination of different options for BECCS including carboxylic acid based solvents (University of Leeds 2021), oxy-combustion chemical looping (Fleiß et al. 2024). In a techno-economic analysis, Fleiß et al. (2024) examined the use of chemical looping with either a synthetic or a natural oxygen carrier using data from a pilot study. While the capture rate was reported to be much higher for the synthetic material due its tailored reactivity (>98.5%), its production and fragility meant that costs were much higher (75 €/tCO_2 compared to 40 €/tCO_2). The authors concluded that the process could be adapted to improve the longevity of the synthetic material. Brigagão et al. (2023) modelled the energy and emissions efficiency of an oxy-combustion versus post-combustion with second generation amines including PZ for a BECCS power plant running on corn-cobs. They found that oxy-combustion outperformed post-combustion CCT.

Several researchers have also conceptualised hybrid CCT options for power plants. Habib et al. (2024) modelled the potential performance of a combination of membranes with a MOF solid sorbent for a natural gas combined cycle power plant. Using a number of absorber beds operating in parallel with temperature swing desorption using steam for CO_2 recovery, a capture rate of around 85% during peak and off-peak operation was predicted. When combined with a membrane separator, this increased to over 98%.

Power Industry (Energy from Waste)

Energy from waste (EfW) covers a range of activities including incineration with energy recovery (electricity and heat), anaerobic digestion for biogas and biomethane, and other biochemical processing to produce fuels such as bioethanol (Defra 2021 and 2024). Bioethanol and other similar fuels are discussed separately for the chemicals industry (see Chemicals Industry). In 2022 (Muslemani et al. 2024), EfW facilities generated around 3.2% of the UK's total power output but also emitted around 3.5% (14.4 Mt CO_{2e}) of its net annual greenhouse gas emissions.

Muslemani et al. (2024) suggested that EfW makes a vital contribution to emission reductions for the UK because it diverts wastes from landfill (reducing potential methane emissions) and for certain biogenic feedstocks, such as crop residues, acts as a greenhouse gas removal method. Between 50 – 70% of CO_2 emissions come from biogenic sources in the waste (Dal Pozzo et al. 2023, Su et al. 2023). A similar set of advantages were noted by Moioli et al. (2024) in an assessment of an EfW plant in Italy.

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[5] Bioethanol production, another form of BECCS, is discussed in the section on the chemicals industry.

However, Dal Pozzo et al. (2023) reported that the low energy efficiency of such systems is a significant hurdle to achieving overall emission reductions.

Muslemani et al. (2024) considered three factors in assessing the suitability of existing UK EfW plants for CCT implementation. The first was capacity, a minimum emission of around 0.1 Mt CO_2 pa, and the second was the physical space needed for CCT construction as a proportion of plant capacity. The third and final factor was the distance to and availability of pipelines for CO_2 transport and storage. The results of the analysis were that between 60-65% of the 57 EfW facilities in the UK were found to meet the minimum criteria for capacity and space. These facilities represented between 74-78% of the total CO_2 emissions from all UK EfW facilities. However, suitable CO_2 transport options represented a major technical barrier to implementation. Use of a pipeline or road tankers were the only options for transporting captured CO_2 from around 19% of sites. Dal Pozzo et al. (2023) noted that EfW plants could benefit significantly from CCT because they were often point sources with emissions in the range 0.1 – 1 Mt CO_2 pa. Despite this, Boré et al. (2024) noted that globally the implementation of CCT to EfW was limited and almost non-existent in China. In addition to CO_2 transportation, Otgonbayar and Mazzotti (2024) highlighted the challenges of coupling CCT with EfW plants connected to district heating networks. Kumar et al. (2023) reported that an alkali solvent CCT system has been proposed for the new district heating Stockholm Exergi power plant.

Commercial and demonstration-scale examples from the available literature are summarised in Table 7.

Most literature presented modelling studies for the retrofitting of CCT to existing EfW plants and processes with a focus on energy efficiency and economics. Boré et al. (2024) modelled the energy requirements and capture efficiency for a generic 20 MW combined heat and power EfW in China with post-combustion CCT using an amine-based solvent system. Boré et al. (2024) found that a capture rate of between 85 and 95% resulted in an increasing energy penalty of between 13 and 17%, respectively.

Table 7. Examples of commercial and demonstration-scale plants with capacities greater than 0.2 Mt CO_2 pa.

Example	CCT Description	Reference
Hafslund Oslo Celsio, Norway EfW	Post-combustion solvent absorption using CanSolv amine-based system (0.4 Mt CO_2 pa)	Muslemani et al. 2024
ZEROS Project, Texas, USA EfW	Oxy-combustion process using pure oxygen, followed by post-combustion separation of high concentration CO_2 from flue	Jing et al. 2024 Jones and Clark 2011

Example	CCT Description	Reference
	gas and compression for use (1.5 Mt CO_2 pa)	

One common option to offset the energy penalty associated with CCT is to use excess heat from the CCT plant as part of a district heating scheme (Bisinella et al. 2021, Moioli et al. 2024, Otgonbayar and Mazzotti 2024, Su et al. 2023). However, this leads to seasonal differences in the energy penalty related to the demand for the excess heat. In an analysis of an amine-based solvent system using MEA at a plant in Como, Italy, Moioli et al. (2024) concluded that the energy penalty ranged from 17.4% in a winter scenario to 21% in the summer. Bisinella et al. (2021) conducted an analysis of using an amine-based CCT plant to capture emissions from a state-of-the-art EfW facility in Copenhagen. They concluded that the electrical power output from the plant would be reduced by 50% due to the need for energy for CCT, but that this would be offset by using the excess heat generated by the plant as part of the district heating scheme. In an energetics study of an EfW in Switzerland used for power and district heating, Otgonbayar and Mazzotti (2024) reported an energy penalty of at least 34%, even if excess heat was recovered from the CCT system (a piperazine-based solvent process). They also concluded that although available excess heat allowed capture of only 60% of CO_2 emissions, this still resulted in negative emissions from plant operation.

Several researchers have reported typical flue gas compositions from an EfW plant of between 7 – 11% CO_2, 7 – 17% water, 66 – 75% N_2, and 6 – 9% O_2 (Fagerlund et al. 2021, Moioli et al. 2024, Su et al. 2023). They have also noted that impurities in the flue gases complicates the design and performance of the CCT plant for EfW, which necessitates pre-treatment to remove particulate matter, sulphur oxides, nitrogen oxides, carbon monoxide, and hydrogen chloride (Boré et al. 2024, Dal Pozzo et al. 2023). Although many of these are already subject to abatement, flue gas complexity is considered an area in need of further research (Dal Pozzo et al. 2023).

Dal Pozzo et al. (2023) noted this complexity leads to two significant challenges for current post-combustion solvent systems: solvent degradation (oxidative reactions triggered by oxygen and acid components) and entrainment in the flue gas. Ensuring solvent stability over long-term operation is an issue under highly variable flue gas conditions, which might only be resolved with long-term trials at pilot- or demonstration-scale. Impurities are also considered an issue for membrane systems, where they cause fouling (Dal Pozzo et al. 2023). Acid components such as hydrogen chloride and sulphur oxides could also inactivate alkaline solid sorbents such as those used in calcium looping.

Fagerlund et al. (2021) reported the findings of a CCT pilot study at Fortum Oslo Varme's EfW plant in Oslo, Norway in 2019. The CCT plant was based on a proprietary amine-based solvent system with a particular focus on a reduction in amine emissions. It was noted that the full-scale plant was designed to operate with a rate of between 2 – 4%

amine degradation. The overall conclusions from the 2,000 hour study was that the CCT plant operated at a capture efficiency between 90 – 95%, while keeping amine emissions to less than 0.4 ppm. The main emissions detected were acetaldehyde, formamide, acetone, and several unidentified oxygenated and nitrogenated hydrocarbons. However, the results indicated that the design range for solvent degradation was likely to be exceeded after 3,000 operational hours and that the rate of degradation accelerated over longer periods (suggested by the data but not proven before end of study). Solvent degradation may have been related to the observed increase in particulate matter.

