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Review

Low-Energy Regeneration Technologies for Industrial CO_2 Capture: Advances, Challenges, and Engineering Applications

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Abstract

High carbon dioxide (CO_2) emissions from industrial processes have intensified the need for large-scale, sustainable, and low-energy-consumption carbon capture technologies. Amine-based chemical absorption is a promising method for large-scale CO_2 reduction, but it faces challenges like high regeneration energy consumption, technical limitations, and commercialization difficulties. To reduce energy consumption in regeneration, this paper reviews low-energy regeneration methods, including absorbent optimization, catalytic regeneration, process waste heat recovery, and calcium-based chemical desorption, and explains the energy-saving mechanisms of each approach. Focusing on technical development bottlenecks, this paper provides a comprehensive review of the technical advantages, application limitations, and key challenges associated with various methods. Based on commercialization needs, this paper thoroughly investigates the development process and industrialization status of carbon capture technology in the iron and steel industry. Research has revealed that optimized absorbent designs reduce regeneration heat loads, catalytic acid sites promote proton transfer and lower desorption temperature, utilization of waste heat reduce additional energy consumption, and calcium-based compounds offer both low energy consumption and economic advantages in desorption. This article constructs a theoretical framework for low-energy regeneration technology, identifies innovation priorities, and analyzes scalability challenges and development pathways, providing theoretical support and technical guidance for industrial implementation.

Keywords: carbon dioxide; carbon capture; absorption; low-energy regeneration; iron and steel industry

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1. Introduction

The rising concentration of greenhouse gases in the atmosphere is one of the key factors contributing to global warming and climate change. Over the past few decades, rapid industrialization and urbanization have brought unprecedented economic development and population growth. It has led to a dramatic consumption of fossil fuels, such as coal, oil, and natural gas, which are the primary sources of greenhouse gases, particularly CO_2 [1]. Currently, the concentration of CO_2 in the atmosphere has exceeded 425 ppm and continues to rise [2]. 2024 has become the warmest year since global records began in 1850. To successfully limit global temperature rise to 1.5 °C above pre-industrial levels,

CO_2 emissions must be significantly reduced, particularly in the industrial sector [3,4]. Carbon Capture, Utilization, and Storage (CCUS) is considered one of the key technologies for mitigating climate change by capturing CO_2 [5], from large point sources, and subsequently reusing it, such as converting CO_2 into high-value-added chemicals through catalysis [6,7], like methanol [8,9], etc., or storing it.

Carbon capture technologies mainly include: pre-combustion capture, mid-combustion capture, and post-combustion capture technologies [10]. Pre-combustion capture involves separating CO_2 from fossil fuels before combustion starts, converting the fuel into a gas mixture of H_2, CO, H_2O, and CO_2 through gasification, thereby achieving CO_2 separation and removal [11]. However, this process requires high energy consumption and costs, limiting its widespread application. Oxy-fuel combustion is the most widely used mid-combustion capture technology, which puts the fuel in a high concentration of oxygen or pure oxygen combustion rather than direct using air, to make the fuel fully combusted, the main combustion products are CO_2 and H_2O [12]. Therefore, it can increase the CO_2 concentration in the flue gas after combustion, facilitating subsequent CO_2 capture. Oxygen-enriched combustion can be implemented through simple modifications to traditional combustion equipment, with low investment costs. However, this technology requires a large amount of O_2 during operation, resulting in high operating costs. Additionally, the presence of water vapor can cause corrosion to the equipment [12,13]. Post-combustion carbon capture technology, which does not interfere with or alter existing process flows, offers high adaptation and is widely applied in industrial sectors [14].

