A comprehensive review on carbon capture, transportation, storage, and

utilization technologies; part I: Carbon capture technologies

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Graphical Abstract

Abstract

In today's world, environmental concerns have gained significant attention. The increasing effects of climate change have heightened the necessity for new strategies to reduce carbon dioxide (CO₂) emissions, which are the primary driver of global warming. Carbon capture utilization and storage (CCUS) is one of the promising solutions that are being considered to address these environmental concerns. The primary objective of this review paper is to provide a comprehensive overview of the current status of carbon capture utilization and storage technologies, as well as the CO_2 transportation infrastructure, highlighting their potential advantages and the challenges that need to be addressed for successful implementation. This part provides a comprehensive overview of carbon capture technologies, including pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture. The overview additionally discusses the current state of these technologies, their advantages, and limitations, as well as potential future developments. In addition, various CO_2 separation methods regarding these technologies are introduced and discussed. Finally, this paper can be used as a resource for researchers looking to explore carbon capture systems further to minimize CO_2 emissions.



1. Introduction

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Within the last decades, environmental challenges have gained crucial attention worldwide [1]. One of the critical factors influencing this issue is energy consumption. With the industrialization and growing populations of countries, energy demand is steadily increasing. Energy supplies are mainly dependent on fossil fuels, which significantly contribute to environmental degradation via greenhouse gas (GHG) emissions. Typically, GHGs comprise carbon dioxide (CO₂), nitrous oxides, methane, and others [2]. CO₂ accounts for the most significant portion of GHG emissions. Consequently, it is imperative to invest in renewable energy sources, optimization to minimize energy consumption, and technologies to mitigate CO₂ emissions across many industries in order to diminish our carbon footprint and address climate change [3-5]. In 2021, the power production sector constituted the majority portion of total CO₂ emissions worldwide, contributing to approximately 40% of global emissions. Alongside the power production sector, transportation, industry, buildings, and other sectors also play a significant role in contributing to CO₂ emissions [6]. Figure 1 illustrates the CO₂ emissions by sector globally from 1990 to 2021 [6].



Note: Land-use change emissions can be negative.

Fig. 1. CO₂ emission by sector in the world from 1990 to 2021 [6].

Carbon capture, utilization, and storage (CCUS) technologies are among the solutions that have recently emerged to address the growing concerns regarding climate change [7]. These systems operate through two main mechanisms: capturing CO_2 directly at its emission sources, such as power plants and industrial facilities, and removing existing CO_2 from the atmosphere [8]. These include the technology options for carbon capture, which are comprehensively discussed in the rest of the sections. In addition to CO_2 capture, the captured CO_2 can be converted for various applications, including enhancing oil recovery, producing synthetic fuels, or even as a chemical feedstock for manufacturing [9]. Therefore, these integrated approaches not only have a mitigating effect on GHG emissions but also contribute toward building a sustainable future. In this part of this review paper, a comprehensive overview of carbon capture technologies is presented. Various techniques, including pre-combustion, post-combustion, oxyfuel combustion, chemical looping combustion, and direct air capture, are introduced and investigated. By exploring their mechanisms, advantages, challenges, and future potential, this study aims

to provide a comprehensive overview of these technologies and their role in achieving global decarbonization targets. In addition, the CO_2 separation methods of different carbon capture technologies are presented and discussed.

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2. Carbon Capture Technologies

In recent decades, significant global consensus has been reached on mitigating GHG emissions and preventing global warming and climate change [10]. As mentioned, CO_2 emissions are a major contributor to GHGs, which can be captured from different sources such as power plants, cement, and steel industries. Carbon capture technologies are the key component of carbon capture, transportation, storage, and utilization (CCTSU) methods, significantly contributing to the reduction of CO_2 emissions through integration with various industries [11]. Carbon capture technology could be categorized into three main types: pre-combustion, post-combustion, and oxy-fuel for industrial applications. Also, there is another way for carbon capture known as direct air capture (DAC), which involves removing CO_2 directly from the atmosphere [12]. In this section, carbon capture technologies are discussed.