Dal Pozzo et al. (2023) also noted that the complexity of waste fuels poses challenges for pre-combustion systems such as oxy-combustion, where the effects of the combustion atmosphere and temperature on pollutant formation behaviour needed further research. Nonetheless, García-Luna and Ortiz (2024) explored the conceptual design of EfW plants that emphasised carbon capture and methane conversion processes. In the first scenario, waste combustion was combined with CCT treatment of the flue gases to produce a CO_2 rich stream that was converted to methane using added H_2. In the second scenario, partial oxy-combustion was achieved using O_2 produced by a PEM electrolyser to produce methane. Both systems incorporated a CCT process based on MEA as the amine solvent. In an economics analysis, the authors concluded that partial oxy-combustion was favourable to reduce H_2 costs and was potentially more economical than an existing EfW without CCT. Salomone et al. (2023) also investigated the energy requirements for a power-to-gas plant attached to a EfW incinerator with CCT. H_2 generated by an electrolyser was combined with CO_2 purified from the CCT in a methanation process. The study concluded that heat generated by methanation was sufficient to satisfy heat demands from the CCT plant using a range of different solutions including amine-based solvents and temperature swing adsorption using solid sorbents.

In terms of anaerobic digestion and biogas, Jørsboe et al. (2024) noted that amine-based scrubbing systems were commonly used to upgrade biogas. Practical challenges identified with current systems such as those based on MEA include amine degradation, foaming, corrosion, and high operating costs. Jørsboe et al. (2024) noted several developments to address these issues including the use of heat pumps to reduce the heat requirement in the stripper/reboiler, the use of rich solvent recycling (RSR) within the absorber to increase the mass transfer of CO_2 into the solvent, and the use of water-lean solvent systems, where water was replaced by an organic diluent. Jørsboe et al. (2024) investigated a solvent consisting of MEA (30%), monoethyleneglycol (15%), and water (55%) in a mobile pilot scale amine scrubbing unit with a capacity of 1 tonne CO_2 per day. Compared to an existing MEA approach, they found that the energy use from the boiler was only reduced when combined with RSR. They also observed that the two chemicals combined to form 2-methyl-dioxolane, which resulted in increased emissions.

Other Industries

Although the pulp and paper sector accounted for around 2% of global CO_2 (150 Mt CO_2 pa) industrial emissions in 2007 (Brown et al. 2012), Ganzer and Mac Dowell (2023) noted that research on CCT in this sector was limited. In a review of Austrian industry, Nagovnak et al. (2024) noted this subsector had the second highest energy demand and was responsible for approximately 2 Mt CO_2e pa. Most of the projected emission reductions come from energy supply including recovering energy from waste and from use of heat pumps. Facilities are often remote from industrial clusters, complicating implementation of CCT (Leeson et al. 2017). The majority of emissions are reported from the boilers and the lime kiln.

Barón et al. (2023) undertook a techno-economic evaluation of decarbonisation strategies for the glass industry. Although the sector is diverse, global container and flat glass production accounted for 81 Mt CO_2 pa in 2020. Glassmaking involved five main processes including batch preparation, melting, forming, annealing and finishing. The melting stage is the most energy- and carbon-intense. Research has focused on energy efficiency, material recycling, and fuel substitution as the main decarbonisation options for the glassmaking industry. Barón et al. (2023) modelled a combination of power-to-gas (reaction of CO_2 with H_2 to produce methane used for heating) with post-combustion capture via calcium looping. The latter was chosen in preference to the more established amine-based systems because of its advantages in process integration (some of the CaO could be used as a raw material in production, which reduces the hazard of sintering of the sorbent). The optimised system modelled a reduction in CO_2 emissions from 80 to 86% compared to a conventional plant. There was a predicted energy penalty for the system of up to 35 MJ/kg CO_2, mainly due to electricity consumption by the electrolyser to generate H_2 for methanation.

Environmental Impacts

There is sparse information on the wider environmental impacts for different CCT options in the published literature with the focus on greenhouse gas emission reduction and related factors such as energy efficiency and cost (Gowd et al. 2023). In many cases, the information is also limited because these novel processes are at an early stage in their development (conceptual and bench-scale) and wider impacts including waste management require more experience at scale and over longer durations (Aldaco et al. 2019, Bello et al. 2022). However, it is also apparent that in early investigations and designs, potential impacts on the wider environment are not often a central consideration.

The following impacts are considered in this review:

- Mitigation of CO_2 emissions including capture efficiency and energy demand
- Resource use with a focus on water demand
- Emissions to air, water, and land from capture operations
- Waste management including liquid and solid wastes

Mitigating CO_2 Emissions

In assessing the decarbonisation effectiveness of CCT, there are primarily two considerations. The first is the effective carbon capture efficiency, which measures how much of the CO_2 is captured by the process from the flue gases and is subsequently retained for utilisation and storage. It is often reported as a percentage (%) of the CO_2 captured from a flue gas. A lower capture efficiency is likely to allow emission of more CO_2, leading to a higher impact on the wider environment through contributions to climate change. However, the amount of CO_2 captured will depend on the CO_2 concentration and volume of flue gas processed and is industry as well as technology-specific. Table 8 presents capture efficiencies reported for different CCT options and their potential industrial applications from the available literature.

The second consideration is the energy penalty, which is the amount of additional energy needed to run the CCT plant at a given capture rate. It is important because the local combustion source often supplies the additional power and heat for the CCT, which means additional energy is needed to deliver the same output as a source without CCT. The relationship between capture rate and energy penalty is not always linear (Su et al. 2023), but the penalty often increases with capture efficiency. The extra energy needed potentially incurs its own additional environmental impacts from its generation including further emissions, wastes, and resource demands (for example, for cooling water). However, several options identified earlier in this report use renewable energy to offset the energy penalty and provide the necessary power to run the CCT unit. Table 9 presents the estimated energy penalties for different CCT options and their potential industrial applications from the available literature.

Table 8. Capture rates as % CO_2 from flue gases for a range of CCT (data collated and adapted from Boré et al. 2024, Domingos et al. 2024, Duan et al. 2016, Dziejarski et al. 2023, Fagerlund et al. 2021, Fleiß et al. 2024, Ganeshan et al. 2023, Gautam and Mondal 2023, Kammerer et al. 2023, Otgonbayar and Mazzotti 2024, Plaza et al. 2020, Rezaei et al. 2023, Shahbaz et al. 2021, Stockwell 2024, Tan et al. 2024, Yagmur Goren et al. 2024).

Technology	Application	Capture efficiency
Absorption by solvents	Generic	80 – 95%
Amine-based	Power industry (coal, oil, gas)	57 – 81% (operational)
	Energy from waste	60 – 95%
Calcium looping	Cement sector	70 – >90%
	Power industry (coal, oil, gas)	85%
Physical absorption	Generic	90 – 97%
Adsorption by solid sorbents	Generic	55 – 95%
Organic polymers	Generic	90%
Metal oxides	Generic	90%
Zeolites	Generic	90%
Carbon-based	Generic	90%
Cryogenic separation	Generic	90 – 99%
Membrane separation	Generic	80 – 90%
Polymeric membranes	Generic	60 – 90%
Inorganic membranes	Generic	70 – 90%
	Cement industry	60 – 90%

Technology	Application	Capture efficiency
	Power industry (coal, oil, gas)	60 – 90%
Microbiological methods	Generic	10 – 20% (tentative)
Oxy-fuel combustion	Generic	92%
Combustion in O_2	Generic	100%
Chemical looping combustion	Generic	>90%
	Energy from waste	82 – 99%
	Power industry (coal, oil, gas)	>98%
Pre-combustion	Power industry (coal, oil, gas)	>80%

Table 9. Energy penalties as relative % difference compared with sources such as power stations or cement plants without CCT for a range of CCT (data collated and adapted from Boré et al. 2024, Duan et al. 2016, Dziejarski et al. 2023, Ganeshan et al. 2023, Gautam and Mondal 2023, Gowd et al. 2023, Madejski et al. 2022, Otgonbayar and Mazzotti 2024, Stockwell 2024, Tan et al. 2024, Vasudevan et al. 2016, Yagmur Goren et al. 2024).

