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Review

A Guideline for Cross-Sector Coupling of Carbon Capture Technologies

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Abstract: Many governments around the world have taken action to utilise carbon capture (CC) technologies to reduce CO_2 emissions. This technology is particularly important to reduce unavoidable emissions from industries like cement plants, oil refineries, etc. The available literature in the public domain explores this theme from two distinct perspectives. The first category of papers focuses only on modelling the CC plants by investigating the details of the processes to separate CO_2 from other gas components without considering the industrial applications and synergies between sectors. On the other hand, the second category investigates the required infrastructure that must be put in place to allow a suitable integration without considering the specific particularities of each carbon capture technology. This review gives a comprehensive guideline for the implementation of CC technologies for any given application while also considering the coupling between different energy sectors such as heating, power generation, etc. It also identifies the research gaps within this field, based on the existing literature. Moreover, it delves into various aspects and characteristics of these technologies, while comparing their energy penalties with the minimum work required for CO_2 separation. Additionally, this review investigates the main industrial sectors with CC potential, the necessary transportation infrastructure from the point sources to the end users, and the needs and characteristics of storage facilities, as well as the utilisation of CO_2 as a feedstock. Finally, an overview of the computation tools for CC processes and guidelines for their utilisation is given. The guidelines presented in this paper are the first attempt to provide a comprehensive overview of the technologies, and their requirements, needed to achieve the cross-sector coupling of CC plants for a wide range of applications. It is strongly believed that these guidelines will benefit all stakeholders in the value chain while enabling an accelerated deployment of these technologies.

Keywords: carbon capture technologies; CO_2 transportation and storage; CO_2 utilisation; modelling; industries

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1. Introduction

Dependence on fossil fuels for energy generation has contributed to a significant rise in atmospheric CO_2 levels. While the yearly growth rate for CO_2 emissions was recorded at 0.9% during the 1990s, it escalated to 3% throughout the 2000s [1]. If no proactive measures are implemented, CO_2 emissions are predicted to climb from the current 36 Gt/year to a range of 48–55 Gt/year by the year 2050. This increase is largely attributed to a projected rise of 40–150% in energy demand [2]. Future models suggest that, by 2100, the atmospheric concentration of CO_2 could double, ranging between 530 and 980 ppm. As a result, the average global temperature is projected to increase between 1.4 and 6.1 °C [3]. These alarming trends necessitate immediate action to reduce CO_2 levels, which can be achieved through the implementation of carbon capture (CC) methods and carbon capture utilisation and storage (CCUS) systems, aimed at completing the anthropogenic carbon cycle [4].

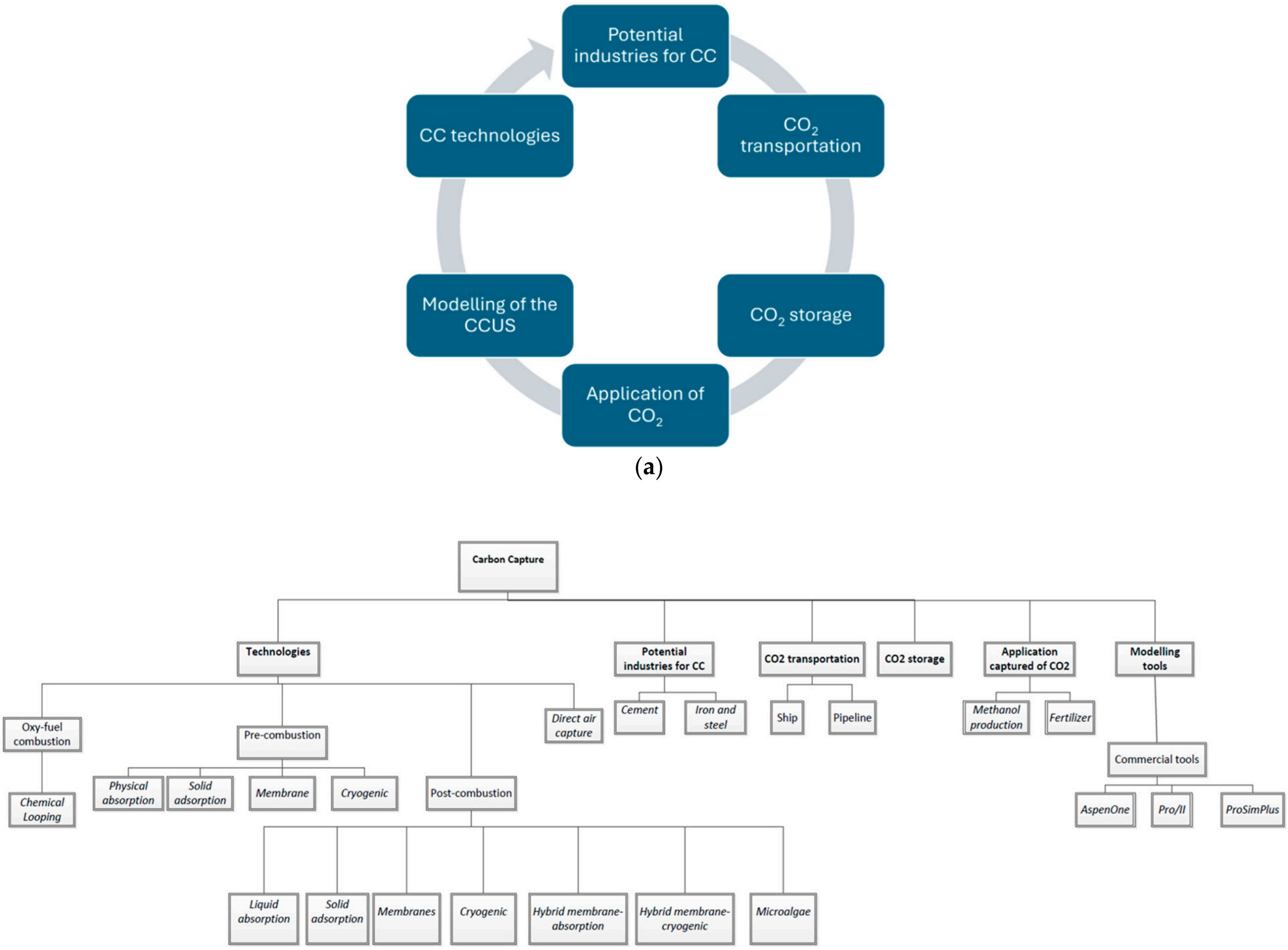
Primarily, carbon capture and storage (CCS) encompasses three fundamental stages: capturing CO_2, transporting it in a compressed form, and securing it in long-term repositories [5]. Of these, the capture phase tends to be the most financially demanding, making up anywhere from 50 to 90% of the entire cost of a CCS operation [6]. CC technologies from point sources can be broadly classified into three categories: post-combustion, pre-combustion, and oxyfuel combustion. When employing the pre-combustion method, carbon dioxide is separated from a gas mixture prior to combustion. This involves converting the fuel into syngas and CO, followed by the introduction of steam to the gas mixture to generate H_2 and CO_2. Consequently, the concentrated CO_2 is separated from the gas mixture, and the remaining H_2 is utilised as fuel. Despite its high efficiency stemming from the elevated CO_2 concentration in the gas mixture, this technology demands substantial investment expenditures [7].

Oxyfuel combustion involves supplying pure oxygen to the furnace instead of air, leading to the production of a flue gas containing pure CO_2 and steam. In such a situation, the capture and separation of CO_2 from the flue gas can be conveniently accomplished by condensing the steam. This technology is deemed advantageous due to the high purity of the captured CO_2, minimal water usage, extremely low production of solid and liquid waste, and very low emissions of NO_x [8]. Moreover, it has been demonstrated that this approach is highly cost-effective and proficient in capturing over 95% of the CO_2 content in the flue gas. Nonetheless, challenges arise in utilising this technology, such as the relatively low flame velocity and flame stability [9]. Additionally, the production of pure oxygen may necessitate a cryogenic air separation unit, a highly energy-intensive process that leads to a reduction in the net power output of the power plant.

Post-combustion CO_2 capture involves diverse CC technologies, including physical adsorption, chemical absorption, membrane-based CO_2 separation, microalgae, and cryogenic CO_2 capture methods. These technologies are gaining more popularity due to their ability to be retrofitted to existing plants. In this scenario, minimal structural alterations are required in the existing plants when employing post-combustion CO_2 capture technologies [7]. It is worth noting that amine-based CO_2 capture technology stands out as the most mature post-combustion CO_2 capture method, boasting a technology readiness level (TRL) exceeding 9. This technology can be effectively integrated with large CO_2 emission point sources, efficiently capturing CO_2 with a relatively high purity, absorption rate, and CO_2 selectivity [10]. Nevertheless, it is crucial to acknowledge that this technology is energy-intensive and currently faces challenges in terms of economic viability for large-scale projects [11]. Furthermore, this technology is considered challenging due to the corrosion of carbon steel, environmental risks, and degradation of the solvent [10,12].

In addition to the above-mentioned CC technologies which capture concentrated CO_2 from large sources of emissions, direct air capture (DAC) can also be considered as a promising solution, especially when targeting negative CO_2 emissions [13]. This technology captures CO_2 from ambient air at any desired location. Employing this technology on a large scale can substantially contribute to lowering atmospheric CO_2 as well as global mean temperature [14]. Nevertheless, this technology demands a substantial initial capital investment [15]. Moreover, this technology is energy-intensive and involves high operating costs due to the extremely low concentration of CO_2 in the air.

This review serves as a detailed guide to navigate through CC technologies and integrate them into broader energy systems to create a comprehensive CO_2 management chain. Unlike most of the review papers in this field which focus solely on specific technologies, this review uniquely covers the entire CC value chain—from designing and simulating CC technologies to CO_2 transportation and utilisation. By presenting the broader perspective shown in Figure 1, this review is particularly crucial. The structure of the review content as shown by Figure 1 is laid out as follows: Section 2 outlines the various CC technological methods as discussed in the existing literature. Section 3 explores industries that show considerable potential for integration with CC technologies. Section 4 elaborates on the logistics for transporting the captured CO_2. Section 5 delves into storage options for the captured CO_2, examining their purposes and attributes. Section 6 describes specific applications where captured CO_2 can be employed as a raw material. In Section 7, the available computational resources for modelling, designing, and simulating CC procedures are presented. Lastly, Section 8 offers conclusive remarks and highlights potential avenues for future research in the domain of CO_2 capture.



(**a**)

(**b**)

Figure 1. (**a**) CO_2 value chain discussed in this study; (**b**) Overview of review's content.

2. Carbon Capture Technologies

To effectively counteract global warming by lowering excess atmospheric CO_2, reliable and economical CC techniques are imperative. A critical element for the success of any CC project involves a tailored design that incorporates appropriate components and processes. Thus, a comprehensive techno-economic evaluation in the early decision-making stages is crucial to evaluate the commercial viability of such technologies [16].

Anthropogenic CO_2 emissions are roughly divided between distributed and centralised sources, the latter mainly comprising industrial setups like cement factories, steel mills, refineries, and power stations. With so many sources emitting significant amounts of CO_2, it is essential to invest in a wide range of CC technologies. A one-size-fits-all solution is inadequate for achieving substantial atmospheric CO_2 reduction. This requires a well-planned infrastructure involving CCS systems, suitable transportation mechanisms for the sequestered CO_2, and practical uses for the captured CO_2 as a raw material. To be most effective, the adoption of CC technologies should coincide with the green transition to renewable energy sources [16]. Pre- and post-combustion CO_2 capture from concentrated point sources have shown effectiveness in slowing the increase in atmospheric CO_2 levels. Additionally, innovative options for negative CO_2 emissions, such as DAC, offer the possibility to remove existing atmospheric CO_2 for potential reuse. Thus, these technologies can reduce the already-existing CO_2 levels in the atmosphere [17]. Nevertheless, capturing CO_2 from the air poses significant thermodynamic challenges due to its extremely low concentration—approximately 0.041%—in comparison to flue gases emitted by point sources, which may contain up to 44% CO_2. Traditional CC methods would require an impractical amount of energy for air-based capture, highlighting the need for innovative engineering solutions for DAC.

In general, CC techniques can be broadly classified into four groups: pre-combustion, oxyfuel combustion, post-combustion, and DAC. Each of these techniques may include various methods for capturing and separating the CO_2. In this part, the above-mentioned technologies will be discussed thoroughly, providing a comprehensive discussion of their advantages and disadvantages.

2.1. Oxyfuel Combustion

Unlike traditional combustion, oxyfuel combustion entails the burning of fuels in a pure oxygen or oxygen-enriched environment rather than in air. This leads to a substantial increase in flame temperatures from around 1600 °C to nearly 2500 °C [18–22]. In this case, as shown in Figure 2, a part of the exhaust gas is reintroduced into the furnace to moderate the furnace temperature. Therefore, the mole fraction of the inlet O_2 varies in the range of 27–35% [23]. Notable benefits of this technology include its compatibility with existing infrastructure, a relatively small physical footprint, and an exhaust gas predominantly consisting of CO_2 and water vapor, substantially facilitating CO_2 capture through water vapor condensation and obviating the need for intricate CO_2 separation and capture processes [24]. Furthermore, this method substantially reduces the flow rate of exhaust gas which leaves the plant by approximately 80%. Over the past decades, oxyfuel combustion has experienced substantial development in fundamental research, exploring the combustion physics and chemistry affected by the altered combustion atmosphere, including radiation heat transfer and homogeneous and heterogenous combustion [25–27]. Technology development has progressed from laboratory studies to commercial deployment [28,29]. The White Rose 426 MWe (gross) plant represents the world's largest supercritical oxyfuel combustion power plant, a collaboration effort by Drax Power, Alstom, Linde, and the UK National Grid [30].

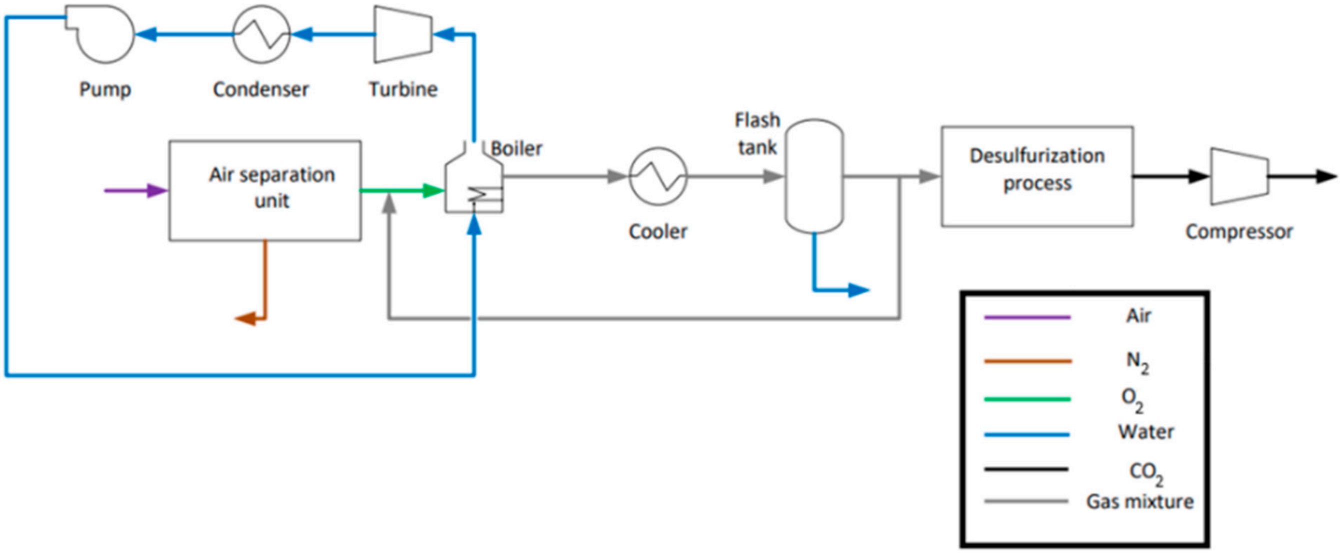


Figure 2. Simplified process flow diagram of the oxyfuel combustion system.

Currently, cryogenic air separation units (ASUs) are widely used to generate the required oxygen for oxyfuel combustion when they are applied for large-scale applications [31,32]. Despite the merits of oxyfuel combustion, commercial barriers to large-scale oxy-combustion deployment persist, impeding the commercialisation of oxyfuel power plants [18,19,28]. The substantial efficiency drops and high energy penalty associated with cryogenic O_2 separation from air contribute to the cost challenges of large-scale oxy-combustion. Nevertheless, a resurgence in oxy-combustion is highly expected, driven by the developments in the hydrogen economy and the potential use of the O_2 byproduct from water electrolysis as a low-cost O_2 supply, as well as by the advancements in oxyfuel combustion technology itself such as using solid oxygen carrier-based and chemical looping combustion.

This technology has been implemented at the Callide Power Station, located in Queensland, Australia [33]. The station uses coal supplied from the nearby Callide mine and consists of three units—Callide A, B, and C—producing a total power output of 1720 MW. Callide A is divided into four units, with the fourth unit modified into an oxyfuel combustion boiler system. This boiler has a rated power output of 30 MWe and is equipped with an ASU capable of producing 660 tons of oxygen per day, with purities of up to 98%.