2.1. Pre-combustion

Pre-combustion carbon capture methods are one of the main categories for reducing CO_2 emissions, particularly in the industrial sector. This technology captures CO2 prior to the combustion of fossil fuels, producing hydrogen as a clean energy carrier [13]. Hydrogen (H₂) can be employed in several applications, including transportation, energy production, and industrial sectors. Typically, coal, biomass, and natural gas are gasified or reformed under high temperature and high pressure with oxygen or steam to produce a gaseous stream known as syngas [14]. This synthesis gas (syngas) consists mainly of carbon monoxide (CO), hydrogen, and trace quantities of CO₂. In order to enhance the yield of hydrogen production and the CO₂ concentration in the syngas for capture, the syngas is subjected to a water gas shift reaction (WGSR). CO is exposed to steam and a catalyst in the WGSR and is converted to H₂ and CO₂ [15]. Then, the CO₂ is captured from the resulting mixture via different capture methods for further processing, compression, storage, and utilization. Figure 2 presents a schematic representation of pre-combustion carbon capture.



Fig. 2. A schematic diagram of pre-combustion carbon capture.

Pre-combustion carbon capture approaches are more efficient than post-combustion capture methods in capturing CO_2 (up to 90%) [16]. Different techniques, such as physical and chemical absorption and pressure swing adsorption (PSA), are typically used for pre-combustion carbon capture. Amine-based solvents like monoethanolamine (MEA), methyl

diethanolamine (MDEA), and diethanolamine (DEA) comprise the most widely used chemical absorption method [17]. The absorption capacity of these solvents is higher than physical solvents in lower partial pressure. Physical solvents such as selexol and purisol require a higher partial pressure for absorption based on Henry's law [18, 19]. Physical solvents have a high performance in low temperatures and high partial pressure, and this requirement for high partial pressure poses a challenge where the concentrations of CO₂ are low in the flue gas stream [20]. Adsorption is another way of capturing CO₂, which consists of two main processes of adsorption and desorption of CO₂. The PSA is the most mature and recognized technology among other types like temperature–pressure swing adsorption (TPSA), temperature swing adsorption (TSA), and vacuum pressure swing adsorption (VPSA) [21, 22]. Solid adsorbents, including zeolites, molecular sieves, and activated carbon, are frequently employed in PSA systems for CO₂ capture at high pressures, whereas it is released in the regeneration phase at low pressure or under vacuum conditions [23].

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Membrane-based separation, ionic liquids, and metal-organic frameworks (MOFs) are emerging technologies for CO_2 separation. Different types of membrane separation technologies, such as polymeric membranes, inorganic membranes, and ceramic membranes, are also being explored for gas separation, air separation, or oxygen enrichment applications. Membranes have some advantages, like low energy consumption and financial feasibility [24]. However, some challenges, including lifetime and durability, remain and need further research [25]. Ionic liquids are promising alternatives for amine-based solvents in CO_2 capture processes. These solvents have advantages such as low chemical and thermal stability, low toxicity, and high CO_2 capacity. Ionic liquids have low vapor pressure and can improve the performance of CO_2 capture by reducing energy requirements for solvent recyclability [26]. Also, these solvents have a broader application in various sections like gas separation, supercapacitors, and battery electrolytes [27]. MOFs are crystalline porous materials consisting of metal ions or clusters coupled with organic ligands, creating highly structured three-dimensional networks. Their high surface area, tunable pore sizes, and chemical versatility make them highly effective for various applications, such as adsorbing and separating CO_2 and hydrogen storage [28]. MOFs can improve the performance of different methods of carbon capture, but due to environmental concerns and the high cost of production and utilization, their widespread use is currently limited [29]. Different CO_2 separation techniques are demonstrated in Fig. 3 [30].



Fig. 3. Illustration of different CO₂ separation methods: a) chemical absorption, b) physical absorption, c) membrane separation, d) adsorption process [30].

Overall, pre-combustion is one of the main techniques for capturing carbon dioxide. The CO₂ concentration of the gas stream is relatively high in pre-combustion (>20%) capture compared to post-combustion capture methods (5-15%) [31]. This results in a relatively lower energy demand and a cost-effective process for carbon capturing. On the other hand, precombustion methods can be more cost-effective compared to oxyfuel and post-combustion approaches by 21-24% and 38-45%, respectively [32]. This method necessitates less investment in capital and equipment size. However, there are some barriers to widespread adoption, such as the complexity and elevated operational expenses associated with retrofitting current systems for pre-combustion carbon capture. The gasification process is considered a complex procedure and also requires a significant amount of energy input. As mentioned, the pre-combustion method is applicable for solid and gaseous fuels but is less suitable for liquid fuels like oil [33]. One of the concerns regarding the pre-combustion method is the environmental impact, specifically the release of harmful byproducts such as NO_X, sulfur compounds, and particulate matter, which require further treatment [34]. Consequently, pre-combustion carbon capture should be improved to minimize energy loss, decrease energy demands, and reduce costs. It also can be integrated with renewable energy sources to further mitigation of CO₂ emissions [35, 36]. At this time, the application of this capture method is limited to integrated gasification combined-cycle (IGCC) power-generation plants [37]. There are different large-scale IGCCs in various countries like the USA, China, and Japan [38]. Water is a critical factor for industrial processes, especially in regions with limited resources. Pre-combustion methods have a lower water consumption compared to post-combustion. The analysis indicates that the water footprint of pre-combustion IGCC is roughly 0.74 m³ per ton of CO₂ captured [39, 40].