Technology	Application	Energy penalty
Absorption by solvents	Generic	8 – 12%
Amine-based	Energy from waste	13 – 34%
	Power industry (coal, oil, gas)	15 – 20%
Calcium looping	Cement sector	4 – 8%
	Power industry (coal, oil, gas)	10%
Adsorption by solid sorbents		

Technology	Application	Energy penalty
Cryogenic separation		
Membrane separation	Power industry (coal, gas, oil)	33 – 38%
Microbiological methods		
Oxy-fuel combustion	Power industry (coal, gas, oil)	16 – 18%
Combustion in O_2	Generic	4 – >7%
Pre-combustion	Power industry (coal, gas, oil)	7 – 15%

Water demand

Addition of CCT to an existing industrial process can substantially increase overall water use (Byers et al. 2016, Element Energy 2022, Rosa et al. 2021, Stockwell 2024, Wang et al. 2021). This includes not only the additional demand needed for the CCT process itself, but also the increased need for extra energy generation to offset any parasitic load from the CCT. Magneschi et al. (2017) concluded that the extra cooling water needed for power generation was much greater than the additional requirements for process water from CCT plants for most post-combustion systems. Water scarcity is an increasing problem globally, due to climate change, overpopulation, over abstraction and poor infrastructure (Rosa et al. 2021, Stockwell 2024). Closer to home, areas of the UK are already seriously water stressed and are expected to be in a water deficit by 2030 (Element Energy 2022). In a modelling study of the impact of climate change and decarbonisation on the river Trent, Byers et al. (2016) concluded that the projected increase in cooling water abstractions for use with CCT would likely exceed available water for all users from the 2030s to 2040s.

Over 80% of industrial water used worldwide is devoted to thermal power generation, while in the US and other industrial countries, the figure rises to almost 90% (Magneschi et al. 2017). A 500 MWe coal-fired power plant uses an estimated 45,000 m^3 of water per hour. The largest demand for water in power generation with CCT was reported to be cooling water via either open or closed loops (Magneschi et al. 2017). In an open loop process, water is abstracted passed once-through the system and discharged back into the water body. In an open loop system water is withdrawn, but not consumed, as it is returned. In a closed loop process, water is abstracted and cooled within a tower, the heat dissipated directly to the air by evaporation, and the water recirculated. In a closed loop system, only fresh makeup water is required to replace that consumed via evaporation.

Magneschi et al. (2017) reviewed a number of water demand estimates for coal-fired and gas-fired power stations (including natural gas combined cycle, NGCC, and integrated gasifier combined cycle, IGCC) from the literature, distinguishing, where possible, between pre-combustion, post-combustion, and oxy-combustion systems. They concluded that water use estimates could not be generalised and were dependent on the type of power plant and CCT deployed. Results from such studies also required careful interpretation (Magneschi et al. 2017). For example, absolute consumption (as a % in m^3/hour) increases much more for gas-fired plants compared to coal-fired plants with CCT implementation. However, this difference is in large part due to gas-fired power plants requiring less water for power generation and therefore makeup water for the CCT process contributes a greater percentage of total demand. For power plants served by closed loop cooling systems, the estimated increased water consumption varies by up to 60%, although this could be more than offset by the implementation of water recovery systems. In open-loop systems, water consumption is predicted to be much lower as most is returned to the water body. In this respect, water consumption is a much less relevant metric for demand than the amount of water withdrawn for use.

In pre-combustion systems, where fuels are converted into syngas, further processing typically takes place within the water-gas shift reactor (Magneschi et al. 2017). The reactor consumes a significant quantity of water, as steam is required to sustain the shift reaction. Because of the much lower energy penalties associated with pre-combustion (<10%), the makeup water needed for the CCT process itself may exceed the extra cooling water needed for power production. In oxy-combustion processes, cooling water is typically required for both the air separation unit and the flue gas recycle system, where the gas is cooled and moisture reduced to minimise corrosion (Magneschi et al. 2017). Condensate collected from the flue gas can be returned to the boiler. In closed loop systems, relative increases in absolute consumption were reported in the range from 2 – 11% with reductions expected with more novel enhanced configurations. In open loop systems, relative rates of absolute water withdrawal increases by up to 12%. Rosa et al. (2021) estimated the freshwater footprint of using either oxy-combustion or integrated gasification combined cycle to be in the range of 1 – 10 m^3/tCO_2 using an integrated environmental control model. The authors defined a footprint as "…*the volume of fresh water consumed to produce goods or services during their life cycle*."

Post-combustion capture has a higher potential water demand than other systems because they not only require water for their direct operation, but the heat and power they need to operate also incurs an indirect water demand from additional power generation (Magneschi et al. 2017, Wang et al. 2021). Post-combustion systems such as amine-based chemical absorption and membrane separation have much higher energy penalties (up to 30 – 40%) as well as significant makeup water requirements. In amine-based CCT, the most significant need for additional water are associated with the water wash in the absorber, which needs to be clean freshwater to reduce potential fouling and corrosion, and the lean water cooler between the absorber and the stripper (Element Energy 2022, Stockwell 2024). In terms of cooling demand, several pretreatment stages require water, such as at the wet gas scrubber, the flue gas cooler and the selective catalytic reduction unit. CO_2 compression also requires additional water, for cooling and for CO_2 saturation.

Magneschi et al. (2017) estimated relative increases in absolute consumption 20 to 60% for closed-loop systems deployed in coal- and gas-fired applications using amine-based CCT. However, they noted that several CCT processes recovered water from the flue gas, and this could potentially offset more than the predicted consumption rates. In open-loop systems, relative rates of absolute water withdrawal increases by between 6 and 51% for amine- and Selexol-based capture systems. Wang et al. (2021) calculated the water use in $m^3/t\ CO_2$ for a 650 MW coal-fired plant using a life cycle analysis model for four different CCT: amine-solvent, ammonia solvent, physical solvent with TSA, and a membrane system. Water costs ranged from 1.7 to 3 $m^3/t\ CO_2$ with membrane incurring the lowest use and the ammonia system the highest. Similar results were obtained by Rosa et al. (2021), who estimated the freshwater footprint of using either amines-based or membrane based technologies to be in the range of 1 – 10 m^3/tCO_2 using an integrated environmental control model. It was notable that BECCS had water footprints in the range 100 – 1,000 m^3/tCO_2 because of the agricultural crop requirements for water and the associated losses via transpiration.

Environmental emissions

Substances are potentially emitted mainly to air and water by CCT processes, although they will often be mitigated by further treatment (Stockwell 2024, Larki et al. 2023). Emissions of many classical air pollutants arising from combustion such as nitrogen oxides and particulate matter will likely increase, on the basis of individual power plants, because of the associated energy penalty from CCT plants (Stockwell 2024). While others may be reduced, if pretreatment of the flue gas is required to prevent fouling of the CCT plant – for example, sulphur oxide emissions may be lowered for some technologies because they impact on the efficiency of carbon capture and recovery process. CO_2 is considered a toxic pollutant (Holt and Simms 2021), and its storage and transportation requires careful management to reduce the potential risks to the public and the wider environment.

Atmospheric emissions of amine-based solvents and their degradation products have been widely studied and reported in the available literature (Muchan et al. 2024, Rezaei et al. 2023) and are considered separately and in more detail within this review. Reducing these emissions have more recently become a design goal for innovation within some of these applications as a result of emerging evidence on potential health risks, although most research still focuses on process efficiency. However, Shavalieva et al. (2021) noted that for many new classes of chemicals such as phase-separation solvents, very little is known about their long-term toxicity and potential degradation.