2.1.1. Chemical Looping Combustion

Chemical looping combustion (CLC) is a promising technique that utilises metal oxides as oxygen carriers, thereby avoiding the energy-intensive cryogenic oxygen separation required in conventional oxyfuel combustion [33,34]. The application of CLC with solid fuels has progressed over the past decade and reached a technology readiness level of 6. Research findings indicate that the effectiveness of electricity production and CO_2 capture in coal-based CLC stands at around 48% and 98%, respectively [35]. This method utilises two fluidised or moving bed reactors, namely an air reactor and a fuel reactor [36–38]. In the fuel reactor, the oxygen carrier undergoes a reduction process through a chemical reaction with fossil or biomass fuels (1). Following this, the reduced oxygen carrier undergoes re-oxidation as it returns to the air reactor (2). The combined reaction for the CLC process is denoted as (3), showcasing an identical reaction and heat release as seen in conventional oxyfuel combustion.

$$C_mH_nO_p\ (\mathrm{fuel,s}) + M_xO_y(\mathrm{s}) \overset{\text{Fuel reactor}}{\rightarrow} M_xO_{y-1}(\mathrm{s}) + CO_2(\mathrm{g}) + H_2O(\mathrm{g}) \tag{1}$$

$$Fe_xO_{y-1}(\mathrm{s}) + O_2(\mathrm{g}) \overset{\text{Air reactor}}{\rightarrow} Fe_xO_y(\mathrm{s}) \tag{2}$$

$$C_mH_nO_p\ (\mathrm{fuel,s}) + O_2(\mathrm{g}) \overset{\text{CLC (combined)}}{\rightarrow} CO_2(\mathrm{g}) + H_2O(\mathrm{g}) \tag{3}$$

The critical operational conditions that affect the CLC performance include the nature of the solid oxygen carrier and its looping rate between the two reactors, the temperature and solids inventory in the fuel reactor, the presence of a carbon stripper between the reactors, and the type and feeding rate of the solid fuel. An oxygen carrier with high reactivity towards combustible gases, such as coal or biomass volatiles and char gasification products, is preferred to minimise the release of unburned gases from the fuel reactor. Commonly, the oxygen carriers investigated and tested in CLC are based on oxides of Ni, Fe, and Mn [36]. Efficient circulation rates of solid oxygen carriers between the reactors are essential for supplying the required oxygen in the fuel reactor for combustion and maintaining the heat balance in the system [37]. The fuel reactor temperature is also a crucial parameter in the CLC, directly impacting char gasification and the oxygen carrier's reactivity to combustible gases within the fuel reactor. High temperatures, around 1000 °C, are recommended in the CLC of coals using a moving bed to enhance CC efficiency and reduce ungasified char in the circulated solids [36]. The quantity of solid inventory in the fuel reactor has contrasting effects on the residence time and pressure drop within the fuel reactor. As a result, when employing a carbon stripper between the two reactors, it is recommended to keep the solid inventory below 1000 $\mathrm{kg/MW_{th}}$.

A prevalent technical problem in CLC is the insufficient combustion of volatile compounds and incomplete gasification of char within the fuel reactor, primarily due to the short contact time between the combustible gases and the solid oxygen carrier. To address this, an oxygen polishing step is often required, employing pure or highly concentrated oxygen to burn out the combustible gases leaving the fuel reactor. However, this inevitably increases the cost of the CLC technology. Mitigation strategies include new reactor designs, such as using a moving bed instead of a fluidised bed as the fuel reactor, selecting more reactive solid oxygen carriers, or developing novel solid oxygen carriers capable of generating gaseous oxygen within the fuel reactor to burn combustible gases and solid char, akin to conventional combustion [37,38].

2.1.2. Alternative O_2 Separation Methods

Currently, oxyfuel plants commonly rely on air separation units (ASUs) to provide the required oxygen for oxy-combustion. Employing a traditional multi-column cryogenic distillation process, an advanced ASU unit can generate oxygen with 99.5% purity and a recovery rate of 97.85%. However, compressing air in an ASU is a very energy-intensive process which results in adding 3–4% energy penalty to the oxyfuel combustion while it also increases the capital costs of the oxyfuel combustion plant by almost 14% [39]. This poses a barrier for the large-scale deployment of conventional oxyfuel plants, emphasising the crucial role of affordable O_2 availability in the success of oxyfuel technologies. Beyond the above-mentioned O_2 byproduct from water electrolysis in the hydrogen economy and chemical looping combustion using solid oxygen carriers, membranes and adsorption technologies emerge as promising avenues for inexpensive O_2 supply and thus cost-effective CO_2 capture.

Significant attention has been directed towards polymeric membranes owing to their notable advantages such as robust mechanical properties, high selectivity between gases, and cost-effective processing capabilities [40]. Incorporating materials like zeolites and carbon-based molecular sieves as inorganic materials into polymetric membranes represents a promising strategy to improve mass transport through polymer films. Alternatively, high-temperature ceramic membranes facilitate oxygen separation from air by incorporating oxygen into the crystal lattice structure, allowing for diffusion through the membrane [41]. While membrane methods offer simplicity and economic advantages over cryogenic oxygen separation, challenges remain, with the primary focus on achieving sufficient thinness and mechanical integrity for high fluxes and durability [31].

In addition to the aforementioned methods for oxygen production, temperature or pressure swing adsorption can be considered as a leading air separation method for oxygen generation. Pressure swing adsorption relies on sorbents with non-unity selectivity for the target components, coupled with pressure cycling to adsorb and regenerate the sorbent for repeated use. Temperature swing adsorption is commonly used when the adsorption and desorption processes take place as a result of decreasing and increasing the temperature, respectively. Utilisation of temperature or pressure swing adsorption contributes to lowering the energy consumption significantly as these methods operate at near ambient temperature and atmospheric pressure conditions. In air separation, zeolites are the most commonly used sorbent materials, preferentially adsorbing nitrogen to produce an enriched oxygen stream [42]. Despite their promise, the primary technical challenge for adsorption processes lies in enhancing the selectivity of sorbents. Moreover, adsorption air separation methods, while very promising, are currently more suitable for small- or medium-sized markets [31].

2.2. Pre-Combustion Carbon Capture

Pre-combustion CO_2 capture is specifically relevant for gasification or reforming plants where solid or gaseous fuels undergo conversion to CO_2 and H_2 before combustion. This CO_2 capture method is shown in Figure 3. In the case of solid fuels like coal and biomass, the pre-combustion capture process involves gasification (4), transforming the solid fuel into syngas primarily composed of CO and H_2. In the case of natural gas (mainly composed of CH_4), it is a reforming reaction (5) that is used to produce the syngas in the pre-combustion capture process.

$$C_mH_nO_p\ (\mathrm{fuel, s}) \overset{\text{Gasification}}{\rightarrow} CO(\mathrm{g}) + H_2(\mathrm{g}) \tag{4}$$

$$CH_4\ (g) + H_2O(\mathrm{g}) \overset{\text{Reforming}}{\rightarrow} CO(\mathrm{g}) + H_2(\mathrm{g}) \tag{5}$$

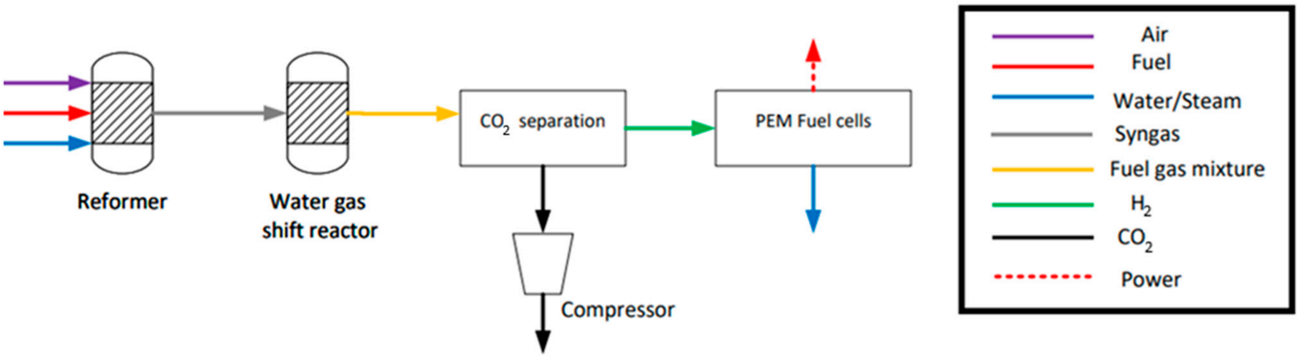


Figure 3. Simplified process flow diagram of the pre-combustion CO_2 capture process.

Subsequently, the generated syngas experiences a water–gas shift reaction (6), converting CO into CO_2 and producing additional H_2.

$$CO(g) + H_2O(\mathrm{g}) \overset{\text{Water}-\text{gasshift}}{\rightarrow} CO_2(g) + H_2(\mathrm{g}) \tag{6}$$

The CO_2 and H_2 out of a water–gas shift column is referred to as a fuel gas mixture. With an elevated CO_2 concentration in the fuel gas mixture, reaching 20–25 mol% [43], effective CO_2 separation from the mixture is achieved. Ultimately, the pre-combustion capture system generates an H_2 fuel stream for diverse power generation applications, such as gas boilers, gas turbines, and fuel cells, effectively mitigating CO_2 emissions into the atmosphere. For solid fuels, such an integrated process is commonly known as the Integrated Gasification Combined Cycle (IGCC).

Many research and development endeavours have been undertaken to advance the pre-combustion capture and elevate its technological maturity and feasibility. A substantial portion of these efforts has been dedicated to the development of CO_2 separation technology. Common CO_2 separation technologies applicable for pre-combustion capture include physical absorption, membrane adsorption, and cryogenic methods. The following provides an in-depth exploration of CO_2 separation through physical absorption, particularly focusing on commercial absorption processes for CO_2 capture, given their unique relevance to pre-combustion capture. In contrast, CO_2 capture through adsorption, membrane, and cryogenic processes is briefly summarised, due to their analogous applications, especially in post-combustion capture scenarios.

2.2.1. CO_2 Separation by Physical Absorption

This technology encompasses both absorption and stripping processes. In the absorption phase, the fuel gas mixture undergoes counter-current contact with a solvent stream, resulting in the physical capture of CO_2 by the solvent. Subsequently, in the stripping process, the solvent which is saturated by CO_2 is heated which results in the desorption of CO_2 and regeneration of the solvent.

The high CO_2 concentration in the fuel mixture and lower energy consumption for solvent regeneration have made physical absorption an appealing method. In contrast to chemical absorption, the degree of CO_2 absorption in physical absorption is linearly proportional to the partial pressure of CO_2, without altering the chemical identities of either CO_2 or the solvents.

Selexol, Rectisol, Purisol, Morphysorb, and Fluor processes have been commercially utilized for CC in pre-combustion applications [44,45]. Table 1 provides a comprehensive summary of the solvents and operation conditions, as well as the pros and cons of these physical absorption processes.

Table 1. Overview of commercial physical absorption processes for CO_2 separation in pre-combustion capture [44–51].

Process	Solvent	Operation Conditions	Advantages	Disadvantages
Selexol	Dimethyl ether of polyethylene glycol	3.6 MPa, 35 °C	High H_2S selectivity; Capable of the simultaneous removal of H_2S/CO_2 and targeted H_2S removal; Possessing high chemical and thermal stability with minimal loss of solvent; Low initial investment and operational costs	High solvent viscosity at low temperatures, lowering the mass transfer rate; Exclusively applicable for CO_2 removal if the CO_2 concentration is higher than H_2S
Rectisol	Methanol	3.6 MPa, −25 °C	Simultaneous removal of H_2S/CO_2, and good removal efficiency (<0.1 ppm); Reasonable solvent viscosity; Chemically and thermally stable, with minimal solvent loss or degradation; More energy-efficient than amine-based processes	Expensive cryogenic process for low-temperature operation; Possible amalgam formation due to mercury absorption at low temperatures
Purisol	N-methyl-2-pyrolidone	6.8 MPa, −15~0 °C	High H_2S selectivity; Compatible with combined removal of H_2S/CO_2, and specific H_2S removal	Volatile solvent, requiring water wash to avoid excessive solvent loss
Morphysorb	Morpholine	6.9 MPa, −48.8 °C	Solvent possesses high loading capacity; Removes H_2S and CO_2 with exceedingly high selectivity; Environmentally friendly with lower corrosion risk; High economic viability due to low operational costs and initial investment costs; Lower energy requirement, recirculation requirement, and hydrocarbon co-absorption	Comparatively novel process with comparatively low technology readiness level (pilot-testing)
Fluor	Propylene carbonate	2.72~5.78 MPa, 25 °C	Low-viscosity and non-corrosive solvent; Enables selective H_2S removal; High CO_2 solubility; No need for make-up water	Expensive solvent; Not economically viable to reach high purity; Requirement of cryogenic operation condition and more efficient gas–liquid contactor

It is worth noting that the Great Plains Synfuel Plant, the only commercial coal gasification plant in the USA, captures CO_2 during the production of synthetic natural gas from lignite coal using the Rectisol process [46]. This facility transfers over 2 million metric tons of CO_2 annually to Canada for use in enhanced oil recovery applications.

2.2.2. CO_2 Separation by Adsorption

Unlike physical absorption technology, adsorption entails the selective creation of either physical or chemical bonds between the adsorbate (in this case, CO_2) and the surface of a solid-phase adsorbent until the adsorbent is saturated [51]. Subsequently, the adsorbed CO_2 is desorbed to regenerate the adsorbent material, achieved by either heating the saturated adsorbent to a specific temperature or reducing the pressure to a certain value, as previously explained in the context of alternative O_2 separation methods for oxyfuel combustion. The former is known as temperature-swing adsorption, a preferred option when the CO_2 concentration is not significant, while the latter is termed pressure-swing adsorption, a method more compatible with high partial pressures of CO_2. The adsorbent regeneration process can also involve a combination of these methods. In this scenario, activated carbon might be used as an adsorbent material to capture CO_2 from a ternary gas mixture of $CO_2/H_2/N_2$ at temperatures ranging from 25 °C to 65 °C and pressures between 5 and 15 bars [52]. Once the activated carbon is fully saturated and the incoming gas composition remains constant, the regeneration process begins. At this stage, nitrogen is introduced into the packed bed, the system pressure is reduced to atmospheric levels, and the temperature is increased to 80 °C for 60 min. It was observed that during the CO_2 adsorption process, higher pressures in the gas mixture contribute to greater CO_2 capture capacities, while increasing the temperature has the opposite effect, reducing the CO_2 adsorption capacity.

In theory, adsorption presents several advantages, such as a high loading capacity under ambient conditions, a regeneration process that is more energy efficient and more cost-effective, ample stability, high rates of CO_2 adsorption, and exceedingly high resilience to moisture and impurities [45]. Frequently employed adsorbents encompass activated carbon, zeolite, carbon molecular sieves, mesoporous silica, metal–organic framework materials, calcium oxide, solid amine-based sorbent, lithium silicate, and lithium zirconium. These adsorbents are also often used in post-combustion capture processes.

2.2.3. CO_2 Separation by Membrane

Dense and porous membranes can serve as selective barriers in gas separation applications. However, according to [53], dense membranes exhibit exceptionally high gas transport resistance, leading to their limited use in this application. When utilising porous membranes for gas separation, gas transport relies on the Knudsen diffusion principle, where the permeate (in this case, CO_2) dissolves in the membrane and diffuses through it. The rate of diffusion correlates with the gradient in CO_2 partial pressure across the membrane [54]. Membrane separation offers several advantages, including the avoidance of steam utility, minimal environmental impacts related to solvent volatilisation and degradation, easy integration into existing plants, compact design, and a small footprint requirement [55,56]. This makes membrane separation particularly suitable for CO_2 removal in pre-combustion CC, given the significantly higher CO_2 partial pressure compared to post-combustion CC. Advancements in membrane technology for CC include the modification of membranes by impregnating polymer membranes with various inorganic fillers [57]. Such modifications enhance CO_2 selectivity and permeability simultaneously, improve mechanical and thermal stability, and reduce processing costs and vulnerability to plasticisation.

2.2.4. CO_2 Separation by Cryogenic Technology

This method is highly recommended for pre-combustion CC as CO_2 concentration in the fuel gas is comparatively high. In this case, CO_2 can be captured and separated from the gas mixture in liquid phase as a result of compression and cooling the gas mixture [58]. This technology has been widely used to separate O_2 from air in oxy-combustion CC and for gasifiers in pre-combustion CC. Moreover, cryogenic separation is utilised to produce high-purity CO_2 in both pre-combustion and post-combustion capture technologies.

2.3. Post-Combustion Carbon Capture Approaches

Post-combustion CC stands as a highly adaptable option for curbing CO_2 emissions from point sources. This is mainly because many technologies within this category can be retrofitted into existing facilities without requiring extensive alterations to the plant infrastructure. Within this category, CO_2 is separated and captured from the combustion products after the burning process but prior to the expulsion of flue gas into the atmosphere. However, the flue gas cannot be directly utilised in these technologies, as it must first undergo a pre-treatment process. As shown in Figure 4, the flue gas is first water-washed in a direct contact cooler, which cools the gas to 40–50 °C and removes hazardous components like mercury. The flue gas then undergoes a desulfurisation process to eliminate its sulphur content, followed by pressurisation by a blower to compensate for pressure drops before entering the CC process. Various post-combustion technologies are available including absorption, adsorption, membrane-based separation, and cryogenic separation. Yet, regardless of the specific technology employed, post-combustion CC introduces a noticeable energy and financial burden to the primary process.