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2.2. Post-combustion

Post-combustion carbon capture is one of the most widely deployed technologies for reducing CO_2 emissions. In contrast to pre-combustion carbon capture, post-combustion technology captures CO_2 from the flue gas after combustion has taken place in industrial processes or power generation [41]. The flexibility of this approach allows it to be retrofitted into existing plants, making it a key solution for mitigating emissions in the short to medium term [27, 42]. A schematic diagram of post-combustion carbon capture is shown in Fig. 4.



Fig. 4. A schematic diagram of post-combustion carbon capture.

Combustion of fossil fuels, including coal, natural gas, and oil, produces exhaust gases comprising nitrogen, water vapor, CO_2 , and other harmful pollutants like SO_X and NO_X [43]. Therefore, flue gas is processed through a series of steps to

remove the pollutants. Then, the stream flow is cooled to a suitable temperature in order to optimize the subsequent CO_2 capture [44, 45]. One of the significant challenges of post-combustion carbon capture is the low partial pressure of CO_2 in flue gas. Flue gas is subjected to atmospheric pressure during this procedure, and its CO_2 content ranges from 3 to 15% [46]. Despite requiring less investment than alternative methods, the costs associated with CO_2 capture and energy consumption are elevated due to the lower partial pressure, necessitating suitable CO_2 separation procedures.

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Similar to pre-combustion carbon capture, there are typical and commercial methods for CO₂ separation in post-combustion carbon capture [47]. The selection of the suitable separation technique primarily relies on various factors such as the concentration of CO₂, physicochemical characteristics of the exhaust gases, flue gas volume, temperature, and pressure [48, 49]. Solvent-based absorption techniques, physical absorption, and membrane separation are the main approaches utilized for CO₂ separation [50]. Chemical absorption based on monoethanolamine (MEA) is the most commonly and commercially used method for large-scale CO₂ capture in post-combustion carbon capture applications [51]. As illustrated in Fig. 3 (a), during the initial phase of the process, an aqueous solvent solution enters the absorber column and interacts with the flue gas to capture CO_2 [52]. Then, the rich-loading solution is stripped in the desorber column to release the captured CO_2 at a high temperature for further processing [44]. The released CO_2 from the desorber column is compressed and transported for storage or utilization, while the lean loading solution is recycled to the absorber column to perpetuate CO₂ capture. A 30% solution of MEA and MDEA is commonly employed for CO₂ capture owing to its excellent efficiency and purity of the obtained CO_2 . The primary issue encountered by this technique is its significant energy requirement [53]. Based on the membrane structure, membranes can be categorized into gas separation membranes and gas absorption membranes for carbon capture [54]. The gas transport mechanism of the gas separation membrane is based on dissolution and diffusion. The flue gas passes the high-pressure side of the membrane, and the CO_2 is taken out on the low-pressure side [55, 56]. Gas absorption membranes, composed of microporous materials, facilitate the transport of CO₂ through their pores, transferring it into a liquid absorber on the opposite side. The efficiency of this separation process is contingent upon the membrane's pore size and the chemical affinity of the absorbing liquid, facilitating the successful separation of CO_2 from other flue gas constituents [57, 58]. schematic of these membranes has shown in Fig. 3 (c).