Post-combustion carbon capture technology uses absorption, adsorption, and membrane separation technologies to directly capture CO_2 from flue gas that has pre-treated with denitrification, desulfurization, and dust removal [15]. Captured CO_2 typically requires subsequent regeneration prior to utilization or storage. Chemical absorption, distinguished by its high reaction rates and substantial CO_2 absorption capacity, is one of the most prevalent and mature technologies for CO_2 capture, and has been used for decades for CO_2 removal [4,16]. In the chemical absorption process, CO_2 in flue gas reacts with absorbents (e.g., amines, carbonates) to form intermediate compounds, after which the solvent is regenerated through heating or other methods. Amine-based absorbents demonstrate high efficacy in capturing CO_2 from flue gases and other emission streams, where stable chemical compounds are formed following CO_2 absorption [17]. Monoethanolamin (MEA) is regarded as the benchmark absorbent due to its elevated reaction kinetics and low cost [18]. Nevertheless, its regeneration process requires heating to above 100 °C, which consumes a large amount of energy and increases the cost of technical application to a certain extent. Therefore, it is necessary to further reduce regeneration energy consumption through methods such as synthesizing new absorbents [17].

In 2023, global carbon emissions from the industrial sector will be approximately 9207 Mt, with the steel industry contributing over 30% and ranking first [19]. In 2019, nearly 74.5% of crude steel production came from coal-based steel plants, mainly in China [20]. Although dynamic modeling analysis has found that production restructuring can promote carbon neutrality in the industry [21], production restructuring poses certain challenges in the short term due to the maturity and widespread use of the blast furnace-basic oxygen furnace (BF-BOF) process [22,23]. Therefore, CCUS plays a key role in carbon emission reduction in the steel industry [24]. In 2016, ADNOC Al-Reyadah Company completed and operated the first carbon capture project in the steel industry in the United Arab Emirates, with an annual CO_2 capture capacity of 800,000 tons [25]. It uses the MEA amine process, whereby captured CO_2 is compressed and transported to enhanced oil recovery sites, and ultimately stored underground [26]. However, regenerating absorbents requires high energy consumption, which increases the cost of carbon capture for enterprises.

Although many scholars have conducted research on low-energy-consumption regenerated absorbents, their studies have been limited to system simulation or laboratory analysis [27].

Although amine chemical absorption technology is widely applied in CO_2 capture, its high energy consumption during regeneration poses a significant bottleneck that severely limits its economic viability. Furthermore, existing research lacks a systematic review of low-energy regeneration technologies. To address this, this paper first comprehensively reviews research progress on low-energy regeneration technologies. It systematically outlines the energy-saving mechanisms, application effectiveness, advantages, limitations, and challenges of 4 primary technical pathways—absorbent optimization, catalytic regeneration, technology integration, and chemical desorption—establishing a theoretical framework for low-energy regeneration in CO_2 chemical absorption. Addressing the immense emission reduction pressure and limited application of carbon capture projects in the steel industry—a typical hard-to-abate sector—this paper further analyzes the current development status and commercialization progress of carbon capture technologies in this industry. In order to provide reference and insights for carbon capture practices in other heavy industrial sectors. On this basis, it looks at the future of low-energy recycling tech, figuring out the challenges and ways to achieve large-scale application. This review establishes a systematic theoretical framework for low-energy CO_2 chemical absorption regeneration technology, aiming to provide important theoretical support and technical guidance for the innovative development and engineering application of the technology. The specific research framework of this paper is shown in Figure 1.

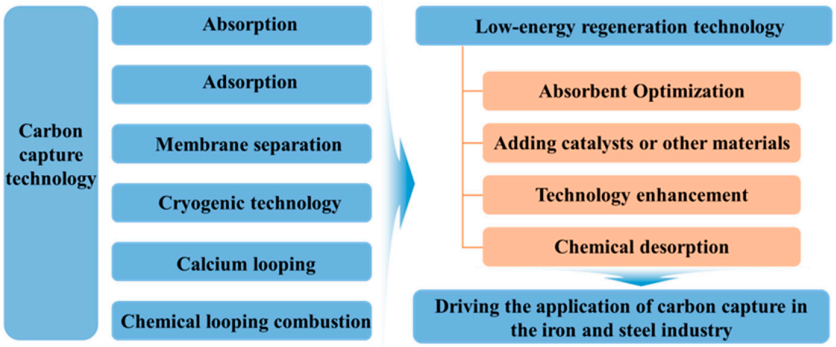


Figure 1. Research framework of this paper.