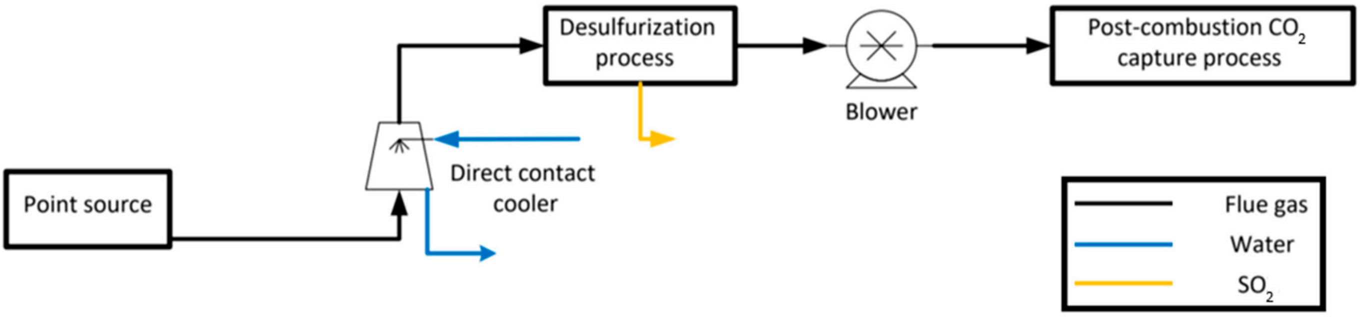


Figure 4. Flue gas pre-treatment process before the post-combustion CC stage.

2.3.1. CO_2 Capture by Liquid Absorption

In the realm of post-combustion CC involving liquid solvents, two predominant methods of absorption are employed: physical and chemical. The mechanisms of both methods rely on equilibrium between the flue gas and the absorbing liquid. As shown in Figure 5, during this absorption, CO_2 is captured from the flue gas by interacting with a suitable solvent within an absorption tower. Subsequent to this, a regeneration column separates the captured CO_2 from the solvent, preparing the solvent for the next round of CC. Conducting the absorption at low temperatures or elevated pressures is advantageous, as the solubility of gases in liquids increases under such conditions. Conversely, the regeneration stage, aimed at solvent recovery and CO_2 release, operates optimally at lower pressures and higher temperatures. A significant challenge involves overcoming mass transfer limitations at the gas–liquid interface in the absorption column, often necessitating large absorbers that contribute substantially to capital costs, sometimes accounting for up to 55% [59].

Regarding chemical absorption, interaction between the solute (CO_2) and solvent typically occurs via a reaction step. In this case, the effectiveness of the chemical absorption process remains high, even under ambient temperature and pressure, due to the formation of strong covalent bonds between the solvent and CO_2 molecules. Typically, this process employs alkylamines for this purpose, with the most commonly used amine solvents being monoethanolamine (MEA), diethanolamine (DEA), or N-methyldiethanolamine (MDEA). Aqueous amine solvents have demonstrated CO_2 removal efficiencies up to 98% and are commercially viable [60]. Obstacles in utilising aqueous amines for CC include corrosion and solvent degradation, which are exacerbated by the formation of heat-stable salts from the reaction of the solvent with flue gas, further increasing the energy demands of the chemical absorption process.

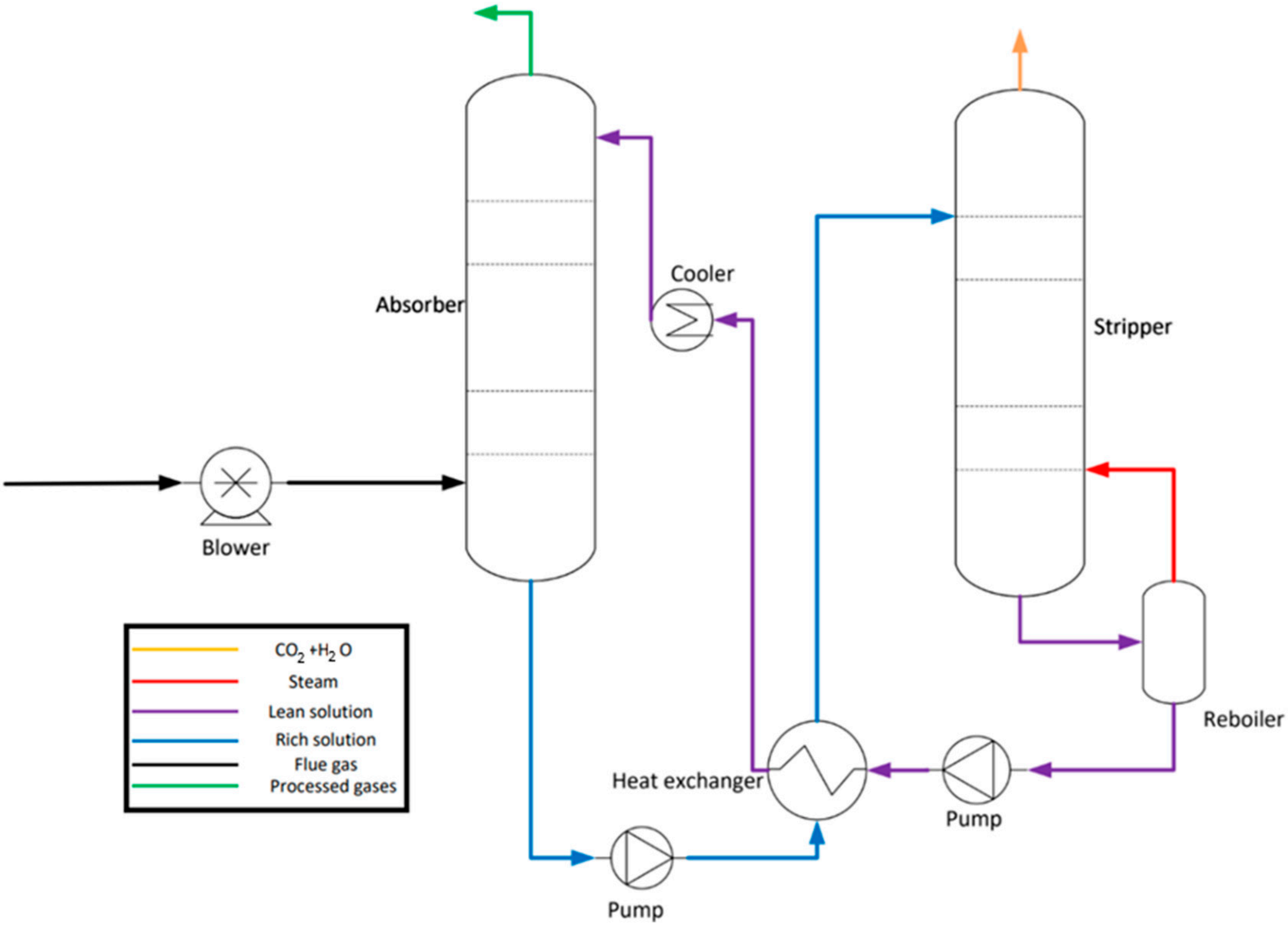


Figure 5. Process flow diagram of CO_2 capture using the absorption process.

The standard operation entails the absorption of CO_2 from the flue gas into a low-volatility amine-based solution. Following the absorption stage, steam stripping regenerates the solvent at temperatures between 100 °C and 120 °C. The resultant stream exiting the desorption column's upper section is subjected to cooling to condense and remove water, thereby achieving high-purity CO_2 suitable for compression and storage. However, vaporised amines can undergo photo-oxidation, producing compounds like formaldehyde and methylmethanamine, posing environmental concerns [61–63].

As previously mentioned, the chemical absorption process is energy-intensive and incurs energy penalties that exceed those of adsorption processes, significantly impacting the power output of coal-fired power plants when it is used for CO_2 capture. In an effort to enhance the energy efficiency of the amine scrubbing technique for CC and to address its associated issues, alternative absorbents have been explored [64]. Among them, the utilisation of aqueous ammonia stands out. In this technique, flue gas interacts with an aqueous solution of ammonia, leading to the formation of either ammonium bicarbonate (NH_4HCO_3) or ammonium carbonate ($(NH_4)_2CO_3$). Even though CO_2 desorption and the regeneration of ammonia solution requires thermal input, this approach has been found to be more energy-efficient compared to MEA-based methods, with up to 64% less energy consumption [64]. According to [65], the energy requirement for solvent regeneration in ammonia-based CC is calculated at 1147 kJ/kgCO_2 which is lower than the 4215 kJ/kgCO_2 for a 30 wt% MEA solution in MEA-based processes.

It is worth noting that the chemical absorption is widely used in post-combustion CC systems. One notable example is SaskPower's Boundary Dam Unit 3 Carbon Capture Facility in Canada, which is the first large-scale CC project at a coal-fired power plant and began capturing CO_2 in 2014 [64]. Initially, the facility faced numerous challenges and was unable to capture more than 70% of CO_2 during its first year of operation. However, performance was subsequently improved, leading to greater reliability, and the facility is now able to capture over 90% of CO_2. Petra Nova, located in the USA, also uses advanced amines for the chemical absorption of CO_2. Notably, Petra Nova captures up to 90% of the CO_2 from the flue gas, achieving CO_2 purities of up to 99.9% [65]. The facility is capable of capturing more than 5000 tons of CO_2 per day, which translates to 1.5 million tons per year.

In contrast, physical absorption methods involve the capture of CO_2 by dissolving it into a solvent without any chemical interactions. These processes usually necessitate low temperatures and high pressures for optimal CO_2 capture. The absorption process is followed by a desorption stage which releases the CO_2. Although there are lower energy requirements for CO_2 release and solvent renewal, this method is limited by its absorption capacity. Pre-cooling the flue gas to ambient temperatures is often a prerequisite for effective absorption, which impacts the thermal efficiency negatively. Ionic liquids (ILs), encompassing a wide category of salts, are regarded as physical solvents capable of effectively dissolving CO_2. They demonstrate high stability at elevated temperatures, reaching several hundred degrees Celsius [47]. Therefore, these solvents can be employed to treat industrial flue gas directly, eliminating the necessity for cooling. Additionally, studies have demonstrated their effectiveness in absorbing pollutants beyond CO_2. Specifically, ILs exhibit a SO_2 solubility 8 to 25 times higher than CO_2 at an equivalent partial pressure [66]. However, ILs that can effectively dissolve, and separate gaseous CO_2, are currently not available in large quantities. As a result, the costs associated with using them for CO_2 capture applications remain high. Nevertheless, it is anticipated that the costs of ILs will significantly decrease in the future as they become more readily available commercially.

2.3.2. CO_2 Separation by Membranes

Over the past 30 years, membrane technologies for gas separation have been widely used in industries, specifically for separating air and enriching oxygen for combustion purposes. Lately, these techniques have seen increased adoption in oxyfuel combustion and IGCC systems for power production [31,67,68]. Selectivity and permeability stand as the crucial factors for polymeric and microporous membranes. The multiplication of these two variables gives the separation power, also known as the separation factor [6,69,70]. A high numerical value for this parameter generally shows an effective and superior membrane. Nevertheless, selectivity and permeability share an antagonistic relationship. Specifically, elevating permeability usually compromises selectivity, and improving selectivity often lowers permeability. This duality constitutes a core obstacle in efforts to concurrently optimise both characteristics.

In polymeric membranes, the fundamental process facilitating gas separation is selective solution-diffusion. Here, specific gas molecules are either absorbed or adsorbed in the polymer matrix's void spaces and navigate through channels within the polymer chains, leaving other gas mixture components relatively less influenced [70]. Achieving absolute selectivity for a particular gas via polymeric membranes is virtually unattainable, necessitating multiple cycles to reach the required enrichment levels. Carbon capture using these membranes poses additional challenges, such as significant surface area requirements due to low CO_2 concentrations in flue gas. Moreover, these membranes must be chemically stable in the face of varied flue gas contaminants, requiring a gas dryer to exclude water vapor for efficient CO_2 capture [71].

Inorganic membranes, classified based on their porosity into porous and dense types, offer another avenue for CC [72]. Only porous inorganic membranes can offer practical features for CC application [6,73]. These membranes might be composed of a range of carbon nanostructures like carbon nanotubes or hollow fibres. They can also be synthesised from various oxides including zeolites, silica, and metal–organic frameworks, along with alumina. Their inherent chemical and thermal stability render them attractive for CC applications. Yet, moisture in the flue gas tends to reduce the performance of most inorganic membranes for CC. Moreover, although these materials can endure elevated temperatures, the optimal operating range generally stays below 200 °C for the majority of inorganic and composite membranes [74]. Several factors influence gas separation via inorganic microporous membranes. For example, surface engineering can enhance CO_2 adsorption capacity and surface diffusion [75]. Likewise, the incorporation of amine functional groups on the membrane surface can have a similar impact [76].

2.3.3. CO_2 Capture by Cryogenic Technology

Cryogenic CO_2 capture (CCC) is a method operating at low temperatures, wherein flue gas is cooled below the temperature threshold at which CO_2 changes from vapor to a solid state. This process effectively captures CO_2 and can recover up to 100% of the CO_2 present in the flue gas. Due to its low energy consumption, CCC proves highly efficient when contrasted with other post-combustion carbon capture methods [7]. As shown in Figure 6, this technology employs a cascade vapor compression cycle to cool down the flue gas to extremely low temperature levels. Even though the cascade refrigeration cycle is known for its high energy consumption, the energy penalty of this process (which varies in the range of 0.71–0.92) is comparatively low due to its efficient heat integration [77]. This technology uses a multi-stream heat exchanger to warm the cold products by cooling the incoming flue gases. As shown in Figure 6, the CO_2 in the gas mixture is cooled to its frost point in a desublimation heat exchanger through direct contact with a contact liquid, which is itself cooled by a methane-based refrigeration cycle.

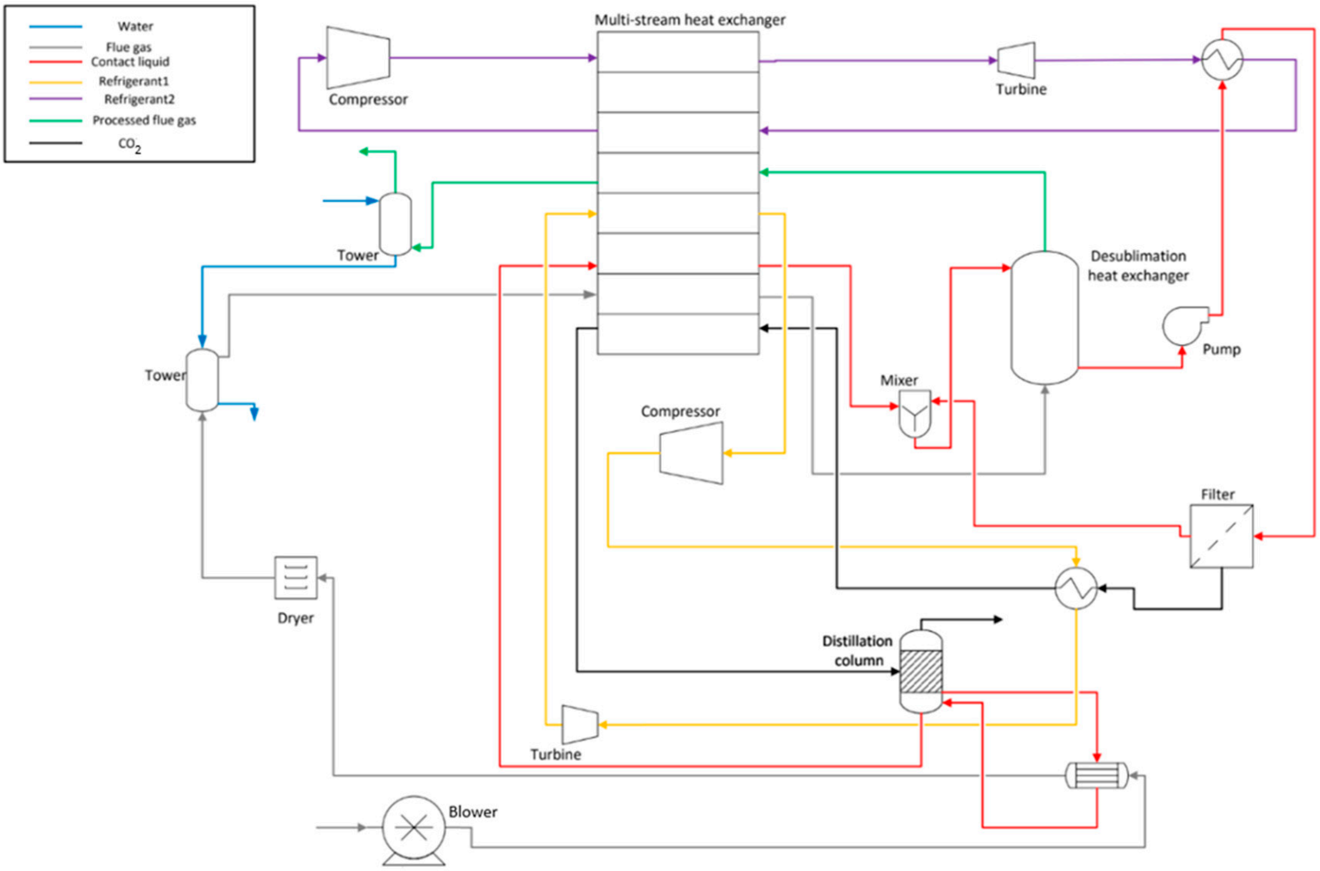


Figure 6. Simplified cryogenic CC process [77].