Other separation methods, like cryogenic and calcium looping (CaL), are also studied and employed for CO_2 capture [59, 60]. The cryogenic separation method has the advantage of a low footprint, no chemical reaction, and high CO_2 purity (>99%). The primary disadvantage of this technology is its substantial energy demand in cooling conditions, rendering it a costly procedure relative to alternative CO_2 capture technologies [61]. According to the economic aspect, it may not be a feasible option for a low-concentration CO_2 stream [62]. The cold energy requirement for CO_2 capture is typically provided via liquefied natural gas (LNG), liquefied nitrogen, and a chiller [63, 64]. This method involves unit processes of compression, expansion, separation, and cooling, promoting a low-temperature stream (below -78 °C), in which CO_2 can be separated in liquid or solid phase [65]. In addition to the mentioned advantages, the cryogenic approach could be integrated with other separation methods like membranes to elevate efficiency and reduce costs [66]. Additionally, liquid CO_2 can be utilized as a potential cold energy sink [67]. However, due to the high operational costs, the wide adoption of this technology is limited [68]. Calcium looping (CaL) is another novel way for CO_2 separation, applicable for post-combustion and oxyfuel carbon capture [69]. The CaL process is based on a reversible reaction between CaO and CO_2 , which are defined as carbonation and calcination, respectively. Eq. (1) shows the main reaction of the capture of CO_2 with solid sorbent [70].

(1)

$CaO + CO_2 \leftrightarrow CaCO_3$

During the carbonation phase, flue gas is introduced into a reactor, where CO_2 reacts with the CaO to produce calcium carbonate (CaCO₃). The CaCO₃ is subsequently sent to a calcination reactor, where it is subjected to high temperatures, typically above 900°C, to release pure CO₂ and recover the sorbent. The regenerated CaO is returned to the carbonation reactor. The output CO₂ stream has a high purity (>95%) in this process [71, 72]. One of the other advantages of CaL is that it utilizes cheap sorbents. Also, this process can be integrated with other industrial processes to heat recovery and enhance overall energy efficiency. However, this process has some drawbacks, like sorbent deactivation and regeneration, which reduce its efficiency over time [73-75]. The calcium looping process is still in the pilot stage and needs more development, but with its high capture efficiency and economic viability, CaL has the potential to play a significant role in industrial decarbonization efforts [76]. A schematic diagram of the cryogenic and CaL process is demonstrated in Fig. 5 [77, 78].



Fig. 5. A representation of a) cryogenic and b) calcium looping technologies [77, 78].

Overall, post-combustion carbon capture technologies are one of the main methods for reducing CO_2 emissions [79]. The ability of this approach to integrate and retrofit with existing industrial infrastructure makes it a promising option for achieving significant emission reductions. Additionally, it is effective across various fuel types, from coal and natural gas to biomass, making it a versatile option for diverse industries [80]. However, there are still challenges to be addressed in terms of cost and scalability. The low partial pressure of CO_2 and high energy consumption results in higher operational costs for carbon capture and diminished performance. In addition, the high cost of solvent replacement or regeneration in chemical absorption processes is a barrier to economic feasibility [81]. Consequently, the advancement of novel materials and technologies is essential for future research aimed at enhancing the efficiency and decreasing the costs of post-combustion carbon capture systems [82].

2.3. Oxy-fuel combustion

The oxy-fuel combustion method possesses advantages compared to post-combustion and pre-combustion carbon capture methods, which make it a more attractive approach for CO_2 capture. One of the main challenges in pre-combustion and post-combustion carbon capture methods is the low concentration of CO_2 in the flue gas [83]. In oxy-fuel combustion, fuels such as coal or natural gas are burned with a pure oxygen stream rather than air, resulting in a flue gas composed mainly of

 CO_2 and water vapor [84]. Typically, two types of high-temperature (~2500 °C) and low-temperature (~1600 °C) boiler designs can be utilized for oxy-fuel combustion. A high-temperature boiler design has a higher cost than a low-temperature boiler design due to the requirement for high-temperature-tolerant materials, which have a higher price and lower lifetime [85]. Recycling a portion of the combustion products back into the boiler helps dilute the reaction system, lower the boiler temperature, and minimize temperature gradients, improving overall system stability [27]. A representation of oxy-fuel combustion carbon capture is shown in Fig. 6.



Fig. 6. An illustration of oxy-fuel combustion carbon capture.

Eliminating nitrogen from the combustion process markedly elevates the concentration of CO_2 in the flue gas relative to post-combustion and pre-combustion procedures, facilitating capture and storage [86]. Utilizing a pure oxygen stream (>95%) alongside elevated CO_2 concentrations substantially reduces equipment size, eliminates the necessity for costly post-combustion CO_2 separation techniques, and reduces nitrogen emissions (NO_X) [87]. However, one of the primary challenges that oxy-fuel combustion faces is the separation of oxygen from air, which is a costly and energy-intensive process. Currently, cryogenic distillation is the most common method for producing oxygen, contributing to the high cost and energy consumption of oxy-fuel combustion [88]. Cryogenic air separation can contribute to 14% of the overall cost of oxy-fuel combustion [89]. Oxygen can be separated by PSA and different methods, but novel methods such as ion transport and oxygen transport membranes should be investigated [90].