2. Overview of CO_2 Capture Technology

Industrial sources (such as the steel industry) emit large amounts of CO_2 into the environment during production operations. Therefore, carbon capture technology is needed to reduce and control CO_2 emissions [16]. To reduce the impact of CO_2 emissions, CCUS technology is regarded as the best solution to the problem [13,16,19]. Among them, post-combustion capture is considered the best option among existing capture technologies [13]. Based on the principles of the capture process, the main capture technologies include absorption, adsorption, membrane separation, and other novel technologies. Among these, absorption, adsorption, and membrane separation have received widespread attention in this field. In addition, emerging carbon capture technologies such as low-temperature technology, calcium cycling, and chemical looping combustion have also attracted extensive research.

2.1. Absorption

Absorption is a relatively mature technology that has already been commercialized. It mainly includes physical absorption and chemical absorption. Physical absorption is based on Henry's law, which absorbs CO_2 under high pressure and low temperature conditions,

and regenerates the solvent under low pressure or high temperature conditions, or a combination of both [28]. Physical absorption operates based on the solubility differences between the solvent and CO_2 as well as other gases. There are several physical absorption methods in industry, such as Rectisol, Selexol, Purisol, and Fluor [29]. Common physical solvents include methanol, dimethyl ether of polyethylene glycol, N-methyl-2-pyrrolidone, and propylene carbonate [13,19,30]. Physical absorption requires low-temperature and high-pressure conditions. In industrial environments, interference from impurity gases, low capture rate of low-concentration CO_2, and high solvent regeneration energy consumption limit its widespread application [30,31]. Chemical absorption involves using a weak alkaline solution to react chemically with CO_2 to form weakly bound compounds, which are then regenerated through heating or other means. Due to its simple process flow, high absorption efficiency, high maturity, and low cost, it is one of the most widely used technologies [32]. The main chemical absorbents include: amine solvents, carbonates, hydrated ammonia, and amino acids, etc. [13,14,19]. Among these, amine-based absorbents exhibit a unique affinity for CO_2, forming stable compounds after reaction, which can be reused after thermal regeneration. They are considered the most practical method for controlling CO_2 emissions from industrial flue gas combustion [15,32].

Common amino compounds include: MEA, diethylethanolamine (DEEA), and N-Methyldiethanolamine (MDEA) [33]. The most classic amine absorbent is 20–30 wt% water-based MEA [15,16,19]. The general process for CO_2 absorption is shown in Figure 2. After combustion, flue gas containing CO_2 contact with a lean amine solution in an absorption tower, where the amine solution selectively reacts with CO_2 to form a CO_2-rich amine solution. This solution is then sent to a stripper for solvent regeneration and CO_2 desorption, resulting in high-concentration CO_2 for further utilization or storage.

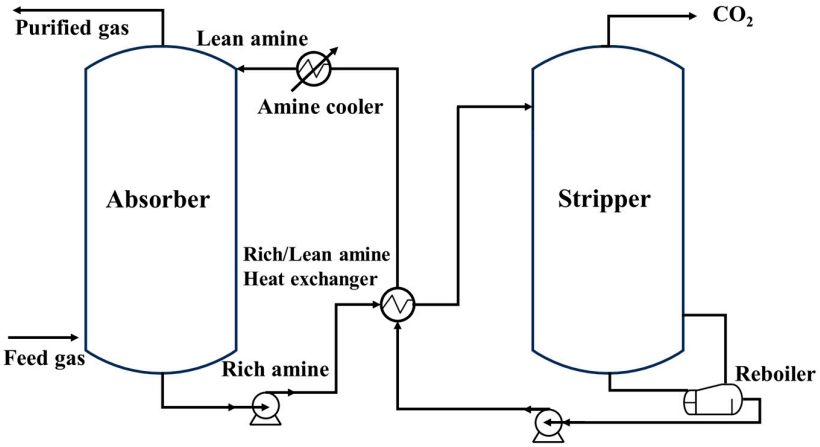


Figure 2. Ammine absorption CO_2 process diagram [34].