Being a bolt-on retrofit technology, the CCC can seamlessly integrate with existing point sources. Furthermore, this technology has a potential to use natural gas as a refrigerant, opening the door for energy storage in the form of Liquid Natural Gas (LNG). In this case, the LNG utilised for cooling the contact liquid undergoes vaporisation and is subsequently pumped into the natural gas pipeline. This feature reduces the operating costs of the CCC process by lowering the electricity consumption of the process during the peak hours when the electricity price is high. In this case, it has been shown that the CCC process consumes no more than 12–18% of the electricity supplied by a power plant if energy storage operates at over 90% efficiency [77]. However, exploiting this option requires access to natural gas networks.

Despite the advantages mentioned above, this technology also has its own challenges when capturing and separating CO_2 from the flue gases. For instance, the introduced flue gas to the CCC process should be completely water-free to prevent the formation of ice in the heat exchangers. Furthermore, similar to other post-combustion CO_2 capture technologies, this method cannot be considered very cost-effective when the CO_2 concentration in the flue gas is exceedingly low. In this case, a significant volume of gas must be cooled to separate a small amount of CO_2 from the gas mixture, which then requires even lower temperatures to desublimate the CO_2 content.

2.3.4. CO_2 Capture by Hybrid Membrane–Absorption Process

Integrating membrane technology with the chemical absorption CO_2 capture process can enhance the overall performance of this technology. It has been shown that this combination can enhance the performance of the absorption CO_2 capture process by removing the acid gases and enhancing the CO_2 absorption reaction in the absorber column [78,79]. As shown in Figure 7, a portion of the flue gas is directed to the membrane separation unit, while the remainder is sent to the absorber column. In the membrane unit, the CO_2 concentration in the gas mixture is increased to over 20%, after which it enters the bottom of the absorption column. This higher CO_2 concentration accelerates the absorption reaction at the bottom, where the solvent has a high CO_2 loading. While high CO_2 loading in the solvent reduces the reaction rate, this can be compensated for by the increased CO_2 concentration in the gas mixture. Studies have demonstrated that the optimal flow rate ratio directed to the membrane separation unit is 50% [78]. In this case, the heat duty of the regeneration process can be decreased up to 20.7%.

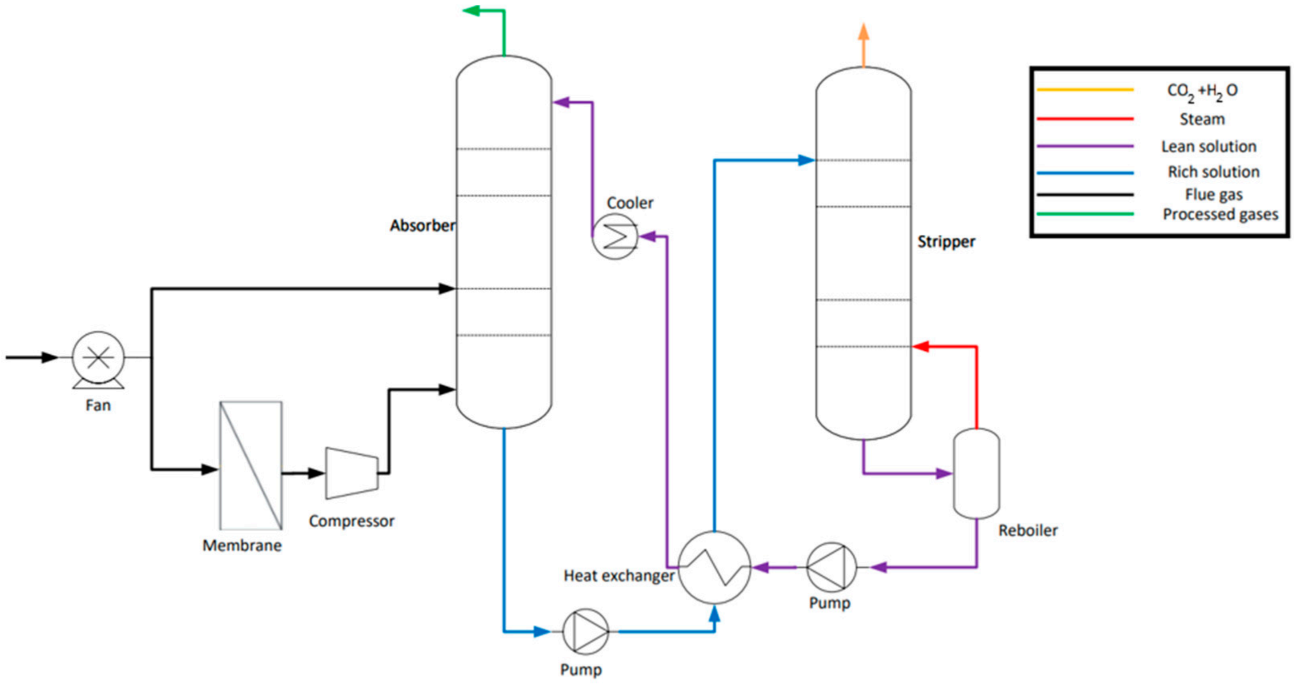


Figure 7. Process flow diagram of a hybrid membrane–absorption CC process.

2.3.5. CO_2 Capture by Hybrid Membrane–Cryogenic Process

This combination is mostly used when the cryogenic CO_2 capture process is used to separate CO_2 from the flue gas in the liquid phase. In this case, the membrane separation unit is used to increase the CO_2 concentration before entering the cryogenic process. As a result of enriching the CO_2 concentration in the flue gas, CO_2 is condensed at higher temperatures which translates to a lower compression power as well as a decreased energy penalty. As shown in Figure 8, the concentration of CO_2 in the gas mixture increases from 5% to 22.6% due to membrane separation. The gas then undergoes a three-stage compression process with intercooler to enhance the energy efficiency and reduce the energy consumption of the compression process. The pressurised flue gas, at a pressure of 6 bars, enters a multi-stream heat exchanger, where it is cooled by warming up the captured CO_2 and the processed gases. Subsequently, liquefied CO_2 is separated from uncondensed components in a flash tank. The liquefied CO_2 exits the flash tank from the bottom, while uncondensed gases leave from the top; both are used to cool the incoming flue gases before they exit the multi-stream heat exchanger at ambient temperature. As illustrated in Figure 8, the processed gases, primarily consisting of nitrogen, are discharged into the atmosphere, while the evaporated CO_2 leaving the multi-stream heat exchanger is liquefied by a three-stage compressor and intercooler, delivering liquid CO_2 at a pressure of 110 bars. It has been shown that this combination is more effective when the CO_2 mole fraction in the flue gas is very low. The results have shown that the utilisation of the membrane in the cryogenic process can lower the power consumption within the cryogenic process by 44% when the CO_2 content in the flue gas is 13.7%. However, this value decreases to 27% when the CO_2 concentration in the flue gas is 40% [80].

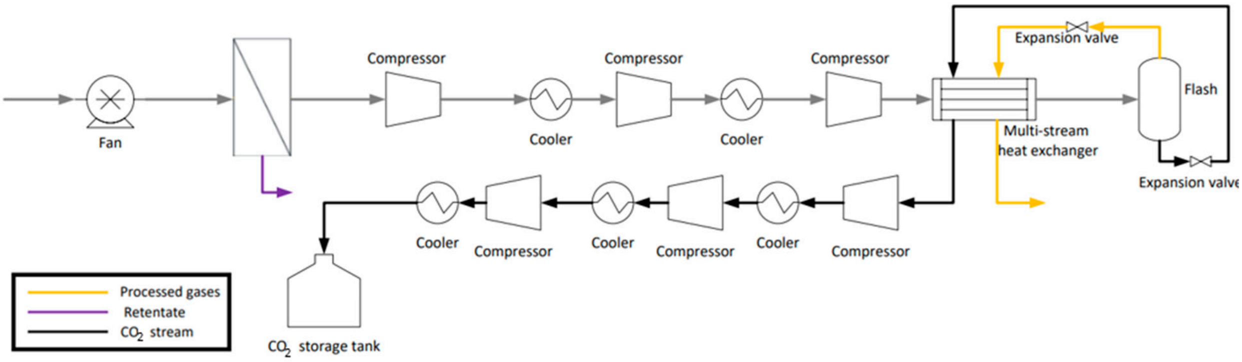


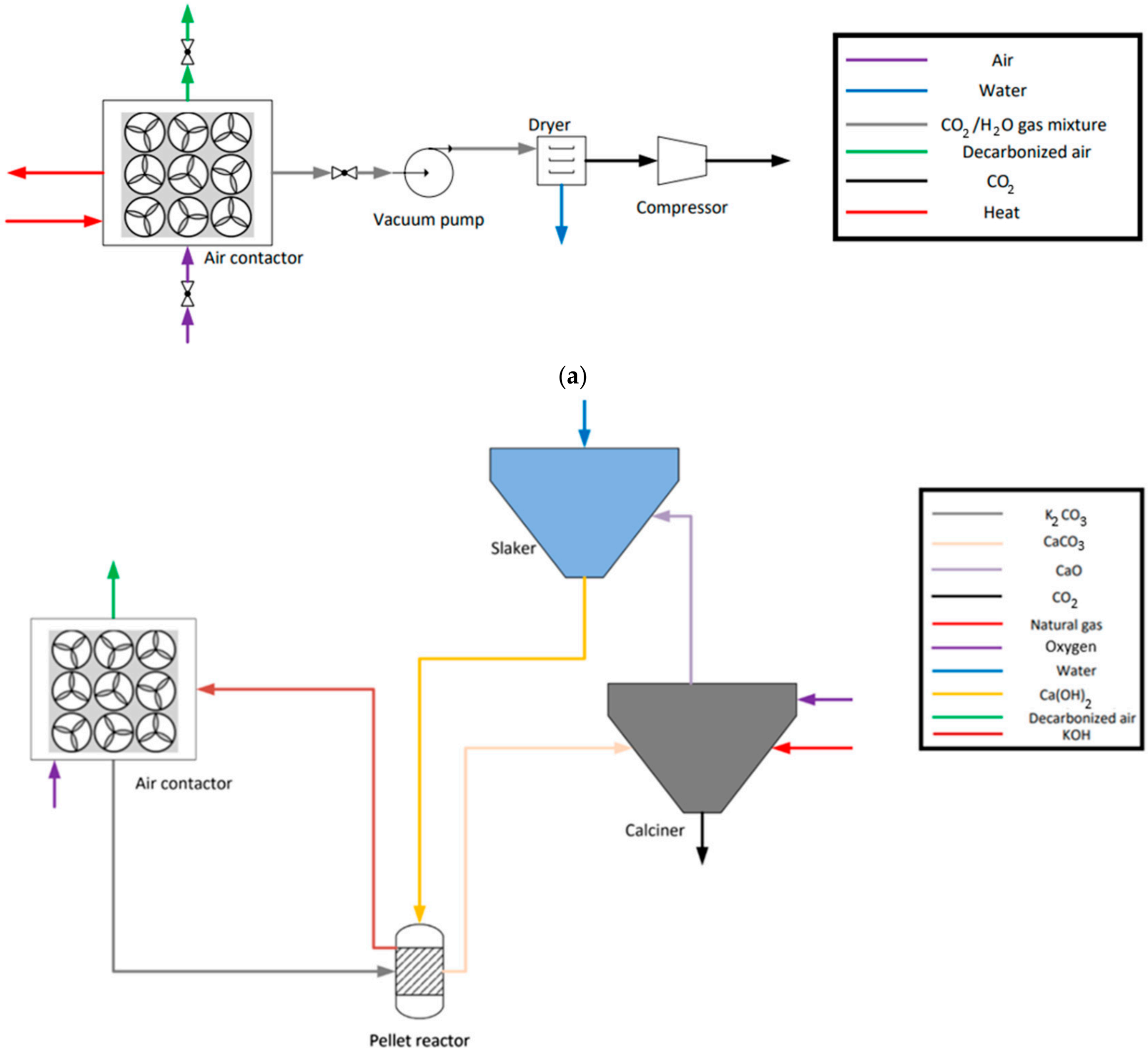
Figure 8. Simplified process flow diagram of a hybrid membrane–cryogenic CC process [80].

2.3.6. CO_2 Capture by Microalgae

Microalgae, which are photosynthetic microorganisms, exhibit the efficient capture and storage of CO_2 across a broad spectrum of CO_2 concentrations. Hence, they can be efficiently employed to capture CO_2 from both the atmosphere and the flue gas discharged by industries [81]. Utilising bioconversion mechanisms during photosynthesis, these microorganisms convert CO_2 into biofuels. Consequently, the use of these microorganisms proves to be a highly beneficial solution to greenhouse gas emissions, offering advantages not only through the capture and sequestration of CO_2 but also by generating biomass that can be transformed into biofuels [82]. Moreover, microalgae have demonstrated superior growth rates and biomass production compared to other terrestrial plants. Additionally, this approach entails straightforward maintenance, making it highly cost-effective with low operational expenses [83]. Microalgae have the capability to utilise nutrients present in wastewater, making them suitable for wastewater treatment purposes [84]. However, the utilisation of microalgae for CO_2 capture comes with several challenges that require careful consideration. For example, previous studies have indicated that the presence of NO_x and SO_x in the flue gas mixture can adversely affect the growth of microalgae [82,85]. Reducing the costs associated with microalgae processing is essential for making this technology economically competitive with existing and well-established post-combustion CC technologies. It has been demonstrated that the processes of harvesting and dewatering microalgae are highly energy-intensive. Consequently, further research is required to diminish the energy consumption of these processes by increasing the cell density.

2.4. Direct Air Capture

DAC covers an extensive pallet of different technologies similar to those used in post-combustion CC but with design adjustments to enable capture of CO_2 from the air despite the low concentration. Currently, the most dominant DAC technologies involve either aqueous or solid sorbent processes [86]. Figure 9a illustrates an adsorption DAC process, which includes an air contactor, vacuum pump, control valves, and heat and cold supply. This cyclic process is considered the most mature adsorption method, where the sorbent material is regenerated once saturated. In this process, ambient air enters the adsorber unit, where water and CO_2 are removed from the gas mixture, and CO_2-depleted air exits the system. When the sorbent becomes saturated, the bed is heated to remove nitrogen gas from the void spaces. This step is followed by further heating and the application of a vacuum pump to facilitate the sorbent regeneration. Notably, this method operates at moderate temperatures (~100 °C), unlike aqueous processes that require higher temperatures.



(**a**)

(**b**)

Figure 9. Direct air capture technologies: (**a**) solid adsorption, (**b**) alkali-scrubbing [86].

Figure 9b also shows the simplified flow of an alkali-scrubbing DAC process, where KOH reacts with CO_2 to form K_2CO_3, which is then converted to calcium carbonate. The generated calcium carbonate is fed to a calciner, where it decomposes into CaO and CO_2 at elevated temperatures exceeding 900 °C. The final regeneration step occurs in the slaker, where CaO reacts with water to form $Ca(OH)_2$.

DAC systems can be strategically positioned near locations designated for CO_2 storage or utilisation, providing a flexible and adaptable supplement to the CO_2 mitigation strategy. Specifically, the Direct Air Capture and Storage (DACS) systems have been highlighted as an essential part of the net zero pathway suggested by the International Energy Agency (IEA) because they have the potential to achieve negative emissions when powered by renewable energy.

Proponents argue that DAC contain significant advantages compared to other Negative Emission Technologies (NETs) based on Bioenergy with Carbon Capture and Storage (BECCS) because the land footprint of DAC is several orders of magnitude smaller which results in a higher overall sequestration efficiency [87]. DAC also provides a potential pathway to cover the increasing demand for green carbon related to the projected expansion of E-fuels and E-chemicals in the future [88]. However, the economic feasibility of DAC is currently not favourable for large-scale deployment with costs estimates in the range of USD 400 to 700 per ton of captured CO_2. In all DAC concepts, the significant energy demand is considered a primary cost factor resulting in a direct link between future electricity prices and the economic feasibility of DAC plants. Moreover, the capture costs of liquid DAC decrease when using it in larger-scale applications, while the costs associated with modular solid DAC technology depend on the expenses related to the sorbent material rather than the scale of application [89].