Oxy-fuel combustion can be integrated into both new power plants and existing facilities with appropriate retrofitting, making it a versatile option for reducing emissions. Despite the advantages of this technology, the widespread adoption of oxy-fuel combustion has been significantly hindered by the high energy requirements of the oxygen separation process. The energy-intensive nature of air separation units (ASUs) imposes substantial energy penalties and increases operational costs, making the technology less economically viable for large-scale applications [91].

2.3.1 Chemical looping combustion

Chemical looping combustion (CLC) is an emerging carbon capture process, initially presented by Ishida, Zheng, and Akehata in 1987 [92]. This method is a form of oxy-fuel combustion that utilizes oxygen instead of air to burn fuel, resulting in a stream of concentrated CO₂ ready for sequestration. This technology typically comprises two air and fuel reactors. In the air reactor, the oxygen carrier (typically a metal particle, such as Co, Ni, Cu, Fe, and Mn) reacts with oxygen in the air, oxidizing the metal and forming a metal oxide while releasing nitrogen as a byproduct [93]. The oxidized oxygen carrier is then transported to the fuel reactor, where it is reduced to provide the required oxygen for combustion. The reduced oxygen carrier is returned to the air reactor for re-oxidizing [94]. Similar to oxy-fuel combustion, which employs pure oxygen instead of air, the resulting flue gas contains a higher concentration of CO₂, making it easier to capture and store. Due to the elimination of the air separation unit in this process, the CLC process is more cost-effective with lower energy loss than oxy-fuel combustion [95]. Nonetheless, several drawbacks, such as inadequate stability of the oxygen carrier and slow redox kinetics at high temperatures, remain an issue [96]. The schematic of the CLC process is shown in Fig. 7.



Fig. 7. A demonstration of chemical looping combustion carbon capture.

2.4 Direct air capture

A sustainable future requires the reduction and control of CO_2 emissions. Technologies that will be useful in this area are pre-combustion, post-combustion, and oxy-fuel combustion carbon capture, all targeted at the source of CO_2 emissions like industrial processes [97]. Nonetheless, the atmospheric CO_2 concentration is at a critically high level (~420 ppm) for environment, posing significant challenges for climate mitigation. Direct Air Capture (DAC) is a novel technology designed to remove CO_2 directly from ambient air, which has received more attention in recent decades [98]. DAC systems operate by passing ambient air through a contactor unit where CO_2 is separated based on various methods. Different methods of direct air capture technologies are demonstrated in Fig. 8 [99].



Fig. 8. A representation of direct air CO₂ capture: a) amine-based b) temperature-vacuum swing adsorption c) cryogenic d) single-stage membrane [99].

| Table 1 Global annual capacity demand for direct air CO ₂ capture (or equivalent) by sector (adopted from [10] | | | | | | |
|---|---------------------------------|----------------------|--------------------------------------|--------------------|----------------------|------------|
| $-\mathbf{i}$ and \mathbf{i}_{1} (nonal annual canacity demand for direct an $\mathcal{O}\mathcal{O}$ (and \mathcal{O}) candidation in the solution of the | Table 1. Global annual c | apacity demand for d | direct air CO ₂ capture (| (or equivalent) by | v sector (adopted fr | om [104]). |