Other technologies report very little emission data even at pilot-scale, which means that implications can only be inferred from an understanding of the process chemistry and the substances used. Operational emissions to air of substances in the form of gases and vapours is most likely from the heating of liquid-based processes such as chemical and physical solvent-absorption (see Table 10), while dust particles may be entrained in the treated flue gas as a result of sintering by solid-based technologies such as sorbent-adsorption and chemical looping. Jaffar et al. (2024) undertook a standardised life cycle comparison of an MEA-based chemical absorption system and a novel silica-alkoxylated polyethyleneimine (SPEI)-based solid sorbent process for a conceptual cement plant. The key difference across the environmental assessment was the significantly higher potential risk to terrestrial ecosystems from the MEA-based technology over the SPEI sorbent. While details of the analysis were limited, the authors assumed a much higher aerial emission rate of MEA compared SPEI, which would likely have accounted for some, but not all, of the higher terrestrial ecotoxicity predicted due to increased nitrogen deposition

Most technologies use water or steam within the process and for a wide range of water-soluble substances, there is potential for wastewater contamination that requires management and treatment prior to discharge (see Table 11). There is often an overlap between substances emitted to air and water with the likely driver being their liquid-air partitioning behaviour at different temperatures and pressures. This not only applies to direct discharges following wastewater treatment, but also indirect discharges via emissions to air through partitioning to water vapour/droplets and washout processes leading to surface deposition.

Table 10. Potential emissions to water from CCT (other than amine-based systems) identified in this review (data collated and adapted from Borhani et al. 2015, Dziejarski et al. 2023, Gautam and Mondal 2023, Kammerer et al. 2023, Kamolov et al. 2023, Liu et al. 2024f, Madejski et al. 2022, Othman et al. 2024, Tan et al. 2024, Wheatley et al. 2019, Zhao et al. 2024).

Technology	Potential emissions to air
Absorption by solvents	
Alkali-based	Potassium carbonate salts Other substances include corrosion inhibitors (such as vanadium pentoxide) and reaction promoters (such as amines, arsenic trioxide, vanadic acid, and arsenious acid)
Calcium looping	Calcium carbonate, sulphate, and oxide salts
Carboxylic-acid based	Phenoxide salts
Ammonia	Ammonia and ammonium salts
Physical absorbents	Methanol, N-methyl-2-pyrrolidone, and different blends of polyethylene glycol dimethyl ethers

Technology	Potential emissions to air
Adsorption by solid sorbents	Carbon-based including porous organic polymers and mineral-based sintered particles such as zeolites, aluminium oxides, magnesium oxide, and lithium silicate and borate Metal oxides are used at higher temperatures, which may increase the risk of flue gas entrainment
Cryogenic separation	Substance emissions less likely from operating conditions
Membrane separation	Surface abrasion of polymeric and inorganic membranes such as polyimides zeolite-based minerals leading to entrained particles and potential loss of reactive additives such as amines as vapours
Microbiological methods	Hydrocarbons formed by microorganisms and bioaerosols
Oxy-fuel combustion	Chemical looping systems using metal oxides such as nickel, manganese and iron oxides may generate sintered particles Chemical looping systems that treat flue gases from coal-fired power stations will need to consider mitigation of mercury releases

Table 11. Potential emissions to air from CCT (other than amine-based systems) identified in this review (data collated and adapted from Borhani et al. 2015, Dziejarski et al. 2023, Gautam and Mondal 2023, Kammerer et al. 2023, Kamolov et al. 2023, Madejski et al. 2022, Othman et al. 2024, Tan et al. 2024, Wheatley et al. 2019, Zhao et al. 2024).

Technology	Potential emissions to water
Absorption by solvents	
Alkali-based	Potassium carbonate salts Other substances include corrosion inhibitors (such as vanadium pentoxide) and reaction promoters (such as amines, arsenic trioxide, vanadic acid, and arsenious acid)
Calcium looping	Calcium carbonate, sulphate, and oxide salts and particulates
Carboxylic-acid based	Phenoxide salts
Ammonia	Ammonia vapour and ammonium salts
Physical absorbents	Methanol, N-methyl-2-pyrrolidone, and different blends of polyethylene glycol dimethyl ethers as vapours
Adsorption by solid sorbents	Mainly entrained sintered particles (see Table X1)
Cryogenic separation	Potential fluids leaks from cryogenic unit
Membrane separation	Mainly entrained abraded particles (see Table X1) and water-soluble additives such as amines
Microbiological methods	Hydrocarbons formed by microorganisms and biofilm materials
Oxy-fuel combustion	Mainly entrained sintered particles (see Table X1)

Amine-based emissions, especially to air, have been widely studied and reported in the scientific literature with the main issues being the loss of the amine solvents and their breakdown products including other amines, aldehydes, amides, ammonia, nitramines, and nitrosamines (Chen et al. 2018, Låg et al. 2009, Muchan et al. 2024, Rezaei et al. 2023, Shahbaz et al. 2021, Svendsen et al. 2024, Wu et al. 2024). Emissions occur as vapour or in the form of a mist as aerosols (Spietz et al. 2020).

Solvent losses from amine-based systems were reported in the range of 0.5 – 2 kg MEA/t CO_2 captured, but results varied by amine and type of power plant (Heo et al. 2015, Rezaei et al. 2023, Wu et al. 2024). Since solvent preservation is the subject of considerable research effort, losses are expected to be lower in future solvent systems and engineering designs. Some researchers such as Heo et al. (2015) predicted that losses from novel proprietary systems could eventually achieve be in the range 0.1 – 0.35 kg amine/t CO_2. Based on the lowest rate, this represents up to 100 t amine pa for a facility capturing around a 1 Mt CO_2 pa.

Amine and alkanolamines constitute a large group of substances with significant variations in mobility, persistence, and toxicity (Burnett et al. 2009, Garner et al. 2008, Gentry et al. 2014, Grant et al. 2015, Haney et al. 2018, Låg et al. 2009, Svendsen et al. 2024). Eide-Haugmo et al. (2009) reviewed the persistence and toxicity of around 40 amines to the marine environment at bench-scale using phytoplankton test conducted according to ISO/DIS guideline 10253. While the toxicity of most substances was considered low (>10 mg/l), some of the most commonly used amines – MDEA, AMP, and PZ – were considered to have long persistence times in marine systems because of their low biodegradation potential. The tested tertiary amines and those compounds containing quaternary carbon atoms did not degrade easily, while amino acids showed low toxicity and high biodegradation potential.

Amines also degrade in the atmosphere to form breakdown products including nitrosamines and nitramines (Manzoor et al. 2015). In a critical review, Nielsen et al. (2012) concluded that the relative importance of the various environmental sinks varied between amines, nitrosamines and nitramines. Alkyl amine chemistry occurs almost exclusively in the gas phase, where particulate matter and water aerosols (clouds) are the dominant phases for alkanolamine sinks and reactions. Reactions with the OH radical are likely to be the dominant sink for emitted amines and their degradation products. Photolysis is likely an important degradation pathway for nitrosamines.

Weir et al. (2023) observed a range of amine emissions from a pilot CCT plant operating at a coal-fired power plant in the Netherlands. Depending on emission control methods, emissions of MEA were around 3 mg/m^3, and emissions of AMP and PZ were around 100 mg/m^3 and 30 mg/m^3, respectively. In an experimental study with limited abatement using a blend of AMP and PZ, Spietz et al. (2021) reported emissions of AMP (28 mg/m^3), ammonia (3.75 mg/m^3), and traces of formic acid, but not PZ. Aerosol emissions may depend on the presence of other flue gas constituents such as sulphur oxides and sulphuric acid (Spietz et al. 2018 and 2020), which increases their formation.

Two main mechanisms for amine degradation are reported in the literature (Fine et al. 2014b, Gautam and Mondal 2023, Wu et al. 2024). Oxidative degradation primarily occurs in the absorber and involves the reaction of the amine with nitrogen oxides and oxygen.