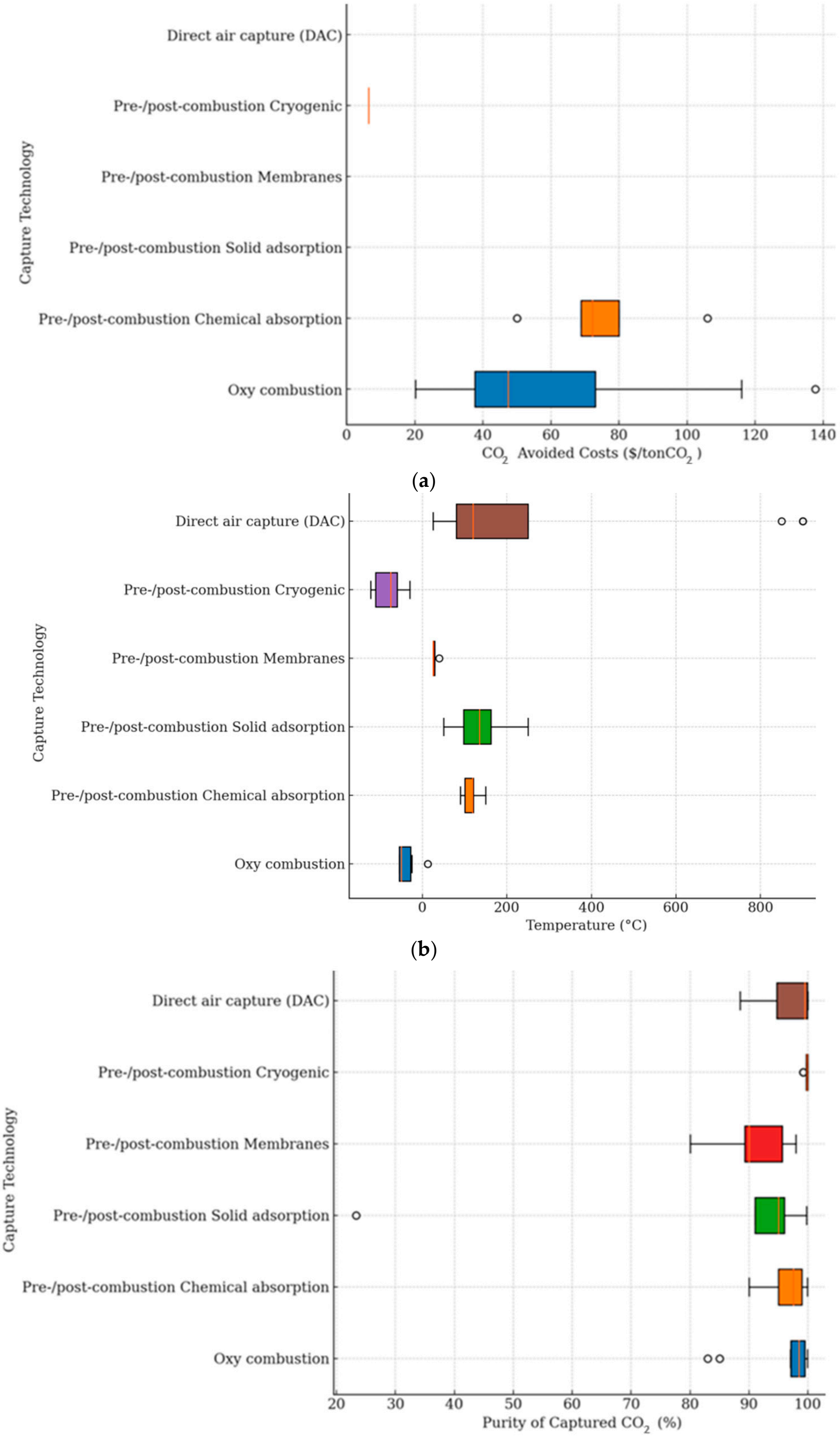
2.5. Summary of the Most Researched Carbon Capture Technologies

Table 2 presents a summary of the techno-economic characteristics of the most extensively researched CO_2 capture technologies, compiled from various literature sources. The table provides insights into the purity of captured CO_2, temperature requirements, energy penalties, CO_2 capture costs, TRL, and CO_2 avoidance costs for different technologies. It is important to note that temperature requirements indicate the extreme temperatures, i.e., the highest or lowest temperatures necessary for separating CO_2, purifying it, or regenerating the sorbent material. Additionally, the energy penalty of the technologies is given based on the form of required energy, which can be in the form of electricity, heat, or both. It is worth noting that the energy penalty is one of the most critical factors in determining the operating costs of the CC systems, making it a key element in their overall performance. As shown in Table 2, DAC has an exceedingly high energy penalty, primarily due to the need to capture CO_2 from a very diluted stream. Chemical absorption also has a high energy penalty, largely driven by the significant energy required for solvent regeneration. However, among all the CC technologies listed in Table 2, cryogenic and membrane processes have higher energy efficiency due to their lower energy penalties. The cryogenic process is particularly advantageous not only because of its lower energy penalty but also due to its ability to achieve higher CO_2 purities, making it more favourable than the membrane process. The TRL of the CO_2 capture technologies may not be entirely precise as this parameter was reported at the time of the respective studies.

Table 2. Summary of techno-economic characteristics of the most researched technologies.

CC Technology		Purity of the Captured CO_2 (%)	Temperature (°C)	Energy Penalty (In the Form of Heat * (MJ_h/kg_{CO_2})) or Electricity **: (MJ_e/kg_{CO_2}) or Power Plant Output Reduction (PPOR%)	CO_2 Capture Costs (USD/ton_{CO_2})	Technology Readiness Level (TRL)	CO_2 Avoided Costs (USD/ton_{CO_2})
Oxy combustion		99.94 [90] 99.5 [91] 83–99.9 [92] 99.3 [93] 85–99.5 [94] 97–98 [95] 99 [96]	−30 to −50 [97] −54 [93] −54.9 to 13.2 [94] −55 to −25 [95]	7–11 PPOR% [98] 12 PPOR% [99] 11.59 PPOR% [100] 10.36 PPOR% [96] 9.53 PPOR% output [101] 12.11 PPOR% [102] 10.7 PPOR% t [103]	36–67 [98] 25.3–34.3 [103] 27.8–53.2 [104] 54 [105]	8 [106] 7–8 [107] >7 [108] 8 [28] 7 [105] 5–7 [109]	45–73 [98] 47.4–74.8 [92] 29.18–46 [103] 37.6–66.83 [104] 22.355–22.42 [110] 116–137.64 [111] 63.27 [105]
Pre-/post-combustion	Chemical absorption	99.9 [112] 90–95 [113] 97 [114] 99 [115] >98 [116] 98 [117] >99 [118] >95 [73]	108–128 [119] 119.1 [116] 101–120.8 [120] 90 [121] 150 [122] 120 [123] 96 [118] 100–120 [124]	3.6 * [112] 3.8 * [114] 3.29 * [115] 4 * [125] 3.9 * [119] 3.63 * [116] 3.8 * [117] 3.5 * [126] 1.379 ** [77]	28–103.5 [127] 58.8–76.6 [115] 35–53 [117] 59.1 [128] 42.2–45.45 [129] 42.06 [130] 44 [105] 49 [131] 80 [132] 73 [133]	9 [98] 9 [134] 8–9 [135] 9 [105] 9–11 [109] 9 [136]	50–80 [115] 106 [98] 68.8 [105] 72.2 [133]
	Solid adsorption	>95 [137] 47.65 [138] 23.33–99.8 [139]	120–150 [137] 105 [140] 80–90 [141] 150–200 [142] 50–100 [143] 100 [138] 200 [139]	3.78 * [137] 1.79–2.14 ** [139]	51–57 [131] 40–49 [137] 19.6–41 [144]	7 [105] 6 [145]	n/a
	Membranes	90 [113] 98 [126] >80 [146] 80–95 [73] 88.5–96.3 [147] 90 [148], [149]	25 [146], [150] 40 [149] 29 [147]	0.89 ** [113] 0.5–1 ** [146] 1.49–2.17 ** [126]	16.96–158.9 [127] 34.4–46.6 [115]	7 [134] 2–6 [135] 6–7 [109]	n/a
	Cryogenic	99.99 [73] 99.8 [151] 99.7 [152] 99.17 [153] 99.9 [154] 99.99 [155] 99.9 [156] 99.2 [77] 99.7–99.99+ [130] 99.99 [105]	−55.97 [153] −63 to −30 [154] −122 to −103 [156] −119 [77] −75 [105]	1.024 ** [156] 0.71–0.92 ** [77] 0.854 ** [130]	10.28 [154] 12.36 [130]	6 [134] 3–6 [157] <6 [135] 9 [136]	6.47 [130]
Direct air capture (DAC)		99.5–99.96 [158] 99.9 [159] >95 [160] 88.5 [161]	850–900 [162] <100 [163] 80–120 [164] 120 [165] 25–60 [166] 900 [167] 250 [158] 25 [160] 250 [168] 90 [161]	12 * [169] 6.7 * [162] 8.81 * [164] 8.3–11.1 * [167]	138 [162] <300 [170] 77–142 [166] 94–232 [167] 250–690 [159] >1000 [161] 1100–1500 [171] 250–690 [172]	7 [173] 9 [174] 7 [175] 7 [176]	n/a

Figure 10 also provides a better overview of the data shown in Table 2. As can be seen, each box plot illustrates the range of values for a specific characteristic (e.g., CO_2 purity, capture costs, or temperature requirements) across various CO_2 capture technologies. The box itself represents the interquartile range (IQR), encompassing the middle 50% of the data. The vertical line within the box marks the median, the point that divides the dataset into two equal halves.

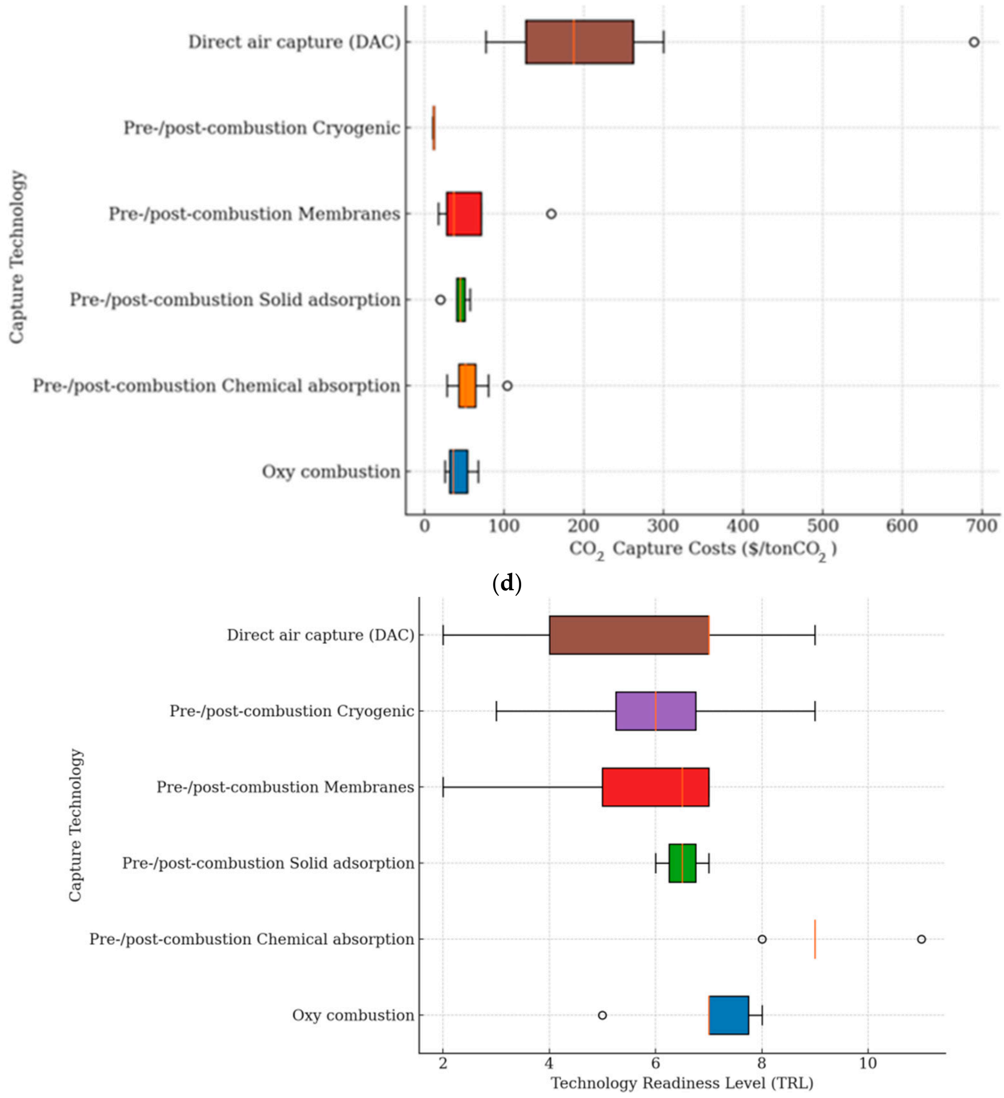


(**a**)

(**b**)

(**c**)

Figure 10. *Cont*.



(**d**)

(**e**)

Figure 10. Visualisation of key characteristics of CC technologies: (**a**) CO_2 avoided costs, (**b**) temperature requirements for CO_2 separation, (**c**) purity of captured CO_2, (**d**) CO_2 capture costs, (**e**) technology readiness level (TRL) [90–176].

When the median is not in the centre of the box, it suggests the data are skewed, meaning the distribution is asymmetrical. If the median is closer to the left side of the box, more data points fall above the median (indicating positive skew), whereas if it is nearer the right side of the box, more points lie below the median (indicating negative skew). The whiskers extend to the smallest and largest values within 1.5 times the IQR, and any data points beyond this range are marked as outliers, shown as individual circles.

Comparing the energy consumption of the state-of-the-art CC technologies outlined in Table 2 with the theoretically minimum energy needed to separate CO_2 from a gas mixture using an ideal CC technology without energy loss is crucial for highlighting the deviation between CC technologies and their ideal counterparts. This minimal energy consumption is calculated by determining the difference between the Gibbs energy of the gas mixture and the separated gas streams, employing the following Equation (7):

$$E_{min} = -\frac{RT}{\eta x_{CO_2}}\left(\left(x_{CO_2} ln x_{CO_2} + \left(1 - x_{CO_2}\right) ln\left(1 - x_{CO_2}\right)\right) - \left(1 - \eta x_{CO_2}\right)\left(1 - \eta\right) x_{CO_2} ln\left(\left(1 - \eta\right) x_{CO_2}\right) + \left(1 - \left(1 - \eta\right) x_{CO_2}\right) ln\left(1 - \left(1 - \eta\right) x_{CO_2}\right)\right)\right) \quad (7)$$

where x_{CO_2} and η represent the mole fraction of CO_2 in the gas mixture and CO_2 recovery rate, respectively. Figure 11 presents a comparison between the energy penalties associated with the state-of-the-art CC technologies and the ideal CC method for capturing 90% of the CO_2 content in the gas mixture. Notably, at lower CO_2 concentrations, the difference between the energy penalties of actual CC technologies and the ideal CC method is more pronounced. However, as the concentration of CO_2 in the gas mixture increases, this difference slightly decreases. Furthermore, the figure emphasises that CC technologies utilising heat show a more substantial difference from the minimum energy required for CO_2 separation under ideal operating conditions.

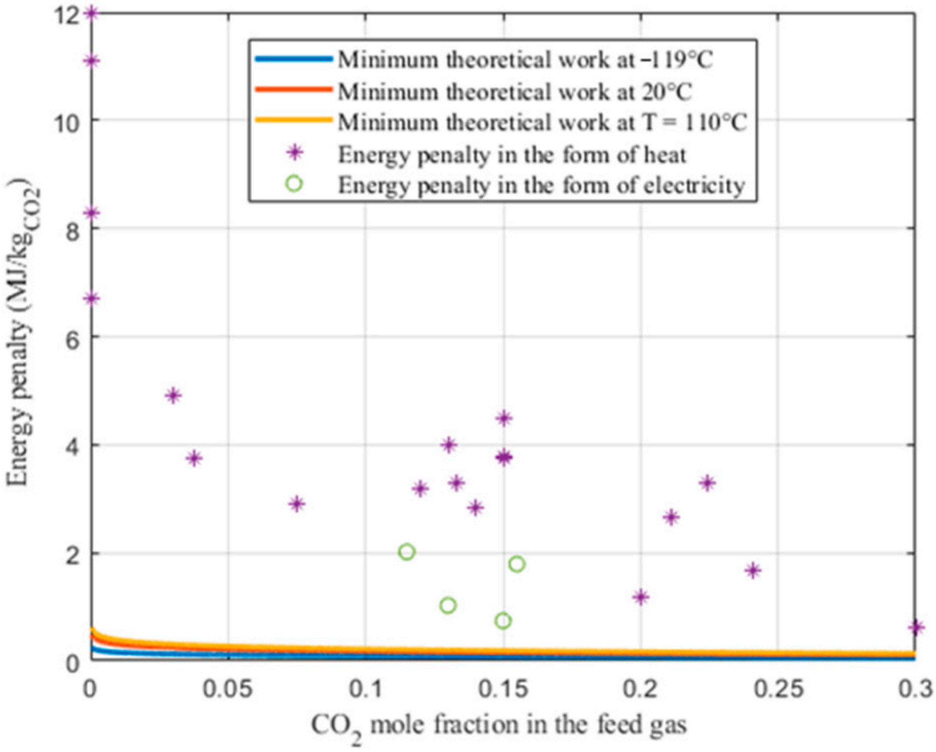


Figure 11. Comparison of the energy penalty of the real CC technologies with the ideal CC method [77,115,125,126,137,146,156,169,177–184].

3. Main Potential Industries for CC

The main industrial sectors with significant potential for CC are presented in this section. Iron and steel factories as well as cement plants can be considered as the largest point sources with the highest potential for CC. Other industries with comparatively high potential are also given in this section. Finally, a comparative analysis is presented based on the extracted data from the literature.

3.1. Iron and Steel

The production of iron and steel is an extremely energy-intensive process, leading to significant CO_2 emissions. This sector stands as the most significant industrial source of direct CO_2 emissions, contributing approximately 25–30% of industrial emissions [136]. On average, this sector emits approximately 1.85 metric tons of CO_2 for each metric tonne of manufactured steel. The primary manufacturing method involves an integrated steel mill with an oxygen blast furnace. This approach comprises approximately 75% of all worldwide steel production and has an associated energy penalty of around 21 to 23 gigajoules per metric ton of produced steel. Hence, integrated steel mills exhibit the greatest potential for integration with post-combustion CO_2 capture technologies, leading to a significant reduction in CO_2 emissions within the steel production sector. Although this sector has become more energy efficient and consequently its CO_2 emissions have been reduced significantly during the last decades, the utilisation of CC in this sector is deemed essential to reach the CO_2 emission targets.