MEA is a primary amine, and its specific reaction process with CO_2 is as follows [14,35]. First, amines react with CO_2 to form zwitterion, which has a faster reaction rate (Equation (1)). After that, the amine molecule reacts with zwitterion as a Bronsted base (proton acceptor) to produce protonated amines and carbamates (Equation (2)). At high pressure, carbamates may undergo hydrolysis, yielding free amine and bicarbonate (Equation (3)). According to the reaction process, the theoretical CO_2 loading was 0.5 mol CO_2/mol amine.

$$R_1R_2NH + CO_2(aq) \leftrightarrow R_1R_2NH^+COO^- \quad (1)$$

$$R_1R_2NH + R_1R_2NH^+COO^- \leftrightarrow R_1R_2NH^+ + R_1R_2NCOO^- \quad (2)$$

$$R_1R_2NCOO^- + H_2O \leftrightarrow R_1R_2NH + HCO_3^- \quad (3)$$

The reaction mechanism of secondary amines is the same as that of primary amines. However, tertiary amines cannot react directly with CO_2 because there are no hydrogen atoms on the nitrogen atom. But they can provide proton acceptors to promote the hydrolysis of CO_2 to form bicarbonate (Equation (4)) [36]. Compared with primary and secondary amines, their theoretical CO_2 loading capacity is 1 mol CO_2/mol amine, but their reactivity is lower.

$$R_1R_2R_3N + CO_2(aq) + H_2O \leftrightarrow R_1R_2R_3NH^+ + HCO_3^- \quad (4)$$

Due to its high reaction rate, high CO_2 absorption capacity, and low cost, MEA is considered the benchmark absorbent [18]. However, the regeneration of CO_2-rich MEA solutions requires a significant amount of energy, which increases the cost of CO_2 capture and hinders the industrial application of chemical absorption. Scholars have already mixed other solvents into MEA to enhance its CO_2 absorption capacity and reduce regeneration energy consumption. By mixing a small amount of tertiary amine (MDEA) into MEA to form a solvent mixture, they fully utilize the advantages of both, thereby improving the solvent's capture performance and reducing the regeneration energy demand [35].

Chemical absorption using amine solvents is currently the most mature technology for CO_2 capture and has been commercially applied for many years. It offers advantages such as high reaction rates, high CO_2 loading capacity, and high recovery rates. However, during operation, the solvent undergoes degradation and evaporation, leading to solvent loss and equipment corrosion issues. Additionally, since the compounds formed after capturing CO_2 with amine-based solvents have high stability, regeneration requires temperatures exceeding 100 °C, resulting in significant energy consumption during the regeneration process. To reduce regeneration energy consumption, further development of new, highly efficient absorbents is necessary.

2.2. Adsorption

The adsorption method for capturing CO_2 involves gas being adhered to a solid porous surface, thereby being captured by the adsorbent. Solid adsorption serves as an alternative to carbon capture technologies, offering advantages such as reduced energy consumption, high adsorption capacity, good selectivity, and simple operation compared to amine-based chemical absorption methods [13,19]. Similarly to absorption, adsorption is also divided into physical adsorption and chemical adsorption [13]. Physical adsorption involves the adsorption of CO_2 through physical adsorbents under intermolecular forces. Common physical adsorbents include activated carbon, zeolites, and carbon nanotubes, etc. [37,38]. based on their main chemical components. Since no new chemical bonds are formed, the energy consumed in regenerating the adsorbent is lower than that in chemical adsorption, but this also results in poorer selectivity in physical adsorption [19]. Zeolite has higher selectivity than other materials, but its CO_2 loading capacity is low, and its efficiency decreases in the presence of water vapor [38]. Metal–organic frameworks (MOFs) have certain advantages in carbon capture due to their functionalized pore morphology and customized structures. After modification with the introduction of active sites, MOFs exhibit high CO_2 loading capacities [39]. However, desorption requires high temperatures or low pressures, which increases regeneration energy consumption.