An example of this is the nitrosation of amines to form nitrosamines. Thermal degradation occurs primarily in the stripper, which operates at a higher temperature and is a complex process that often involves instability in the carbamate complexes. Overall amine stability (resistance to degradation within the CCT process) was reported to increase in the order tertiary > secondary > primary (Gautam and Mondal 2023, Wu et al. 2024). Sterically hindered and cyclic amines also have greater stability (Fine et al. 2014b, Wu et al. 2024). Steric hindrance was identified as a reason for the lower degradation rates for AMP (a primary amine), which was attributed to the reduced reactivity to form carbamate complexes (Gautam and Mondal 2023). Oxidative degradation was found to depend on the concentration of nitrogen oxides and oxygen in the flue gas, while thermal degradation was proportional to the CO_2 loading and temperature (Fine et al. 2014b, Gautam and Mondal 2023, Muchan et al. 2024, Wu et al. 2024).

Muchan et al. (2024) investigated the oxidative degradation characteristics of 29 different amine and alkanolamine compounds in a pure oxygen atmosphere to minimise other chemical interactions. They observed that degradation rate depended on the stability of the free radical, noting that enhanced stability increased degradation. Alkyl groups decrease stability and degradation rate by strengthening the N-C bond. Conversely, hydroxyl groups (OH) increase stability and degradation rate by weakening the N-C bond, although degradation could be reduced by protecting the amine through steric hindrance. Similar effects to the hydroxyl group were observed with increasing numbers of amino groups. Chahen et al. (2016) highlighted the complexities of breakdown reactions in the absorber and stripper by identifying substances in the liquid and gas components of a pilot scale system using 30% MEA. Thirty-two degradation products were identified in liquid phase and thirty-eight in gas phase, seventeen of which were identified for the first time, especially derivatives of pyridine and oxazolidine, 1H-pyrrole and a new nitrosamine, the N-nitroso-2-methyl-oxazolidine. Buvik et al. (2021) noted that, in most cases, oxidative stability was often consistent with biodegradability (that is, the most resistant amines within the CCT are also likely to be the most persistent in the environment).

Weir et al. (2023) observed that solvent degradation could be monitored through the build-up of heat stable salts including acetate, formate, and oxalate.

Ammonia was identified as one of the most significant pollutants emitted from a carbon capture plant as a result of oxidative amine degradation (Heo et al. 2015, Muchan et al. 2024, Spietz et al. 2018 and 2020). Ammonia is direct risk to human health, but it is also a significant contributor to the formation of secondary particulate matter under specific atmospheric conditions (Heo et al. 2015). Its role in the formation of PM2.5 is largely determined by nonlinear interactions with sulphur and nitrogen oxides, and the resulting impact of an ammonia release from a CCT plant will depend on the ambient concentrations of these reactants. Because particulate matter nitrate formation is favoured at cold temperatures, ammonia emissions may create a significant amount of PM2.5 especially in winter or at night. Heo et al. (2015) estimated that ammonia emissions represented between 30 – 50% of the amine losses from a CCT plant. Using the example earlier, this means that between 30 and 50 t ammonia pa for a facility capturing around a 1 Mt CO_2 pa. Translating this into the US context, Heo et al. (2015) estimated that ammonia emissions from the capture of 2 Gt CO_2 pa would lead to an increase in 2 μg/m^3 $PM_{2.5}$/m^3 in winter leading to a substantial increase in the costs to public health.

Knudsen et al. (2013) reported that between 3 – 5 mg/m^3 of ammonia was observed during the operation of an Aker Clean Carbon Mobile Test unit, which had a capacity to capture 4.8 t CO_2 per day. Higher emissions of between 10 – 70 mg/m^3 were reported for a pilot plant capturing 6 tCO_2 per day using MEA and after treatment with a water wash (Khakharia et al. 2014). Spietz et al. (2018) investigated emissions of ammonia from a pilot scale CCT unit (1 tCO_2 per day) using 40% aqueous solution of aminoethylethanolamine, which was used to treat the flue gas from a coal-fired power plant. The results showed that the main source of ammonia emission was the result of solvent degradation in the absorber with ammonia emissions in the range 19 – 35 mg/m^3. It was observed that an increase in make-up water decreased ammonia emissions, while an increase in temperature of the lean solvent increased them.

Many breakdown products of amine solvents including nitrosamines and nitramines are considered genotoxic and mutagenic, although they vary in potency (Bercu et al. 2023, Buist et al. 2015, Chen et al. 2018, EFSA 2023, Fjellsbø et al. 2014, Låg et al. 2009, Ravnum et al. 2014, Svendsen et al. 2024, Thresher et al. 2020, Wagner et al. 2014). Atmospheric modelling of emissions identify the cancer risks associated with nitrosamines as one of the key concerns for public health from industrial decarbonisation with amine-based CCT (de Koeijer et al. 2013, Farren et al. 2015, Gentry et al. 2014, Zhang et al. 2014, Environment Agency 2025). Sørensen et al. (2013) presented experimental data on the hydrolysis and photolysis of a suite of nitramines and nitrosamines relevant to post-combustion CO2 capture from MEA solvent systems. Nitramines including dimethyl nitramine and 2-nitroaminoethanol are resistant to hydrolysis and photolysis and are considered likely to persist in water environments. Nitrosamines including NDELA and n-nitrosopiperazine are resistant to hydrolysis, but susceptible to photolysis, reducing their persistence in the terrestrial and water environments. As a result, Chen et al. (2018) concluded that the persistence of nitrosamines in water depended on the presence of organic matter with increasing levels leading to longer residence times.

Nitrosamines and nitramines are principally formed in the absorber by oxidative reactions with nitrogen oxides and oxygen, a process also known as nitrosation (Chen et al. 2018, Wang et al. 2020). However, they can also form in the stripper from reactions between aqueous nitrite, a hydrolysis product of nitrogen oxides, and amines (Yu et al. 2017). Evidence from studies in the absorber and the stripper show that secondary amines such as DEA and PZ form nitrosamines the fastest, while reaction rates for tertiary amines such as triethanolamine are slightly slower, and primary amines such as MEA have a reactivity two orders of magnitude lower (Yu et al. 2017). Primary amine systems can still be a source of nitrosamines as a result of the formation of secondary and tertiary amine breakdown products (Chen et al. 2018). Nitrosamines and, to a lesser extent, nitramines decompose in the stripper (Yu et al. 2017), and the total amount formed is therefore a balance of these competing processes. For example, primary amines form unstable nitrosamines that are generally considered short-lived in solution, decomposing to form nitrogen gas and a corresponding carbocation (Chen et al. 2018). Secondary amines form nitrosamines through direct reactions, and these substances are considered more stable. Tertiary amines form nitramines directly, but not nitrosamines. Nitrosamines may be formed indirectly from secondary amine intermediates via oxidative and thermal degradation. Wang et al. (2020) conducted investigations on the formation of nitrosamines using a simulated flue gas and fresh MEA, simulated aged MEA, and PZ in a bench-scale test rig with a linked absorber and desorber columns. With fresh MEA, nitrosamine formation occurred primarily in the absorber and strongly depended on the nitrogen oxides and oxygen concentrations in the flue gas. In the desorber, an increase in temperature to between 110 – 130˚C, resulted in the thermal decomposition of the nitrosamines formed. In contrast, nitrosamine formation from PZ was driven by nitrite reactions in the heated desorber and increased with nitrite level. In the aged MEA, the desorber became an order of magnitude more important that the absorber for nitrosamine formation.