A roadmap for future actions, from an industrial perspective is provided by reference [185]. This roadmap highlights taking advantage of scrap resources in time span of 2020–2030, developing and utilising advanced technologies, increasing the share of renewables for power production, and applying CCUS in 2030–2040, and enhancing material effectiveness in 2040–2050 to reach carbon neutrality in the steel industry.

3.2. Cement Plants

Cement serves as an adhesive material that acts as a hydraulic binder. It is primarily employed for the purpose of binding fine sand and coarse aggregates together in the production of concrete. Cement and concrete have been utilised to construct long-lasting structures for a considerable period. Because of the unique binding characteristics of cement, concrete stands as an exceptionally robust and durable material capable of withstanding substantial loads and enduring various environmental conditions [186]. The process of production cement can be divided into two basic steps. In the first stage, clinker which is the main constituent of cement is produced in a kiln and in the second stage, the yielded clinker is ground with gypsum and other materials to form cement. The clinker production involves calcination process that is the conversion of calcium carbonate into calcium oxide. This process generates nearly 60% of total CO_2 emissions in the cement plant while the rest of the CO_2 is emitted by fuel combustion.

The European Cement Association (CEMBUREAU) has presented its vision for a carbon-neutral Europe in 2050 [186]. Achieving carbon neutrality by 2050 necessitates the implementation of a series of phased measures. In line with this, by the year 2030, CEMBUREAU aims to conform to the guidelines set by the Paris Agreement's two degrees Scenario. The objective is to cut CO_2 emissions from cement manufacturing by 30% and make a 40% reduction throughout the value chain.

According to [136], cement production stands as the second most CO_2-intensive industrial process globally, contributing to approximately 2.2 gigatons of CO_2 emissions annually. CO_2 emissions from cement production typically range from 0.9 to 1 ton of CO_2 per ton of cement, when considering both energy use and feedstock sources. The concentration of CO_2 in the flue gas from cement plants typically falls within the range of approximately 20 to 30%. According to CEMBUREAU, the decarbonisation of the cement sector will require significant amounts of low carbon electricity mainly supplied by renewables [186]. In this case, based on the CO_2 mole fraction in the exhaust gas and the substantial energy demands associated with integrating existing post-combustion carbon capture technologies, decarbonisation of the cement sector may double the total electricity used by the cement industry.

There are currently expressive CO_2 utilisation projects under development in the cement sector to produce synthetic fuels. These projects are very costly and require significant CAPEX and OPEX. However, these CO_2 utilisation projects are vital for the decarbonisation of the cement sector since many of the 200 cement kilns in the European territory are landlocked without suitable CO_2 storage sites available nearby the kilns.

In China's cement industry, for example, approximately 51% of the total CO_2 emissions are process-related emissions stemming from clinker calcination [187]. In this case, the utilisation of fossil fuels accounts for 31% of the total CO_2 emissions derived from coal. Indirect emissions resulting from electricity consumption contribute to 16% of the industry's CO_2 emissions. The remaining emissions, approximately 2% of the total, originate from oil and natural gas usage. In this case, short-term mitigation efforts primarily count on enhancing energy efficiency and adopting alternative low-carbon fuels, which may reduce the emissions by 9–12% and 17–22%, respectively [187].

The cement industry stands out as one of the most proactive industrial sectors when it comes to testing and adopting new CC technologies [188]. A significant portion of the world's cement kilns generate CO_2 emissions at a considerably smaller scale compared to natural gas processing facilities or coal-fired power plants. This scale difference significantly affects the cost of CO_2 capture, as the capture cost per metric ton typically increases with a reduction in the scale of the CO_2 source. Consequently, cement kilns may incur higher capture costs when compared to other industrial facilities. Therefore, this provides a great opportunity for companies involved in CC technologies to apply their cost-effective methods to this industry.

3.3. Other Industries

In addition to cement and iron production industries which have the highest CO_2 emissions, there are other industries such as petrochemicals, pulp and paper industries, bioenergy plants, and oil refineries which are potential candidates for CC. The utilisation of CC technologies in bioenergy plants will lead to indirect CO_2 capture from the atmosphere, resulting in negative CO_2 emissions [189]. In this case, plants and microorganisms employed in biomass production capture CO_2 from the atmosphere to carry out the photosynthesis process. Hence, the application of CC technologies to capture and sequester CO_2 during the combustion of biomass in bioenergy plants leads to negative CO_2 emissions. As a result, the incorporation of bioenergy with CO_2 capture and storage (BECC) has the potential to turn the energy sectors into a carbon sink [190]. According to [191], there are seven BECC plants currently operating in the USA, Japan, the UK, and the Netherlands, with CO_2 capture capacities ranging from 365 to 1,000,000 tons of CO_2 per year.

Approximately 2% of the total CO_2 emissions from industrial sectors worldwide originate from the flue gas released by pulp and paper industries [136]. The two prevailing production methods in this industry are integrated kraft mills and mechanical mills. Kraft mills are dominantly used in the production lines and have the highest potential for CC. The primary source of emissions in an integrated kraft pulp and paper plant is the recovery boilers, where black liquor is burned. Implementing MEA absorption as a post-combustion CO_2 capture technology seems a potential approach for CCS in this industry. However, it is worth noting that the available literature lacks an extensive evaluation of CCS within the pulp and paper sector [136]. The retrofitting of CCS in the pulp and paper industry will result in raising the cost of paper and pulp significantly. Additionally, these mills must be situated in proximity to forests, often leading to remote locations. Consequently, CCUS in the pulp and paper industry is frequently disregarded when considering the required networks and integrating infrastructure necessary for CCUS implementation [136].

The oil refinery is renowned for being an extremely energy-intensive unit operation [192]. Oil refineries are responsible for an estimated 10% of industrial carbon emissions, which equates to around 2% of worldwide carbon emissions. These emissions primarily come from boilers, furnaces, and heaters, which together contribute up to 65% of the total emissions within the refinery. Emission metrics from refineries vary, ranging from 0.09 to 0.17 metric tons of CO_2 for each metric ton of crude oil processed, or equivalently, 2.7 to 99.2 kg of CO_2 per barrel (bbl) of crude oil. The variability is influenced by factors such as the crude oil type and processing level. Although these emission levels are comparatively lower than those found in cement and iron and steel production sectors, the sheer volume of global crude oil output—approximately 100 million barrels per day (Mbbl/day)—makes the carbon emissions from this sector significant [192].

Direct emissions from industrial sources are categorised into two distinct types: energy-related CO_2 emissions and process-related CO_2 emissions which are referred to as unavoidable CO_2 emissions [193]. It is worth noting that reducing the process-related emissions is more challenging than reducing the energy-related emissions. In this case, CCS is the most feasible option for reducing unavoidable process-related CO_2 emissions.

Table 3 provides a summary of the flue gas characteristics emitted by the aforementioned potential industries. The concentration of CO_2 in the flue gas significantly influences the associated capture costs, as highlighted in previous studies [194]. Specifically, a higher CO_2 concentration in the flue gas corresponds to a lower energy consumption in CC processes. Consequently, referring to the data in Table 3, the cement and steel industries emerge as prime candidates for CC due to discharging the flue gas with notably elevated CO_2 concentrations. It is noteworthy that harnessing the heat from the flue gas can be effectively utilised in the CC process for purposes such as regenerating the sorbent material and purifying the separated CO_2. This utilisation contributes to a significant reduction in energy consumption within the CC plants. As highlighted in Table 3, the heat of flue gas emitted by petrochemical industries is of high quality and can be efficiently employed in CC processes, further enhancing their energy efficiency.

Table 3. The main characteristics of flue gas emitted by potential industries for CC.

Industries	CO_2 Emissions	Flue Gas Temperature (°C)	CO_2 vol% in the Flue Gas
Cement	$2 \times 10^9 \left(\frac{ton}{year}\right)$ [132] $2 \times 10^9 \left(\frac{ton}{year}\right)$ [195] $561–622\left(\frac{kg_{CO_2}}{ton_{cement}}\right)$ [196] $866 \left(\frac{kg_{CO_2}}{ton_{cement}}\right)$ [197]	100–150 [136] 380 [198] 100 [199] 232 [200]	25 [132] 20–30 [136] 15–30 [195] 14–33 [196] 12–16 [201] 20 [202] 17 [203]
Iron and steel	$2.3 \times 10^9 \left(\frac{ton}{year}\right)$ [195,204] $1.8 \left(\frac{ton_{CO_2}}{ton_{steel}}\right)$ [204]	100 [136] <200 [204]	7–30 [201] 20–30 [202] 30 [204] 21–44 [205] 20–27 [206]
Pulp and paper	$0.4\left(\frac{ton_{CO_2}}{ton_{paper}}\right)$ [207]	184–250 [208]	23–26 [136] 13–20 [202] 13–20.4 [208] 20 [201,209] 10–20 [210] 13–14 [211]
Coal-fired power plants	$763 \left(\frac{kg_{CO_2}}{MWh}\right)$ [212]	120 [213]	13.3 [133] 12–15 [136] 13 [205] 13.7 [212] 13.1 [213] 10–15 [206,214]
Petrochemical	$1.5–2.1\left(\frac{ton_{CO_2}}{ton_{ethylene}}\right)$ [215]	160–215 [206] 189 [216]	12 [195] 7–12 [206] 10.74 [216]

4. Transportation of Captured CO_2

In this section, the main characteristics of pipelines and ships which are available to transport the captured CO_2 will be discussed in detail. Furthermore, important aspects of the required network infrastructure for CO_2 transportation are also discussed.

4.1. Transportation via Pipelines

Pipelines have been used for a long time for hydrocarbon transportation. This approach becomes economically more favourable when a substantial quantity of captured CO_2, exceeding 10 million tonnes per year, needs to be transported over a short distance [217]. However, the transportation of CO_2 streams which contains impurities adds extra challenges. In this case, several issues including the depressurisation frequency and pipe integrity should be taken into account. These issues are related to all transportation modes, i.e., gaseous, liquid, or supercritical phase [218–220].

In the United States, pipelines have frequently been used for transporting nearly pure CO_2 over extensive onshore distances, primarily for EOR purposes. Instances of pipelines transferring CO_2 with impurities in both the U.S. and Canada exist. One example involves a pipeline transporting a CO_2 stream with approximately 0.9% hydrogen sulphide (H_2S) over a span of 325 km [219,221,222]. This network links a gasification facility in the U.S. to an EOR site in Canada. Notably, such pipelines have functioned for over three decades without significant incidents attributed to corrosion [223]. However, there is a relatively limited amount of information available regarding the transportation of CO_2 offshore through pipelines.

The evolution of CCS in large-scale industrial processes (LSIP) has been gradual yet consistent. From the inception of the first-generation LSIPs, the pipeline specifications and operating conditions for CO_2 streams have been a subject of analysis [224,225]. Current operational large-scale CCS projects encompass sectors like power generation, gas treatment, iron and steel manufacturing, chemical industries (including ethanol and fertilisers), and fuel sectors (such as hydrogen production). The majority of these LSIPs utilise pipelines for CO_2 transportation. The supercritical phase of CO_2 demonstrates a superior efficiency for pipeline transport, primarily because of its increased density compared to other states [226–228]. Thus, supercritical CO_2 is identified as the most economically viable option for conveying captured CO_2 for either utilisation or sequestration [229–231]. Preceding such transport, the captured CO_2 needs to be cleansed, dehydrated, and pressurised to supercritical levels—approximately 145 bar [232].

For offshore pipelines, the inlet CO_2 stream entering the system should be further pressurised to around 200 bar [233]. This extra pressurisation is necessary for transporting the CO_2 stream through offshore pipelines, primarily due to the economic infeasibility of implementing subsea compression. This requires multiple compression stages and pumping mechanisms as well as dehydration processes. In addition to higher inlet pressures, it is imperative to meticulously design the pipeline, selecting an appropriate diameter to confine pressure drops and sustain the outlet pressure at above 60 bar.

4.2. Transportation by Ships

Shipping CO_2 is deemed more advantageous than pipeline transportation when the captured CO_2 needs to be conveyed over exceedingly long distances [217]. In this case, pre-conditioning is crucial before transporting CO_2 by ship, aiming to achieve a liquid state at 6.5 bar and -50 °C. This involves successive stages of compression and liquefaction, along with the elimination of unwanted elements. Cryogenic storage infrastructure is also required for maintaining the CO_2 in its liquid phase. On-board reconditioning comprises elevating the CO_2 pressure to 60 bar while also applying heat, ensuring a post-reconditioning temperature above 0 °C.

The maritime CO_2 transport infrastructure consists of four core components: (1) initial and final buffer storage, (2) marine transport, (3) offloading and additional buffer storage, and (4) reconditioning [233,234]. Buffer storage units are essential both before and after shipping to synchronise the continuous operations of CO_2 conditioning with the batch process of shipping. Recent studies indicate that a buffer storage capacity 1.2 times the size of the ship ensures smooth operations year-round at any given port, even when factoring in weather-related uncertainties and maintenance schedules [235].

After the shipping stage, a dedicated receiving facility is crucial for holding buffer storage and a unit for reconditioning the CO_2. In instances where shipping is between ports, an onshore terminal fulfils this role. However, when the destination is an offshore site, the vessel itself acts as the receiving setup. The reconditioning of CO_2 at this juncture is important to meet the specific criteria required for the subsequent phases of transport and injection. This reconditioning phase consists of pressurising the CO_2 to the required levels and warming it to temperatures above 5 °C. In real-world scenarios, positioning industries close to CO_2 terminals that require cooling can pose logistical challenges. Therefore, the CO_2 stream is commonly reheated using seawater via a titanium heat exchanger to mitigate corrosion issues. When the CO_2 is received at an onshore terminal, pressure adjustments are made to 200 bar post-reconditioning, aligning with the inlet conditions of onshore pipelines. Conversely, at an offshore receiving point, the pressure is configured to 90 bar, meeting the specifications of the riser responsible for CO_2 transport to the seabed [236].

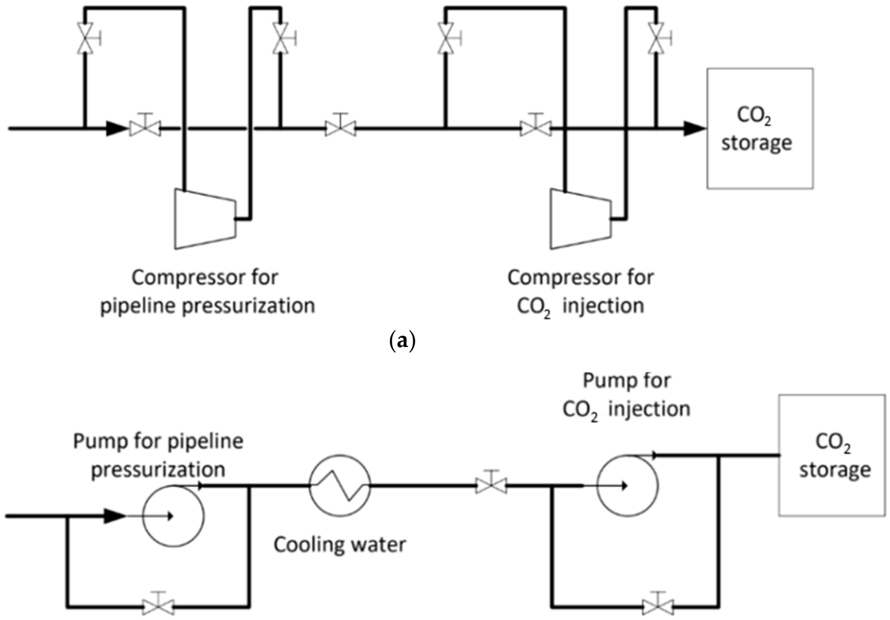
4.3. Transportation Network Infrastructure

For CO_2 transport to offshore locations, pipeline and shipping methods are generally considered viable. Pipeline transport is usually cited as the more cost-efficient approach for moving large volumes and allows for automated, continuous flow. However, it demands significant upfront investment. Conversely, shipping requires lower initial costs and possesses greater flexibility for accessing storage locations, albeit being less cost-effective for short distances when transporting large volumes.

Traditionally, CO_2 transport expenses have been viewed as a secondary cost in the overall CCS framework. In the case of pipelines, however, the transportation costs can escalate when small quantities of CO_2 are moved over long distances [237]. Although the conditioning costs for pipeline transport may be lower than those for shipping, pipelines are not cost-efficient for moving small amounts of CO_2 over long distances [238]. When the pipeline infrastructure is utilised by multiple industrial plants of similar sizes, the transport costs attributed to each plant can be cut by 50% [237]. Moreover, when utilising a shared pipeline infrastructure, the costs associated with conditioning and transporting CO_2 can be reduced by up to 30% compared to shipping as a means of CO_2 transportation. Therefore, a shared pipeline infrastructure establishes a network involving multiple stakeholders and holds significant potential for lowering the overall costs of CCS. Nevertheless, implementing a shared transport solution can be deemed challenging due to the necessity of collective interest in utilising the infrastructure, assurances from contributors, coordination of deployment, and the substantial initial investment, thereby entailing considerable investment risk. Generally speaking, a strong commitment and financial support are imperative prerequisites for establishing a shared infrastructure. When these conditions are not met, transporting captured CO_2 by shipping may be a more practical alternative [239].