Chemical adsorption has stronger selectivity than physical adsorption, mainly because modified solid materials can form new chemical bonds with CO_2. The main types of modified materials include two categories: organic amines [40] and inorganic metal oxides (alkali metals or alkaline earth metals) [37]. Most chemical adsorbents are prepared by impregnation, which allows active sites to be uniformly distributed on the adsorbent [41]. Jialiang Li et al. [40] analyzed the mechanism of interaction between amine-functionalized graphene oxide and CO_2 through simulation, and found that there exists physical adsorp-

tion between the two via van der Waals forces and hydrogen bonds, as well as chemical adsorption between the amine groups and CO_2. Shaoliang Zhu et al. [42] co-impregnated two amine solutions on γ-Al_2O_3 and found that under the synergistic action of the two amines, the maximum CO_2 loading was 2.65 mmol/g. The CO_2 adsorption process mainly includes three steps: external diffusion, internal diffusion, and adsorption reaction. CO_2 enters the interior of the adsorbent through external diffusion, then reaches the active adsorption sites via internal diffusion, subsequently undergoing a physico-chemical reaction. The CO_2 adsorption reaction process of amine-functionalized adsorbents is illustrated in Figure 3.

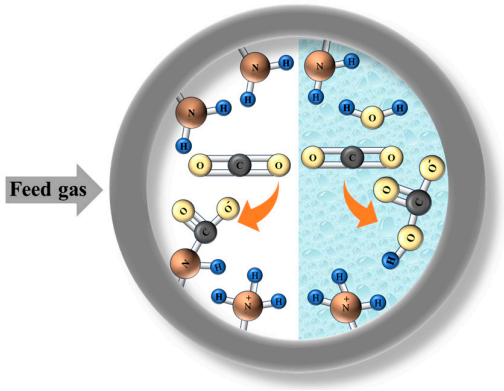


Figure 3. CO_2 adsorption reaction of amine-functionalized adsorbents [43].

Under anhydrous conditions, the main reaction processes are shown in Equations (5) and (6) [44]:

$$R_1R_2NH + CO_2 \leftrightarrow R_1R_2NH^+COO^- \quad (5)$$

$$R_1R_2NH^+COO^- + R_1R_2NH \leftrightarrow R_1R_2NH_2{}^+ + R_1R_2NCOO^- \quad (6)$$

In the presence of water, the reaction process is similar to chemical absorption, and the reaction rate is faster than under anhydrous conditions [43].

In the CO_2 capture process, organic amine adsorbents exhibit high selectivity and are suitable for low-concentration CO_2 capture [45]. Additionally, they have advantages such as lower regeneration energy consumption compared to water-based amine absorbents. However, in practical applications, the adsorbent may become deactivated or degraded under the influence of CO_2, O_2, acidic gases, and heating, thereby affecting its CO_2 capture efficiency [43]. Furthermore, their relatively low CO_2 adsorption capacity and high cost limit their industrial-scale application.

2.3. Membrane Separation Technology

Membrane separation technology is a process that uses semipermeable membranes to separate mixed gases composed of two or more components [46]. During membrane separation, the membrane acts as a filter, allowing specific molecules (such as CO_2) to pass through, thereby enriching CO_2 on the other side of the membrane. CO_2 permeates through the membrane via two mechanisms: facilitated transport and solution-diffusion, while other gases only pass through the membrane via the solution-diffusion mechanism, as shown in Figure 4. Its ability to separate CO_2 depends on the permeability and selectivity of the membrane material to CO_2 [47]. Depending on the composition of the material, common membrane materials used for CO_2/N_2 separation after combustion include polymers, ceramics, zeolites, and MOFs [13].

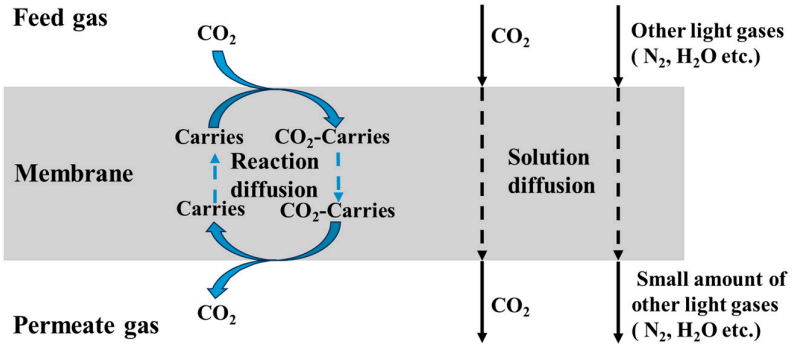


Figure 4. The membrane separation technology reaction process diagram [46,48].