Weir et al. (2023) noted that emission management and recovery could be cost-effective in some circumstances, offsetting the cost of solvent replacement. They reported a range of methods for water washing including refinements such as a proprietary dry bed or a turbulent spray scrubber to extend contact time and improve recovery. Wash water systems are often used in the absorber to strip out unused amines (Yu et al. 2017). A long-term experiment as part of the ALIGN–CCUS project reported that reducing emissions of MEA below 3 mg/m^3 was achievable for a 30% MEA solvent, while also remaining below 10 mg/m^3 even under transient operating conditions (Moser et al. 2020 cited by Wier et al. 2023). Multiple studies have shown removal efficiencies for MEA from the depleted flue gas ranging from 60% to 99.9% compared to inlet concentrations of between 270 to 370 mg/m^3 (SEPA 2015). Chen et al. (2018) noted that nitrosamine and nitramine levels in wastewater from the water wash are often one or two orders of magnitude lower than reported in the absorber. However, Yu et al. (2017) noted that nitrosamines have been reported to accumulate in wash water units in several bench- and pilot-scale plants. Levels of total nitrosamines of 59 and 0.73 µg mol^{-1} were reported in wastewater from a 25% AMP/15% PZ and a 35% MEA solvent system, respectively (Chen et al. 2018, Yu et al. 2017). These levels were three orders of magnitude higher than guidelines at the time for the protection of drinking water (Chen et al. 2018). Methods for water treatment are available. Chen et al. (2018) noted that 90% of nitrosamines and nitramines in water could be destroyed by effective UV treatment. Fine et al. (2014a) noted that some nitrosamines such as nitrosodiethanolamine (NDELA) are susceptible to thermal degradation in basic buffer solutions at temperatures found in the stripper, although some substances such as n-nitrosopiperazine (MNPZ) require temperatures greater than 150 ˚C. Yu et al. (2017) reported that higher temperature desorption has been shown to facilitate nitrosamine decomposition, but it is applicable only to amines with high thermal stability such as PZ, and at an increased energy cost. Other innovative treatments reported in the literature include the use of metal based catalysts, requiring hydrogen gas, and an electrochemical treatment using a carbon xerogel electrode for absorption and decomposition of nitrosamines (Thompson et al. 2019, Yu et al. 2017).

Other chemical additives may also represent important operational emissions. The intermediate products of CO_2 absorption by amines, notably the carbamate and HCO_3^-

ions, are known to be corrosive to steelwork through the formation of iron carbonate and iron hydroxide (Stockwell 2024, Zhao et al. 2023). Rates of corrosion increase with amine and CO_2 concentration as well as operating temperature, since the electrochemical reactions driving corrosion are thermally activated (Zhao et al. 2023). Chen et al. (2024) noted that some novel amine carriers such as diethylenetriamine have significantly higher corrosion rates than MEA-based systems. Corrosion inhibitors work by the delaying the corrosive process, often forming a protective barrier over metalwork. A wide range of substances have been proposed (Wu et al. 2024) including vanadium compounds, sodium sulphide and thiosulphate, and organic compounds including amines and carboxylic acids. These substances may accumulate in wastewater systems and require treatment before discharging to the environment (Stockwell 2024).

Waste management

Solid and liquid wastes from CCT processes are often not considered prior to the later stages of scaling-up of a technology. In many cases, more experience at scale and over longer durations is required to fully understand the issues (Aldaco et al. 2019, Bello et al. 2022). Demonstration- and commercial-scale applications of CCT for industrial decarbonisation are still limited and are typically amine-based systems (Stockwell et al. 2024).

In several commercially operated amine-based CCT systems, the main waste streams reported from operations are laboratory waste, wastewater, reclaimer waste, pre-coat filler waste, clarifier sludge waste, and heat system blowdown waste (Stockwell 2024). However, the two most important by volume are wastewater and reclaimer waste.

Wastewater from amine-based systems comes from various parts of the CCT plant including the wash water and acid washings, condensate recovery, cleaning waters, and wastewater from the thermal reclaimer (Dong et al. 2019, Stockwell 2024). Wastewater generated from the wash water, condenser and reclaimer units is considered amine-rich and consists of heat stable salts (formed by reaction with acid gas impurities), nitrosamines, nitramines, ammonia, carbamate polymers and water (Dong et al., 2019, Heo et al. 2015). These wastewaters are often complex, and several studies have detected many breakdown products. Fine (2015) noted that many nitrosamines are water-soluble and stable in solution and are likely to be transferred to solution during flue gas abatement such as through water and acid-washes. Shavalieva et al. (2021) added that innovations that decrease the energy required for stripping CO_2 from solvent solutions often involve lean solvent separation and recycling, which may lead to the build-up of water-soluble contaminants over time. Dong et al. (2019) estimated that the quantity of reclaimer wastewater generated during plant operations varies from 1.2 to 3.9 kg/t CO_2 captured (approximately 1 to 4 l/t CO_2). For a plant operating at 1 Mt CO_2 pa, this amounts to up to 4,000 m^3 pa. Wastewater can be treated on-site to remove pollutants or tankered off-site for further treatment at a specialist waste company.

Reclaimer waste is produced in the thermal reclaimer unit, which recovers spent amine from unwanted degradation and corrosion products (Sexton et al. 2014, Stockwell 2024).

It is a sludge with a strongly alkaline pH (SEPA 2015) containing a mixture of salts, metals such as copper, iron, nickel and mercury, amines and their degradation products, appreciable amounts of sulphur, and corrosion inhibitors. SEPA (2015) concluded that estimates of the amount of reclaimer waste produced by amine-based plants varied considerably from <0.1 – 16 kg/t CO_2 captured with one estimate of 3 kg/t CO_2 captured for an MEA system. Sexton et al. (2014) reported that for an MEA-based system, the amounts of reclaimer sludge generated was ranged from 1.2 to 3.3 kg/MWh for a gas and coal-fired power plant, respectively. For a CCT plant capturing 1 Mt CO_2 pa, the amounts produced, based on the estimated rates of production, varies from 100 to 16,000 t pa. Waste management options for this waste stream include hazardous waste landfill disposal and incineration (Stockwell 2024).

Corrosion products including iron carbonates and hydroxides from steel infrastructure were identified as another waste source by Shao and Stangeland (2009), since amines and heat stable amine salts are highly corrosive. The amount produced will depend on the rate of corrosion, which itself depends on the amine solvent, the amine concentration, the solution temperature, and dissolved oxygen content. Heat stable salts will also increase the corrosion rate. Use of corrosion inhibitors such as sodium metavanadate and copper carbonate have been used to reduce the corrosion of carbon steel to less than about 0.25 mm pa (Shao and Stangeland 2009). The operational costs associated with corrosion are potentially high and therefore innovations to reduce the rate of corrosion would be anticipated in future research and innovation.

Summary and Recommendations

This review examined three aspects of development and innovations in CCT plant. In addition to identifying emerging trends and technologies since the BEIS (2022) study, the primary aim of our review was to collate and review the evidence on the potential environmental and health impacts of these novel CCT systems. The review also examined whether the implementation of these technologies differs across industrial sectors because of the nature and scale of the processes involved. Our findings are summarised in the following sub-sections.