For evaluating the costs of pipeline transport, Integrated Carbon Capture and Storage Economics Models (ICCSEMs) are commonly used. These models calculate the dimensions of required equipment and conduct heat and mass balance analyses [240–242]. The Capital Expenditure (CAPEX) for pipeline transport comprises the costs of pipeline construction, laying, and compression equipment. Operational Expenditure (OPEX) includes electricity, labour, and upkeep expenses. Figure 12 illustrates CO_2 transportation in both gas and liquid phases via pipeline. As shown, when CO_2 is transported in the gas phase, it must be pressurised to meet the phase's pressure requirements, which can range from 48 to 150 bars. It is also worth noting that sometimes gaseous CO_2 with an elevated pressure in its supercritical state may need to be throttled and depressurised to match the pipeline's pressure requirements. Additionally, as indicated in Figure 12, transporting CO_2 in the liquid phase may be simpler, but it requires strict temperature control to prevent vaporisation or solidification of CO_2.

For shipping, the stages involved are compression, liquefaction, onshore storage, and loading and unloading at ports. The CAPEX in this scenario covers the vessel costs and the expenses associated with the required equipment for the compression and liquefaction of CO_2. OPEX covers expenses for electricity, diesel, port fees, labour, and maintenance [240]. Notably, when CO_2 is stored in the vessel, heat loss from the storage container leads to a phenomenon known as gas boil-off, causing a reduction in the CO_2 in the liquid phase at a rate of approximately 0.2% per day [243].



(**a**)

(**b**)

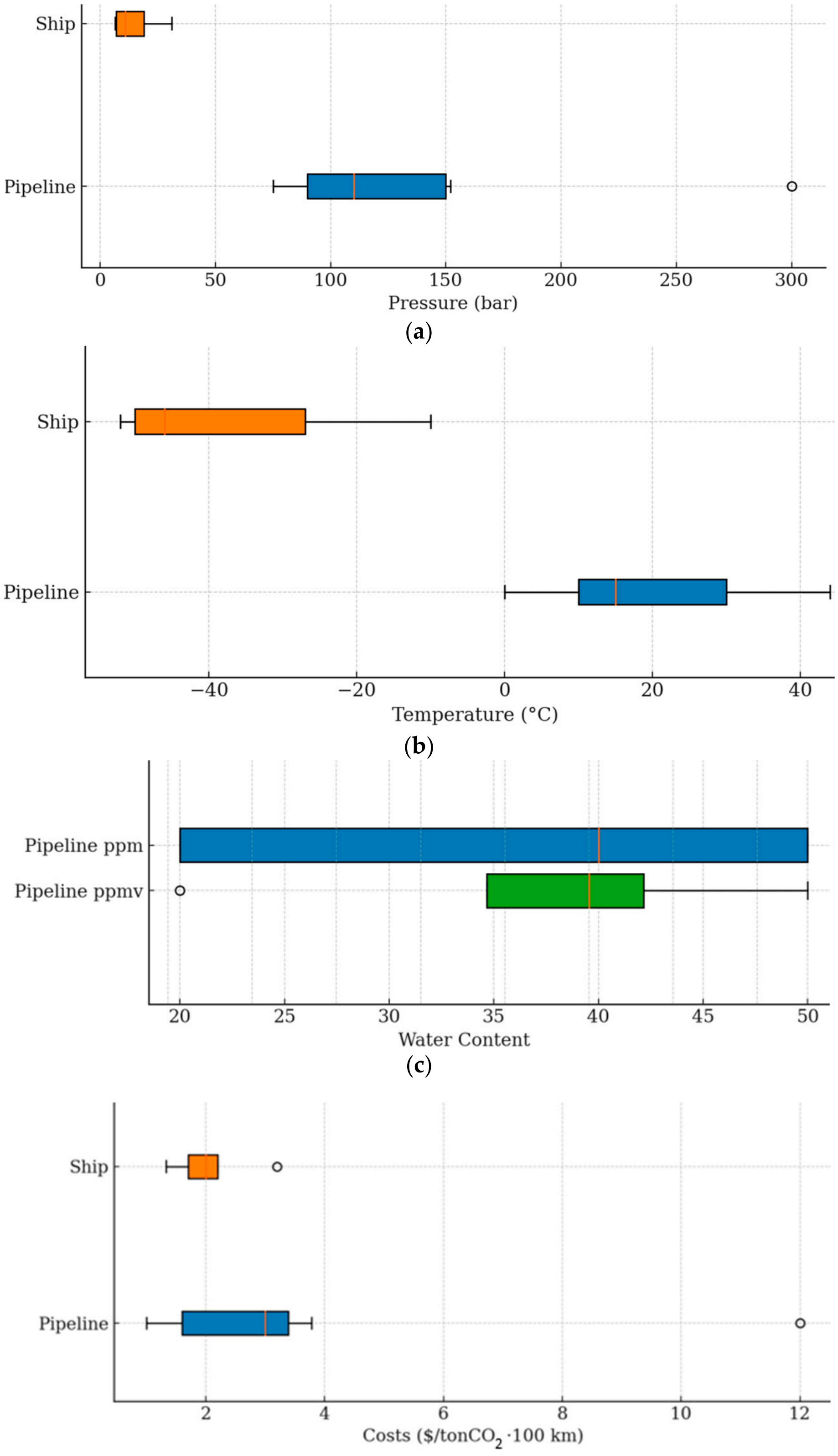
Figure 12. CO_2 transportation in (**a**) gas phase and (**b**) liquid phase [241].

Table 4 provides insights into the required pressure, temperature, maximum water content, and transportation costs associated with conveying the captured CO_2 through pipelines and ships. Figure 13 also summarises the characteristics presented in Table 4 for CO_2 transportation via pipeline and ship. It has been shown that for CO_2 transportation via pipelines, maintaining high purities with a minimum threshold of 95–98% is crucial to prevent the occurrence of two-phase flow in the pipeline [244]. Prior research indicates that, among all impurities in the CO_2 stream, water constitutes the largest portion when utilising post-combustion CC technologies for various CO_2 emission sources [245]. It is crucial to note that the water content in the CO_2 streams must be closely monitored and controlled to prevent pipeline corrosion [246].

Transporting CO_2 streams with high impurity levels via pipelines leads to heightened transportation costs, primarily attributed to increased inlet pressure requirements in the network [247,248]. In other words, transporting CO_2 streams containing impurities may result in costs that are 20–40% higher than the transportation of a pure CO_2 stream [249].

Table 4. The main characteristics of CO_2 transportation by pipeline and ship.

Transportation Means	Pressure (bar)	Temperature (°C)	Water Content (in unit of ppm * or ppmv **)	Transportation Costs [USD/(ton_{CO_2}.100 km)]
Pipeline	90–150 [249,250] 150 [251] 100–150 [252] 85–150 [253] 110–300 [254] 75 [255] 152 [256]	0–30 [257] 5–35 [250] 40 [251] 15–30 [252] 13–44 [253] 6–20 [254] 10 [255] 14 [256]	<50 * [246,258] 40–500 * [257] 500 ** [250] 20–257 ** [252] 50–630 * [259] <20 * [255]	3–12 [260] 1–3 [261] 3.78 [251] 1.6 [254] 1.59 [256]
Ship	6.5 [243,256,262] 7 [263,264] 15 [265] 31 [266]	−52 [243,256,262] −50 [263] −27 [265] −46 [264] −10 [266]	-	1.33–2 [243] 2.2–3.2 [262] 1.7 [256]



(**a**)

(**b**)

(**c**)

(**d**)

Figure 13. Summary of characteristics from existing studies for CO_2 transportation by pipeline and ship (**a**) pressure requirements (**b**) temperature requirements (**c**) maximum water content (**d**) cost of CO_2 transportation [250–266].

5. Storage of Captured CO_2

This section describes and investigates the CO_2 storage options. In this case, the storage characteristics as well as the factors that affect them are investigated.

5.1. Storage Purposes

According to [267], CO_2 storage has been increased in recent years as one of the actions to avoid climate change. CO_2 storage is part of the strategy to achieve carbon neutrality, jointly with the necessary actions to reduce the CO_2 emissions. The potential for utilising and storing CO_2 in enhanced oil recovery applications (EOR) has been substantially highlighted. CO_2-EOR was evaluated thoroughly by Jiang et al. [268] and they discussed the economic benefits of this technology along with its challenges with regard to CO_2 emissions. Firstly, CO_2-EOR is economically beneficial when compared to other technologies. However, this technology may not effectively contribute to reducing the CO_2 emissions. In other words, the injection and storage of 0.75–1.5 tonnes of CO_2 will result in recovering 1 barrel of oil which may result in the emission of 1 tonne of CO_2 if completely combusted [268].

CO_2 interim storage (CIS), as an innovative approach, can serve the dual purpose of enhancing the value of captured CO_2 and bridging the disparities between its supply and demand. This approach enables the upgrading of CO_2 utilisation, making it a versatile tool in managing CO_2 resources effectively [269]. CIS involves temporary storage of CO_2, to be later used in CO_2-EOR or other industrial applications. The CIS importance as an expressive tool for CO_2 infrastructure and market development is related to its role in meeting variable and localised CO_2 demand.

5.2. Storage Characteristics and Effective Factors

Sequestration of CO_2 in underground formations is a well-known geological phenomenon where CO_2 is stored naturally in underground reservoirs. Data and knowledge obtained from EOR projects which involve CO_2 injection and storage confirm the feasibility of CO_2 storage in geological formations. Generally, exhausted oil and gas reservoirs, coal deposits, and saline formations show the highest potential for CO_2 storage [269]. In fact, the depleted gas reservoir is known as the most favourable option for CO_2 storage [270,271]. In the case of using a gas reservoir for CO_2 storage, a locally single miscible fluid is created, comprising a combination of natural gas and carbon dioxide [272]. Supercritical fluid injection can also be utilised to store CO_2 in deep saline formations. In this case, the injected CO_2 possesses lower density and lower viscosity than the water which is naturally present in the formation and because of that it would be immiscible in water [273]. The CO_2 injected into an oil reservoir might be miscible or immiscible and it is highly dependent on the composition of the oil as well as the overall system temperature and pressure [274]. When CO_2 is injected into the coal seams, the storage mechanism is completely different from the storage mechanism in oil or gas reservoirs. In this case, the injected CO_2 is adsorbed on the coal seams and fills the pore space [275]. The maturity level of this storage method is not as advanced as that of storing CO_2 in oil and gas reservoirs, and it is currently at the development stage. Therefore, more research is needed in this field to evaluate the economic aspects and stability of this method.

Introducing carbon dioxide to an underground reservoir may result in significant changes in the physical and chemical properties of the rocks, potentially affecting their mechanical and petrophysical characteristics [276–279]. Thus, it is important to take into account the interaction of CO_2 with reservoir rocks, as well as the consequent modifications. Reservoir properties may change when they are used for CO_2 storage, and this is due to the reactions which takes place between the injected CO_2 and the minerals which form the rocks [280–283]. The limitations and validity of the material balance equation, which estimates the CO_2 storage capacity, are investigated under several reservoir characteristics in reference [284]. Considering the investigated cases, the most expressive factor influencing the CO_2 storage capacity is the rock compaction reversibility. When the compaction is completely irreversible, the CO_2 storage capacity will be reduced by 20%. It is mostly due to decreasing the gas bearing space and also the aquifer surface under the gas–water contact.

6. Application of Captured CO_2

In this section, the possible applications of the captured CO_2 from different industrial plants are elaborated and discussed. In this regard, reference [285] has provided a comprehensive study about the recent advances in CC technologies as well as CO_2 utilisation. In fact, CO_2 is a very useful feedstock, and it has numerous chemical and industrial applications. For instance, it has been used in the oil and power industries, food processing, pharmaceutical sector, pulp and paper, steel sectors, etc. [285]. Within these industries, the chemical and petroleum sectors exhibit the highest capacity for CO_2 utilisation, with widespread applications in processes such as EOR, urea synthesis, polymer manufacturing, and fuel production. Furthermore, the cement industry can also be considered as a potential candidate for CO_2 utilisation.

In fact, the utilisation of CO_2 neutral fuels (e-fuels) can substantially decrease CO_2 emissions in the transportation sector [286]. Furthermore, e-fuels produced using captured CO_2 can be considered as a promising solution for challenges regarding the intermittency of renewables [287]. In this case, the electricity generated by intermittent renewable sources can be stored in the form of e-fuel. Under this situation, the intermittent renewable electricity can be used for hydrogen production using water electrolysis. Afterwards, the resulting hydrogen is combined with the captured CO_2 to synthesis useful fuels like e-methanol. In the following section, the utilisation of captured CO_2 for e-methanol production as well as fertiliser production is elaborated and discussed.

6.1. Methanol Production

The transformation of captured CO_2 from a cement plant to e-methanol is evaluated by reference [288]. This study provides a comprehensive environmental and techno-economic analyses for the entire process chain where an MEA-based process was considered to capture CO_2. The captured CO_2 was directly used in the conversion unit to generate e-methanol using catalytic conversion. The production of methanol using captured CO_2 and hydrogen generated through water electrolysis with renewable sources not only significantly reduces CO_2 emissions but also prevents the depletion of fossil fuels.

Methanol is among the chemicals which has been used extensively worldwide, with a demand of 98 million metric tons in 2019 [289]. Methanol primarily serves as a raw material for the synthesis of hydrocarbons, including formaldehyde, ethylene, and propylene. Additionally, it can also function as a fuel or be blended with gasoline or diesel components. It is worth noting that the energy density of methanol is 10 times higher than that of hydrogen [290]. Methanol serves a dual role in the economy, acting both as a precursor for chemical compounds and as an energy source. The market for direct methanol fuel cells (DMFCs) is on the rise, along with its use as a hydrogen carrier, particularly as steps are being taken towards a hydrogen-based economy [289]. This indicates that the methanol market has a promising growth trajectory. While there are technical challenges to overcome, such as suboptimal conversion rates and selectivity in synthesis, methanol remains a front-runner for wide-scale carbon dioxide utilisation (CDU) applications.

6.2. Fertiliser Industry

Urea stands as a cost-efficient and effective nitrogen-based fertiliser [291]. Urea is also one of the longest-standing fertilisers employed globally, produced through a two-step process involving the reaction of CO_2 and ammonia at elevated temperatures and pressures. The Haber–Bosch process is the primary method for producing ammonia which entails the reaction of hydrogen and nitrogen. Methane steam reforming is dominantly used to supply the required H_2 and CO_2 for urea production. However, renewable energy-driven water electrolysis can also be utilised for hydrogen production, while CO_2 can be supplied by integration of CC technologies with large CO_2 point sources. This issue has been investigated thoroughly in reference [291] where an amine-scrubbing process based on MEA solvent was used to capture CO_2 from the flue gas emitted by the Sarbottam cement plant. The captured CO_2 from the cement plant was planned to be used for urea production. It should be mentioned that the captured CO_2 from the cement plant cannot be used directly in the urea production process and it requires further compression and cooling. The captured CO_2 from the cement plant can be used to satisfy 25% of the urea requirements in Nepal based on 60% of CO_2 conversion.

The global urea generation was 233 Mt in 2019 while it is expected to rise to 300 Mt by 2030 [289]. The projected need for urea is forecasted to increase by 2.1% annually from 2021 to 2026, resulting in a market worth of USD 212 million [289]. Therefore, urea generation is anticipated to have a substantial impact as a primary application of CDU. Therefore, industries need to focus more on this issue to optimise the urea production process. In this case, they can use the heat loss from the ammonia synthesis process in the urea production process.

6.3. Other Applications

CO_2 captured in the liquid phase holds substantial potential for diverse applications, demonstrating significant economic viability and market appeal [292]. Liquid CO_2 finds common utility in several applications, such as serving as a refrigerant in the food industry, acting as a shielding gas in welding processes, maintaining pH balance in water treatment plants, functioning as a fire suppressant, and promoting plant growth in greenhouse environments. Furthermore, CO_2 in a liquid phase has been utilised mainly in EOR wells serving as both a fracturing and extraction fluid. Recently, researchers have studied and investigated the application of liquid CO_2 for unconventional uses including rising solvents for photoresist polymers and a green solvent for chemical processes [292].

In fact, CO_2 is widely used in the construction industry to produce construction materials [292]. In this case, the captured CO_2 either from a source point or from a DAC can be used in mineral carbonation processes to generate concrete and aggregates [293]. This process involves the reaction between CO_2 and alkaline materials which transforms CO_2 into thermodynamically stable carbonates [294]. Direct and indirect pathways are mostly followed in mineral carbonation processes [289]. However, carbonate minerals are also widely used across other industries such as paper and pulp, pharmaceuticals, and agriculture. Calcium carbonate ($CaCO_3$), for instance, is extensively used as a feedstock in the paper processing and glass-making industries [290]. In fact, calcium carbonate is a very beneficial product resulting from CDU since it is exceedingly stable. Therefore, in addition to the above-mentioned industries, it can be also used in the pharmaceutical industry. Sodium bicarbonate (baking soda) is another useful product which can be generated by the carbonation process. It has a wide range of applications and can be used in diverse industries including the pharmaceutical, food, textile, and chemical industries [295]. In this case, apart from soda ash, the sole requirement for carbonating the solubilised barrel and facilitating the desired reaction to produce baking soda is carbon dioxide. Baking soda can be produced either by the Solvay process or sodium sulphate route. However, the Solvay process is a more beneficial technology, and it is preferred due to its economic advantages over the sodium sulphate route [295]. In this case, the production cost of baking soda using the Solvay process is 195 USD/ton with a benefit/cost ratio of 1.12.