Polymer materials are widely used due to their heat resistance, chemical resistance, excellent film-forming ability, and processability [13,49]. The flue gas produced after combustion mainly contains gases such as CO_2, H_2O, and N_2. The separation of CO_2 and N_2 mainly relies on surface diffusion and solution diffusion, which is driven by differences in adsorption capacity and solubility between the gases. Since the diffusion selectivity of CO_2/N_2 in polymers is similar, CO_2/N_2 separation membranes enhance their separation capabilities by introducing functional groups that can undergo reversible reactions with CO_2 [50]. For selective membranes containing functional groups, CO_2 dissolves in the polymer on the high-pressure side and reacts with the functional groups. The reaction products diffuse along the concentration gradient on both sides of the membrane. On the low-pressure side, the reaction products undergo a reversible dissociation reaction, releasing CO_2. Related studies have found that functional groups containing nitrogen, oxygen, sulfur, or phosphorus can increase the affinity between CO_2 and the membrane [51]. Although there are already a large number of polymer membrane materials available, polymer membrane materials exhibit trade-off effects in gas separation processes, making it difficult to achieve both permeability and selectivity simultaneously [49]. In addition, polymer membranes face issues such as physical aging and plasticization induced by CO_2, leading to a decline in separation performance and selectivity [49].

To overcome the limitations of polymers, researchers prepared hybrid matrix membranes by adding inorganic materials to polymers [52]. It fully leverages the low cost of organic membranes and the high permeability, selectivity, and stability of inorganic materials. Currently, there are various hybrid matrix membranes synthesized using different inorganic materials, such as carbon nanotubes, carbon molecular sieves, zeolite molecular sieves, and MOFs [47]. Jiangnan Wang et al. [53] used the MOF material Zeolitic Imidazolate Framework-8 (ZIF-8) to synthesize a mixed matrix membrane and found that it has excellent CO_2 separation performance and good selectivity. Related studies have also found that enhancing the interaction between the polymer matrix and the filler helps alleviate physical aging and plasticization phenomena [47]. Although mixed matrix membranes can improve CO_2 separation performance and selectivity, problems such as agglomeration, sedimentation, and poor dispersion of fillers during the preparation process limit their further application [52].

Membrane-based CO_2 capture technology offers advantages such as low cost, ease of operation, low energy consumption, and modularity [46,48]. Compared with traditional amine chemical absorption technology, it does not cause corrosion or require the handling of harmful solvents, thereby reducing the environmental impact caused by solvents and their by-products. Polymers are widely used as membrane materials, but their application in separation processes is constrained by trade-off effects. Hybrid matrix membranes can effectively improve CO_2 separation performance and selectivity, but their preparation process still poses challenges. Therefore, it is necessary to further explore advanced gas separation

membrane materials to prepare hybrid matrix membranes with stable performance and high selectivity.

2.4. Emerging Carbon Capture Technologies

(a) Cryogenic technology

Cryogenic technology is a physical capture method that separates CO_2 gas from flue gas by utilizing its different condensation and sublimation characteristics compared to other flue gas components. Depending on the type of phase change, it can be divided into liquefaction capture and sublimation frost capture [54]. The cryogenic process is shown in Figure 5. The flue gas is continuously cooled, causing CO_2 to separate from the flue gas in liquid or solid form, while the nitrogen-rich flue gas is emitted into the atmosphere or used for cooling water [55]. Since this method employs low-temperature condensation separation, it does not introduce additional chemical reagents, thereby avoiding the byproduct pollution and equipment corrosion issues associated with chemical absorption processes [56]. Additionally, this technology achieves high CO_2 purity (99.99%) and recovery rates (99.99%), making it a carbon capture technology with significant potential and practical value [13,56,57].