Innovations in CCT for Industrial Decarbonisation

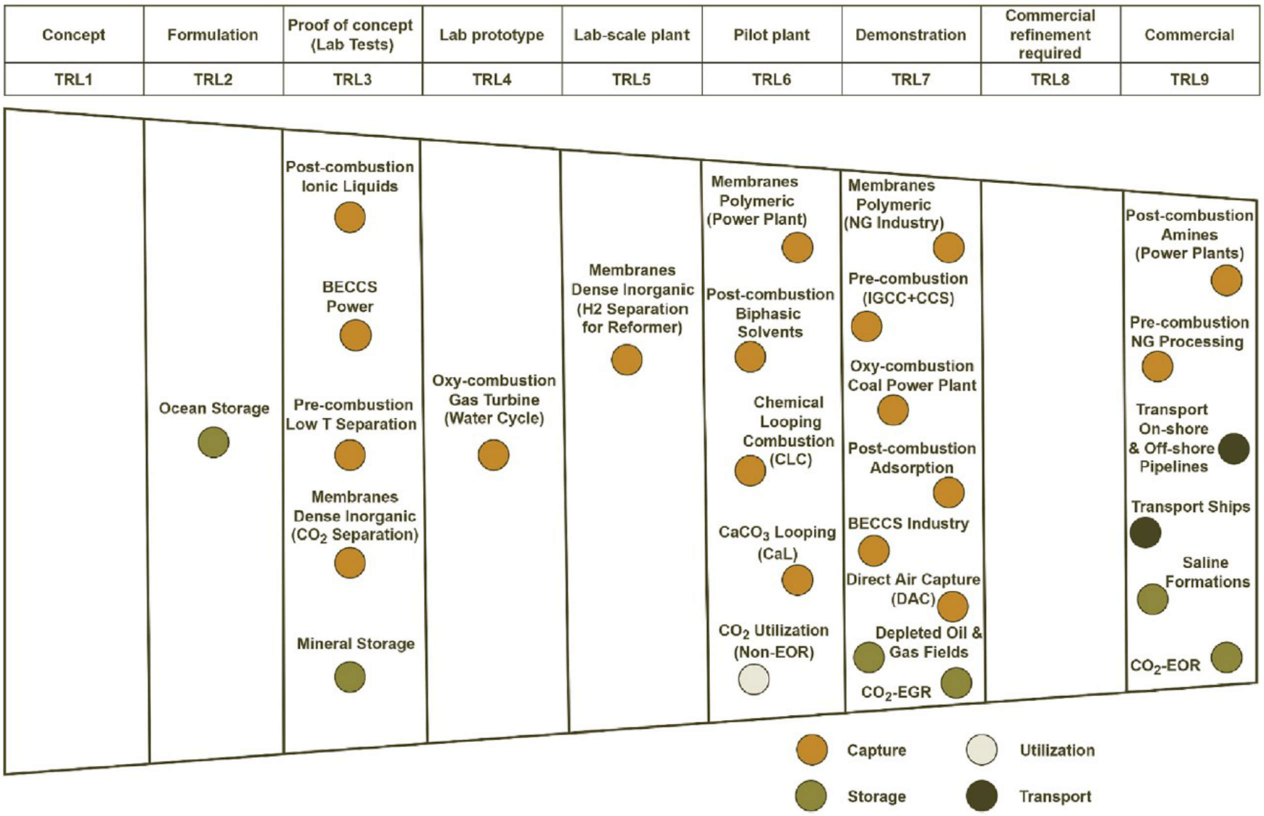
Many options have been proposed for CCT (Shabaz et al. 2021, Gautam and Mondal 2023, Peu et al. 2023), although few of these have reached the level of commercialisation (see Figure 17). Gowd et al. (2023) noted that most developments were centred around conceptualisation (TRL3), laboratory-scale (TRL6), and pilot-scale (TRL7). The outcome of our review supports that view. Many technologies have yet to consider the engineering, environmental, and cost challenges associated with scaling-up to commercial readiness.

There are several common factors driving innovation in CCT. In discussing the power sector, Gowd et al. (2023) noted that the main influences on the speed of uptake are:

capital cost, energy penalty, and the ability to retrofit to existing industrial infrastructure. These are likely to be the primary drivers for innovation and development of new CCT across most industrial sectors. However, several additional drivers have also been identified including a move to less-hazardous technologies (environmental and operational) and systems that are more robust to cope with operational conditions and other hazards within flue gases. The former appears particularly relevant to amine-based solvent systems, where concerns about amines and their breakdown products have been publicly discussed for many years.

In terms of technological deployment up to 2035, Rezaei et al. (2023) concluded that only amine-based solvents are ready for commercialisation, but that several other CCT are at TRL>6 and are making rapid progress. These technologies include other solvents, adsorption-based sorbents, membranes, and cryogenic systems.

Figure 17: Technology Readiness Levels (TRLs) of various CCT options.



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Trends for Sector-by-Sector CCT

Although the power sector is often seen by researchers at the forefront of efforts to reduce CO_2 emissions from fossil fuels, other industries such as the cement, iron and steel, and petrochemical sectors have made significant contributions to global emissions (Peu et al. 2023, Rajabloo et al 2023). Three options for decarbonisation were generally highlighted across a wide range of industrial sectors (Jing et al. 2024):

- Source control, which includes energy substitution and improved efficiency
- Process optimisation to improve manufacturing efficiency
- CCT deployment

It was considered that different industrial sectors are likely to rely on these options to varying degrees. Ganzer and Mac Donald (2023) noted that some energy intensive industries could achieve decarbonisation only by coupling their energy use with efforts made by the power sector. Other key drivers for differences in the implementation of CCT between different industries included: the characteristics and composition of the flue gas (and most notably the CO_2 concentration), the balance of capital and operational costs for deployment of CCT, and other practical factors such as the degree to which sources within a plant can be readily combined for treatment. It was noted by several studies (Podder et al. 2023, Jing et al. 2024) that pre-combustion offers lower operating costs and potential reductions in harmful emissions, but this is at the expense of much higher capital costs and challenges with retrofitting to existing plant.

The sectors with the most developments at 0.2 Mt CO_2 pa and above are power (coal, gas, and oil), chemicals (biofuels and fertilisers), and oil and gas refining.

Environmental Impacts in CCT

There is limited information on the wider environmental impacts of CCT reported in the literature beyond considerations of the energy penalty and water use. Mostly, this reflects a lack of operational experience and reporting in the scientific literature, with most researchers focusing on conceptual/modelled designs and bench-scale experiments. While life-cycle analysis is undertaken to compare several CCT options in different industrial situations, the standardised methods for reporting outcomes such as chemical toxicity are often limited in the detail provided in journal articles to a single index or chemical standard. In many cases, the only emission of interest is CO_2 itself.

Environmental impacts were grouped in this review into four areas:

- Mitigation of CO_2 emissions – capture efficiency and the energy penalty
- Resource use – principally water
- Environmental emissions – mainly to air and water
- Waste management – solid and liquid wastes

In some areas, reducing environmental impact is aligned with reducing costs (a major driver for innovation), and are subject to considerable interest as a result. For example, reductions in the energy penalty or improvements in the capture efficiency through process design or integration with low carbon energy sources was commonly reported. Impacts that either depend on operational experience or are not associated with significant cost reductions such as waste management were rarely considered. Many studies at bench- or even pilot-scale failed to consider the emissions or waste management challenges associated with scaling-up for commercial use.

Capture efficiency is widely reported for different technologies, although most of the evidence comes from pilot-scale studies. Efficiencies are often greater than 80% with limited variation between industrial sectors (reflecting a lack of data). In the case of amine-based systems, where operational experience is available, the capture efficiency achieved in practice is lower than that promised by designers due to teething problems with continuous plant operation.

Similarly, energy penalties were also found in the available literature for some, but not all, CCT. In general, post-combustion options has the highest penalties, and pre-combustion options the lowest. Some technologies appear well-suited to some industries, for example, the implementation of calcium looping in the cement sector, where either CCT products can be utilised within the production process or energy management is seen as complimentary. Su et al. (2023) noted that the relationship between energy penalty and capture efficiency is not always linear, although they tend to increase together.

Resource use almost exclusively focuses on the need for water, either for processing/transporting (such as a solvent carrier) or cooling. It is clear from researchers that the demand and availability of water represents a significant challenge for many CCT processes, especially post-combustion plants.

Reducing emissions is identified as a design goal for several innovations in amine-based capture systems with researchers first identifying the toxicity of amines and their breakdown products more than fifteen years ago. Amine emissions remain a challenge for current systems, but several options including new solvent blends and better engineering have been proposed to address it. If the time gap between hazard identification and design innovation for amine-based systems is reflected in other CCT development pathways, then it is perhaps unsurprising that so little research attention has been paid to it to date. While it may be that some technologies do not have comparable hazards to amine-based systems that require careful management, this also largely reflects a lack of research to understand what environmental emissions may result from scale-up of these technologies.