CO_2 can also be used to produce polymers [289]. In fact, a wide range of carbon-based polymers including polyol and polyurethane (PU) and polycarbonate (PC) are commercialised and produced at a large scale by companies like Covestro Inc. In this regard, Asahi Kasei developed a process which uses CO_2 to produce PC polymers. The commercialised process has reached the capacity of 150,000 tonnes of PC per year where 1 tonne of PC can mitigate 0.173 tonnes of CO_2 emissions. The benefits of polymer synthesis for carbon emission mitigation are substantial. It provides the possibility for the sequestration of carbon as a product for longer periods compared to CDU-based products. Moreover, the potential market for polymers is extensive due to the wide range of polymers which can be synthesised by CO_2. Additionally, after the end of a polymer's lifespan, it can be recycled to create new polymers, preventing the re-emission of CO_2 into the atmosphere.

Table 5 provides a summary of the necessary conditions for the captured CO_2 in various applications, such as enhanced oil recovery (EOR), methanol production, urea synthesis, and its use as a working fluid in power plants. The table indicates that for applications like power plant working fluids and urea production processes, the CO_2 supplied by CC technologies must possess exceptionally high purities. Given the information presented in Table 2, the CC technologies capable of attaining high purity levels (>99.9%), such as the amine-based methods, the CCC process, and DAC, appear suitable for these applications.

Table 5. An overview of CO_2 conditions for different applications.

Application	CO_2 Purity (vol%)	Temperature (°C)	Pressure (MPa)
EOR	>95 [245,258] 99.9 [296]	95.5 [296] 110 [297] 82.2 [298] 89 [299]	6.34–13.73 [296] 34.47 [297] 20.685 [298] 23 [299]
Methanol production	98 [288]	210 [300] 250 [288] 220 [301]	7.8 [288] 8 [288] 3.5 [301]
Urea production	99.46 [302]	180 [300] 180–185 [303]	14.1 [300] 14 [303]
Working fluid in power plants	99.99 [304]	50–400 [304]	15–35 [304]

6.4. Sector Couplings

Electrification plays a pivotal role in shaping the future energy systems, driving the transition toward more sustainable, resilient, and energy-efficient landscapes. Its importance is particularly tied to decarbonisation, increased efficiency, and the integration of renewable energy sources (wind, solar, hydropower) as the main energy vector of the future. It is also crucial for producing green hydrogen via water electrolysis powered by renewable electricity. CC technologies, especially post-combustion and DAC are critical tools in mitigating climate change by capturing CO_2 emissions from industrial processes and the atmosphere, and they can also be powered by renewable electricity. The excess heat from some CC technologies can be used for district heating, improving the energy efficiency and minimising the overall energy penalties. The captured CO_2 combined with green hydrogen from water electrolysis can be converted into synthetic fuels like e-fuels (methanol or synthetic natural gas) for use in aviation, shipping, and heavy-duty transport. An illustration of the sector coupling opportunities for CC technologies is given in Figure 14. Overall, the sector coupling of CC technologies can enable decarbonising hard-to-abate sectors where direct electrification is challenging but is a key enabler for synergies across sectors. Through these sectoral synergies, CC technologies can create cross-industry efficiencies, reduce carbon footprints, and accelerate the transition to a low-carbon economy.

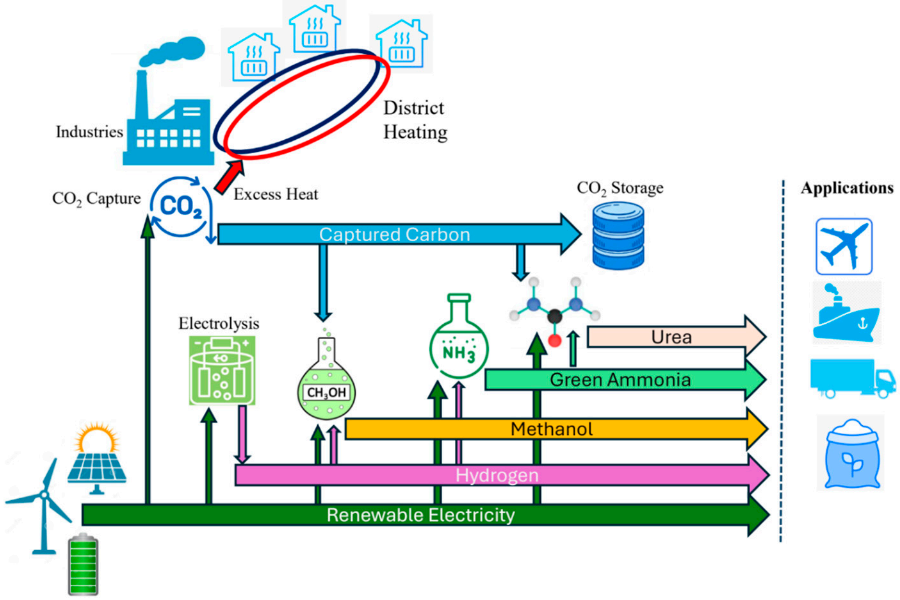


Figure 14. Overview of cross-sector couplings in CC technologies.

7. Computation Tools for Simulation of CC Processes

Developing a commercially viable technique for carbon capture and storage is a challenging task. To achieve the desired outcome, it is necessary to carefully coordinate and combine various unit operations, such as chemical reactors, distillation columns, heat exchangers, flash tanks, etc. Process simulation software is employed to optimise CC processes by harnessing the power of physics-based computations and mathematical optimisation methods. It offers engineers a platform on which they can create a block diagram representing the process. Once the block diagram of the desired CC process has been developed within the software, engineers can virtually test and modify the process to improve its efficiency, reduce the energy and material consumption, and minimise the waste. In addition to the benefits of design and optimisation, process simulation software provides a range of other useful features and capabilities. These include real-time production monitoring, dynamic process simulation, and advanced process control, all aimed to ensure the installation functions as intended.

Three widely used process simulation software tools are AspenOne [305], Pro/II [306], and ProSimPlus [307]. In this section, the above-mentioned tools are concisely presented and their specific potentials for modelling the CC processes will be highlighted.

AspenTech is a US-based company providing software and services for process industries. Aspen HYSYS, Aspen Plus, and Aspen Adsorption are the most popular products among a wide range of tools offered by AspenOne. Aspen HYSYS is widely used for process modelling, equipment sizing and design, heat integration, and environmental compliance. Aspen Plus, another popular process simulation tool, is extensively used in the chemical process industries. It enables engineers to model, simulate, and optimise a variety of chemical processes. Aspen Plus includes steady-state and dynamic simulation, process modelling, equipment sizing, energy integration, and economic analysis features. Apart from its exceptional capabilities to model and design different CC technologies, it can be effectively used for economic analysis and estimate the component costs in a specific CC plant. It can also interface with other software packages, like Excel (version 2013), for data transfer and analysis. Aspen Adsorption® is widely used to simulate and optimise various breakthrough and cyclic processes, encompassing temperature swing, pressure swing, and vacuum swing adsorption [308]. Furthermore, it can conduct dynamic simulations allowing for the modelling of transient behaviours in the adsorption process.

Pro/II is also a simulation software developed and marketed by Aveva. It is widely acknowledged as one of the top process simulation software packages in the industry. The software's primary strength is its ability to simulate complex chemical processes accurately and reliably, made possible by its advanced algorithms that have been fine-tuned over time. Pro/II is known for its user-friendly interface, making it relatively simple to use, even for those new to the process without a background in simulation software.

ProSimPlus is a widely used process simulation software in industries like chemical, pharmaceutical, and energy. It helps users to model and simulate complex processes, such as distillation, crystallisation, and reactions. Its user-friendly interface makes it easy to model and simulate complex processes. The software also includes advanced features like thermodynamic property estimation, heat transfer calculations, and optimisation tools, making it versatile and efficient for various industries. The software is also utilised in academic research and engineering consulting firms.

Aspen, Pro/II, and ProSimPlus are all process simulation software packages widely used in the chemical and petrochemical industries. They share some common features but also have key differences in their use, cost, features, and advantages. The comparison among these software packages is presented in Table 6.

Table 6. Comparison of AspenOne, Pro/II, and ProSimPlus.

Feature/Aspect	AspenOne	Pro/II	ProSimPlus
User Interface	Comprehensive, customisable	Simple, user-friendly	Intuitive, user-friendly
Additional Features	Advanced economic optimisation	Robust simulation for complex chemical processes	Thermodynamic property estimation, heat transfer calculations
Software Integration	Best with other AspenTech products	Can interface with software like Excel	Can interface with other software, but not as strongly integrated with other products
Academic Usage	Widely used in academia, extensive resources	Widely used in academia, some resources	Used in academic research, fewer resources
Market Presence	Market leader, largest user base	Second most popular, significant user base	Growing popularity, smaller user base
Flexibility	Broad range of applications	Focused on chemical processes	Focused on specific industries
Technical Support	Comprehensive support and training	Comprehensive support and training	Standard support and training

The aforementioned tools have their own capabilities and features, and it is a very hard task to determine the best commercial software for modelling CC processes. According to Table 7, AspenOne products have been used more than other commercial software for the modelling and simulation of CCUS technologies. In addition to exceptional features of the products offered by AspenOne, the variety of these products make it possible to cover different aspects of the CCUS. To illustrate, Aspen Plus and Aspen HYSIS can be effectively used for techno-economic analysis of chemical processes including post-combustion, pre-combustion, and oxyfuel combustion methods along with the processes which use CO_2 as a feedstock. Additionally, Aspen Plus Dynamics can be used to develop a transient model and study the dynamics of CCUS processes. Furthermore, AspenOne also offers Aspen Adsorption which can be effectively used to model adsorption-based CC processes. As a result, AspenOne products have been used more frequently in numerous research papers published in the field of CCUS.

Table 7. Overview of utilisation of AspenOne, Pro/II, and ProSimPlus for the modelling of CCUS.

Simulation Method/Software	Maximum Error	Application	Thermodynamic Model	Reference
Aspen Plus	0.95%	Techno-economic analysis of CO_2 capture process using membranes	Peng–Robinson	[309]
Aspen HYSYS	6.89%	Establishing a process model for capturing CO_2 from natural gas through membrane technology	Ideal	[310]
Aspen Plus	3.56%	Modelling membranes for CO_2 capture	Redlich−Kwong	[311]
Pro/II	5%	Modelling CO_2 capture using amine-based solvent	NRTL	[312]
Pro/II (version 9.0)	5%	Modelling MEA and DEA for CO_2 capture	Amine package and electrolyte algorithm	[313]
Pro/II	-	Modelling post-combustion technologies for gas turbine cycles	GPSA	[314]
Aspen Plus	5.8%	Post-combustion using MEA-based CC	Electrolyte NRTL with Redlich–Kwon	[315]
Aspen Adsorption	-	Temperature-vacuum-swing-adsorption for DAC	Ideal	[316]
Aspen Plus	-	High-temperature DAC integrated with Fischer–Tropsch synthesis	Unsymmetric electrolyte NRTL with Redlich–Kwon	[317]
Aspen Plus and Aspen Adsorption	-	Comparison of post-combustion CC including membranes, MEA-based absorption and solid adsorption	Membrane: Peng–RobinsonMEA: Electrolyte NRTLAdsorption: Ideal	[318]
ProSimPlus (version 3.1.2.1.2)	-	Modelling membranes for CO_2 capture from a power plant	-	[319]
Aspen Plus	-	Modelling the CO_2 process using amine-based solvent	Electrolyte NRTL	[320]
Aspen HYSYS (version 7.2)	-	Modelling amine-based CO_2 capture from a power plant	Li–Mather model and Redlich–Kwong equation of state	[321]
Aspen Plus	-	Modelling the cryogenic CO_2 capture from a coal-fired power plant	Peng–Robinson equation of state for SVE calculations	[322]
Aspen Plus	7%	Modelling CO_2 capture from power plants Using MEA	Electrolyte NRTL	[323]
Aspen Plus	3.8%	Simulation of MEA-based CO_2 capture process for a coal-fired power	Electrolyte NRTL	[324]

Table 7. *Cont.*

Simulation Method/Software	Maximum Error	Application	Thermodynamic Model	Reference
Aspen Plus (version 8.6)	6.9%	Modelling CO_2 capture by chemical absorption	ENRTL-RK	[325]
Aspen Plus	-	Modelling and optimisation of oxyfuel combustion	-	[326]
Aspen HYSYS	-	Techno-economic analysis of oxyfuel combustion when solvent is used to for CO_2 separation	NRTL	[327]
Aspen Plus (version 10)	Techno-economic analysis of CO_2 capture and utilisation	Techno-economic analysis of CO_2 capture and utilisation	Electrolyte NRTL for modelling the CO_2 capture process andLangmuir–Hinshelwood–Hougen–Watson model to simulate the methanol production reactor	[288]
Aspen HYSYS	-	Techno-economic analysis of CO_2 capture by physical absorption	SRK	[328]
Aspen Plus (V.12)	-	Modelling DAC using ionic liquids	COSMOSAC property method	[329]
EnergyPLAN	-	Modelling and comparing the cryogenic and amine-based technologies in the future of Denmark	-	[330]
Aspen Plus	-	A techno-economic analysis of blue ammonia production using a cryogenic process	Peng–Robinson	[331]
Aspen Plus	-	A techno-economic analysis of a cryogenic process combined with an absorption refrigeration cycle for capturing CO_2 from a cement factory	Peng–Robinson	[332]
Aspen Plus Dynamics (version 9)	-	Transient model for green methanol synthesis	Predictive Soave–Redlich–Kwong	[301]

8. Conclusions and Future Directions

CCUS is a complex concept that extends beyond just the technologies and their efficiency in capturing and separating CO_2. Industries and researchers working with CC technologies should focus not only on the efficiency and energy penalties of these technologies through modelling but also on the conditions of the flue gas from various industries, the purity of the captured CO_2, CO_2 transportation and storage, and the conditions required for its utilisation. This review thoroughly addresses all these aspects and offers valuable insights into the different stages of CCUS. As the particularities of each CC project are distinct, the analysis to determine the best approach among the CC technology options highly depends on local project conditions and requirements. However, it is highlighted that post-combustion approaches based on chemical absorption are distinguished as the most mature CC technology. Therefore, considering this approach as the reference category, any other category that provides a better CC performance can be evaluated as a more advantageous technology.

Regarding the transportation of the captured CO_2, the main means will be pipelines and ships. Pipeline networks will allow us to boost the transportation of the captured CO_2 from local and isolated point sources to regional and integrated networks composed of several plants. The integration of pipeline networks reduces the CO_2 transportation cost and motivates the participation of new players. Additionally, a meshed pipeline network allows the transportation of other substances, such as hydrogen and ammonia, which are key elements in the green energy fuel industry, adding flexibility to the market. The ships are more related to the CO_2 transportation through long distances connecting far ports around the world, where an offshore pipeline network is not feasible.

As CC constitutes a new market, the storage of the captured CO_2 should be investigated more thoroughly. At the initial CC market phase, the main storage purpose will be to retain the captured CO_2, avoiding its release to the atmosphere. At a second phase, the captured CO_2 will become a feedstock of different industrial sectors. Therefore, we can identify a transition where captured CO_2 moves from storage to being utilised by market players in the medium and long term. This transition will create a more cohesive environment involving both CO_2 producers and consumers.

This study highlights the importance of giving priority to the development and application of post-combustion, pre-combustion, and oxyfuel combustion CC technologies. Various industrial sectors, including iron, steel, cement, pulp, and paper, should adopt these technologies to minimise their emissions. This is primarily because capturing concentrated CO_2 from major point sources is more cost-effective than separating diluted CO_2 from the atmosphere using DAC technology. However, the need to simultaneously develop and conduct research on DAC technologies cannot be overlooked since these are projected to become a fundamental part of the longer-term mitigation strategies by achieving negative emissions and providing a vital source of green carbon. While various facets of CCUS have undergone comprehensive evaluation and study, there remain several domains that necessitate further investigation, as outlined below:

- The available literature lacks an extensive study on the influence of CC technologies on the national energy sectors. These studies are crucial, given the energy-intensive nature of the CC technologies and their significant influence on national energy landscapes.
- Furthermore, a comprehensive assessment of utilising the heat from flue gas in CO_2 capture technologies remains largely unexplored. It is essential to evaluate the potential impacts of integrating this heat on lowering the energy penalties associated with these technologies.
- Despite the existence of numerous studies that have simulated and modelled CO_2 capture technologies, the majority of them have been carried out under steady-state conditions. It is crucial to evaluate the dynamic behaviour of these technologies and investigate how these systems respond to fluctuations in power demand, given that the required power for these technologies is predominantly expected to be supplied by intermittent renewable sources.
- Novel CO_2 capture technologies and materials, including metal–organic frameworks (MOFs) and covalent organic frameworks (COFs), have yet to be commercialised.
- The operating costs of the DAC remain significantly higher compared to CO_2 capture technologies that capture emissions from point sources. As a result, DAC is still in its early stages and requires further research to become more cost-effective.
- For a truly circular economy, it is more beneficial to permanently sequester CO_2 by converting it into long-lasting materials like carbonates, rather than using the captured CO_2 for enhanced oil recovery, which ultimately emits CO_2 when the oil is burned.
- Currently, there is no specific standard governing the purity of captured CO_2 for pipeline transportation. It is imperative to thoroughly investigate CO_2 transportation, particularly through pipelines, and establish a robust standard outlining the conditions for CO_2 transportation. This standard significantly influences the infrastructure of CCUS, as well as the selection of the most suitable CC technology.

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