| Sector | | unit | 2020 | 2030 | 2040 | 2050 |
|------------------------------------|-----------------------------|-------------------------|------|------|------|--------|
| power | power-to-gas | Mt_{CO_2}/a | 3 | 7 | 142 | 363 |
| | waste-to-energy | Mt_{CO_2}/a | 0 | -17 | -99 | -165 |
| | sewage plant | Mt_{CO_2}/a | 0 | n/a | n/a | n/a |
| transport | road (cars/bus/trucks) | Mt _{CO2} /a | 0 | 218 | 1309 | 1101 |
| | Rail | Mt_{CO_2}/a | 0 | 7 | 66 | 82 |
| | Marine | Mt_{CO_2}/a | 0 | 56 | 962 | 1667 |
| | Aviation | Mt_{CO_2}/a | 0 | 54 | 964 | 1543 |
| industry | chemical industry | Mt_{CO_2}/a | 0 | 224 | 1157 | 3255 |
| | pulp and paper | Mt_{CO_2}/a | 0 | -8 | -52 | -95 |
| | cement mills (limestone) | Mt _{CO2} /a | 0 | -69 | -425 | -607 |
| | Others | Mt_{CO_2}/a | 0 | n/a | n/a | n/a |
| CO ₂ DAC, energy system | | Mt_{CO_2}/a | 3.0 | 473 | 4025 | 7144 |
| CO ₂ removal | | $Mt_{CO_2, captured}/a$ | 0 | 0 | 1000 | 10 000 |
| thereof other Negative | | Mt /~ | 0 | 0 | 300 | 2500 |
| Emission Technologies | | $Mt_{CO_2,captured}/a$ | U | 0 | 500 | 2500 |
| thereof CO ₂ DAC, | | Mt (a | 0 | 0 | 767 | 8213 |
| CO ₂ removal | | $M \iota_{CO_2}/a$ | 0 | 0 | 707 | 0215 |
| CO ₂ DAC, total | | Mt_{CO_2}/a | 3 | 473 | 4791 | 15 356 |

DAC approaches focus mainly on reducing CO_2 emissions from atmospheric sources. This method's main advantage is that it can be employed anywhere, making it highly flexible and suitable for addressing emissions in locations without concentrated CO_2 sources [100]. DAC is a promising approach for capturing CO_2 in the transportation sector [101]. However, this technology faces some challenges, including energy-intensive processes and high implementation costs [102]. Integrating DAC with renewable energy sources could help address these challenges and enhance its performance [103]. Therefore, further research and development are needed to improve DAC's efficiency and economic feasibility. Table 1 presents the global annual demand for direct air capture CO_2 (or equivalent) capacity categorized by sector [104].

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3. Conclusion

Increasing the GHG concentration, especially CO_2 , in the atmosphere can lead to more severe climate change impacts, such as global warming. Addressing the challenges posed by climate change requires urgent and effective strategies to reduce CO_2 emissions. Carbon capture technologies are considered an effective approach to mitigate CO_2 concentrations in the atmosphere and combat climate change. Developing and implementing these technologies can lead to meeting global emissions reduction goals and limiting global warming. Carbon capture systems enable capturing CO_2 from its source, such as power plants and industrial operations, as well as directly from the atmosphere. This part of this review paper provided a comprehensive investigation in terms of carbon capture technologies. Pre-combustion, post-combustion, oxy-fuel combustion, and direct air capture are the main categories that were introduced and discussed. The advantages and disadvantages of each technology were also explored. A summary of each technology is provided:

- Among these technologies, pre-combustion and post-combustion carbon capture methods are employed on a commercial scale, although the use of oxy-fuel combustion carbon capture and direct air capture remains limited at present.
- Pre-combustion carbon capture is the most cost-effective method compared to other approaches. However, the gasification's complexity is one of the main challenges and requires considerable modification. In addition, the application of this technology is currently limited to integrated gasification combined cycle.
- Post-combustion carbon capture methods are the most commonly used technology for reducing CO₂ emissions in existing infrastructure. However, due to the low concentration of CO₂ in this process, it has high energy consumption and operational costs. Additionally, the high cost of regenerating the solvent presents a significant challenge to its economic viability.
- Oxy-fuel combustion carbon capture has the highest concentration of CO₂ in the outlet flue gas compared to other carbon capture technologies. However, this process requires a pure oxygen stream, which increases the cost of operation, and it is so energy-intensive. Chemical looping combustion operates on a principle similar to the oxy-fuel process but requires significantly less energy input, making it a more energy-efficient alternative. These technologies are not utilized at a commercial scale and need more development.
- Unlike previous methods that capture CO₂ at the emission source, direct air carbon capture captures CO₂ directly from the atmosphere. This method is now expensive and energy-intensive.

Besides the overview of carbon capture technologies, CO_2 separation methods such as adsorption, absorption, membrane separation, calcium looping, and cryogenic approaches are also discussed in this paper. Despite challenges such as high costs, energy intensity, and scalability, advancements in technology, materials, and integration with renewable energy sources have the potential to enhance their viability. Therefore, carbon capture technologies will help reach near net-zero

emissions and make our energy use more sustainable. Collaborative efforts by industries, governments, and researchers

will be very important in fully realizing these technologies and making the global economy resilient and low-carbon.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have

appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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