Recommendations

The main issue to emerge from this review was the lack of available information on the wider environmental impacts of different technologies and the broad lack of consideration of such issues within design goals. The following recommendations aim to address this gap:

- Early engagement with researchers to raise awareness of wider environmental impacts in the evaluation and design of innovative CCT
- Review implementation of related technologies in other industrial sectors to examine the potential to read across to CCT for a range of operational issues, for example, how waste management has worked for membranes used by other industries
- Engage with regulators and operators in other countries, where plants have been operating at either demonstration or commercial scales, to better understand emission and waste management issues for a range of technologies

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List of abbreviations

ACNF	Activated carbon nanofibres
AIPOS	Alumino-phosphates
AMP	2-amino-2-methylpropanol
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business, Energy, and Industrial Strategy
CCS	Carbon capture and storage
CCT	Carbon capture technology
CCUS	Carbon capture utilisation and storage
CLC	Chemical looping combustion
CO	Carbon monoxide
CO_2	Carbon dioxide
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CNF	Carbon nanofibres
CNT	Carbon nanotubes
DACCS	Direct air carbon capture and storage
DCC	Direct contact cooling
DEA	Diethanolamine
DESNZ	Department for Energy Security and Net Zero

DGA	Diethylene glycol amine
DIPA	di-2-propanolamine
DMSO	Dimethyl sulfoxide
DRI-EAF	Direct reduced iron-electric furnace
EfW	Energy from waste
EMAR	Electrochemically mediated amine regeneration
Fe	Iron
FeO and Fe_3O_4	Iron oxides
GPU	Gas permeation unit
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulphide
H_2SO_4	Sulphuric acid
HCO_3^-	Bicarbonate anion
H_2CO_3	Carbonic acid
HFMC	Hollow fibre membrane contactor
IGCC	Integrated gasification combined cycle power plant
K_2CO_3	Potassium carbonate
kg	kilogram
kPa	1,000 Pascals

kt or kT	1,000 tonnes
kWh	Kilowatt hour or 1,000 Watts per hour
LAES	Liquid air energy storage
LEILAC	Low emissions intensity lime and cement process
m^3	Cubic metre
MEA	Monoethanolamine
MDEA	N-methyldiethanolamine
Mg	Magnesium
MgO	Magnesium oxide
MJ	Megajoules
Mn	Manganese
MnO	Manganese oxide
MNPZ	N-nitrosopiperazine
MOF	Metal organic frameworks
MOPS	Microporous organically pillared layered silicates
Mt or MT	1,000,000 tonnes
MW	Megawatt or 1,000,000 Watts
MWh	Megawatt hour or 1,000,000 Watts per hour
N_2	Nitrogen
NDELA	N-nitrosodiethanolamine

NGCC	Natural gas combined cycle
NH_3	Ammonia
NMP	N-methyl-2-pyrrolidone
O_2	Oxygen
OH	Hydroxyl radicals
pa	Per annum or per year
PEM	Proton exchange membrane electrolysis
pKa	Acid dissociation constant
PM2.5	Particulate matter <2.5 micron
PSA	Pressure swing absorption
PZ	Piperazine
RSR	Rich solvent recycling
RTIL	Room temperature ionic liquid
SAPO	Alumino-silico-phosphates
SEPA	Scottish Environmental Protection Agency
SILM	Supported ionic liquid membrane
SO_2	Sulphur dioxide
SPEI	Silica-alkoxylated polyethyleneimine
SRF	Solid recovered fuel
TGR-BF	Top gas recycling blast furnace

TSIL	Task specific ionic liquid
TRL	Technology readiness level
VPSA	Vacuum pressure swing absorption

Glossary

Absorption	The process by which one substance, such as a solid or liquid, takes up another substance, such as a liquid or gas, through minute pores or spaces between its molecules
Adsorption	Adsorption is the physical adherence or bonding of ions and molecules onto the surface of another molecule, which occurs when a gas or liquid solute accumulates on the surface of a solid or liquid (sorbent) to form a molecular or atomic film.
Alkanolamines	Amines that have one or more alcohol functional groups (R-OH).
Amines	Amines are hydrocarbons that contain carbon-nitrogen bonds. They have one or more amino functional groups ($R\text{-}NH_x$). A primary amine has an amino functional group connected to a single carbon atom and two hydrogen atoms ($R\text{-}NH_2$). A secondary amine replaces one of the hydrogens with an additional carbon bond (R-NH-R). A tertiary amine replaces all of the hydrogen atoms with a carbon bond.
Energy penalty	The amount of additional energy needed to run the CCT plant at a given capture rate.
Flue gas	A mixture of gases produced by the combustion of fuel.
Lean solvent	Solvent with little or no carbon dioxide content (usually the state of the solvent on leaving the stripper)
Pinch analysis	A methodology for minimising energy consumption of chemical processes by calculating thermodynamically feasible energy targets (or minimum energy consumption) and achieving them by optimising heat recovery systems, energy supply methods and process operating conditions.
Primary amine	See Amines
Rich solvent	Solvent enriched with captured carbon dioxide (usually the state of the solvent on leaving the absorber)

Secondary amine	See Amines
Sintering	The process of compacting and forming a solid mass of material by pressure or heat without melting it to the point of liquefaction.
Syngas	A mixture of primarily hydrogen and carbon monoxide gas, which is used as a fuel and chemical feedstock.
Technology readiness level	Originally developed by NASA in the 1970s, the technology readiness level is a method for estimating and comparing the maturity of technologies undergoing commercial development.
Tertiary amine	See Amines
Zwitterion	A molecule containing both a positively charged group (cation) and a negatively charged group (anion), which can be connected by a carbon-carbon or carbon-nitrogen bond or fused together in a common ring system.

Appendix 1: Search Methodology

Using BEIS (2022) as a starting point, we undertook a Quick Scoping Review of the published scientific literature from January 2020 to March 2024 (Collins et al. 2015). Further details on our methodology are presented in this appendix.

We undertook a series of searches of the academic literature using Scopus, a comprehensive citation and abstract database, in March and April 2024. The following search terms were used:

(TITLE-ABS-KEY(("carbon capture" OR CCS or CCUS) AND ("carbon dioxide" OR CO2)) AND TITLE-ABS-KEY(impact OR health OR waste OR emission OR water OR toxic* OR harm OR hazard OR sludge OR liquor OR risk) AND TITLE-ABS-KEY(pre-combustion OR post-combustion OR decarbonisation)) AND PUBYEAR > 2019*

(TITLE-ABS-KEY(("carbon capture" OR CCS or CCUS) AND ("carbon dioxide" OR CO2) AND (pre-combustion OR post-combustion) AND NOT "direct air") AND TITLE-ABS-KEY(impact OR health OR waste OR emission OR water)) AND PUBYEAR > 2019*

These searches generated a list of 1,401 articles. The titles of these articles were reviewed and a short list of 675 was compiled into an Excel spreadsheet. Further references were identified in following up the initial review – especially when chasing down descriptions of process fundamentals (often described in older articles). This added a further 86 articles to give a total of 761. Article titles and abstracts were examined to determine whether they were general review articles or reported only on specific studies. 278 articles (37%) were identified as reviews. In addition, titles were reviewed to identify whether they were most likely to address the question of novel technology development, industrial trends in CCT, and/or the environmental impacts associated with CCT. Most articles concerned technology development with very few focussing on environmental impacts as a central theme of the article.

Articles were reviewed using the following methodology. All articles identified that dealt with either industrial trends and/or environmental impacts were prioritised for review irrespective of publication date. In a small number of cases, articles were not reviewed because the paper could not be obtained without a fee (that is, they were neither open access nor available under the Environment Agency's Science Direct subscription service). The majority of articles that dealt only with technology development were reviewed chronologically, starting with the most recent from 2024 and working backwards as project time resource permitted. Articles identified as citations of interest, which were published prior to 2020, were all reviewed. A summary of the number of articles identified by year and the proportion reviewed is shown in Table A1. In total, 303 articles were examined in detail for this study.

Table A1. Articles identified by publication year.

Year	Identified	Reviewed (%)	Unavailable (%)
2024	109	99 (91%)	8 (7%)
2023	187	117 (63%)	34 (18%)
2022	154	8 (5%)	1 (<1%)
2021	144	14 (10%)	1 (<1%)
2020	110	8 (7%)	4 (<1%)
<2019	57	57 (100%)	0 (0%)

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