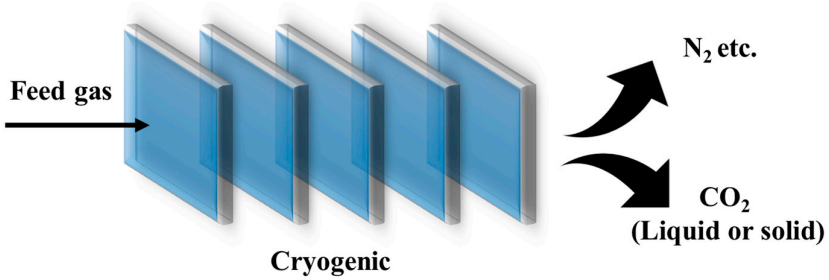


Figure 5. Cryogenic process diagram [58,59].

However, the application of low-temperature technology in the CO_2 capture process presents certain challenges. Industrial flue gas typically contains gases such as SO_2, NOx, and H_2O, which can interfere with the CO_2 cooling process and lead to equipment corrosion and blockages [60]. In addition, cryogenic technology is limited in its widespread application due to issues such as incomplete specific phase change mechanisms and the high economic costs associated with creating cryogenic conditions [19,54,56,57].

(b) Calcium looping

The calcium cycle process captures CO_2 using CaO at high temperatures, as shown in Figure 6. Due to the abundance, low cost, and environmental friendliness of its raw materials (such as limestone and dolomite) and its synergistic effects with other industrial processes (such as the cement industry), the calcium cycle process has gained widespread recognition in the field of CCUS technology [61–63]. The process consists of two circulating fluidized beds, named the carbonizer and the calciner [64]. CaO circulates between the two reactors. In the carbonation reactor, CaO reacts with CO_2 in the flue gas to form $CaCO_3$. The $CaCO_3$ is then calcined in the calciner at a higher temperature to regenerate CaO and produce high-concentration CO_2. The regenerated CaO recycles back into the carbonation reactor, while the concentrated CO_2 can be stored and utilized. The carbonization reaction occurs at high temperatures and releases heat, enabling effective heat recovery and reducing the energy and economic costs of the carbon capture process [61].

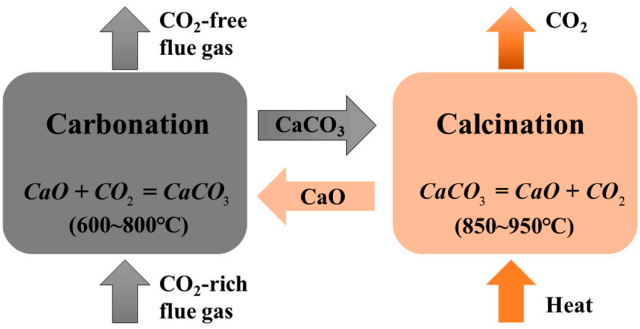


Figure 6. Calcium looping process diagram [65].

The calcium looping process has advantages of using environmentally friendly materials, low energy consumption, and synergistic effects with other industrial processes that require CaO. But as the number of cycles increases, CaO gradually sinter, reducing the effective surface area available for reacting with CO_2 and decreasing the gas–solid reaction rate, thereby lowering the CO_2 capture efficiency [64]. Additionally, collisions between particles and the reactor cause CaO wear, which further affects the reaction rate. These issues slow down its industrial application [62].

(c) Chemical looping combustion

Chemical looping combustion (CLC) is a promising CO_2 capture technology that can achieve nearly 100% capture efficiency while ensuring low energy consumption [66]. The CLC system consists of two reactors: a fuel reactor (FR) and an air reactor (AR), as shown in Figure 7. Air in the system does not come into direct contact with fuel, but rather oxygen is transferred between two reactors [67]. In the air reactor, oxygen in the air reacts chemically with the oxygen carrier, causing it to oxidize. At the same time, nitrogen, residual oxygen, and other inert gases are expelled from the reactor. The oxidized oxygen carrier then enters the fuel reactor, where it undergoes a reduction reaction with the fuel, converting the oxygen carrier into metal or a lower oxidation state [19]. During this reaction, the oxygen carrier releases oxygen and reacts with the fuel, producing water and CO_2 as the main reaction products [68]. Through further combustion with pure oxygen, the products of incomplete combustion are further reduced. After compression and condensation, almost pure CO_2 can be obtained [66].

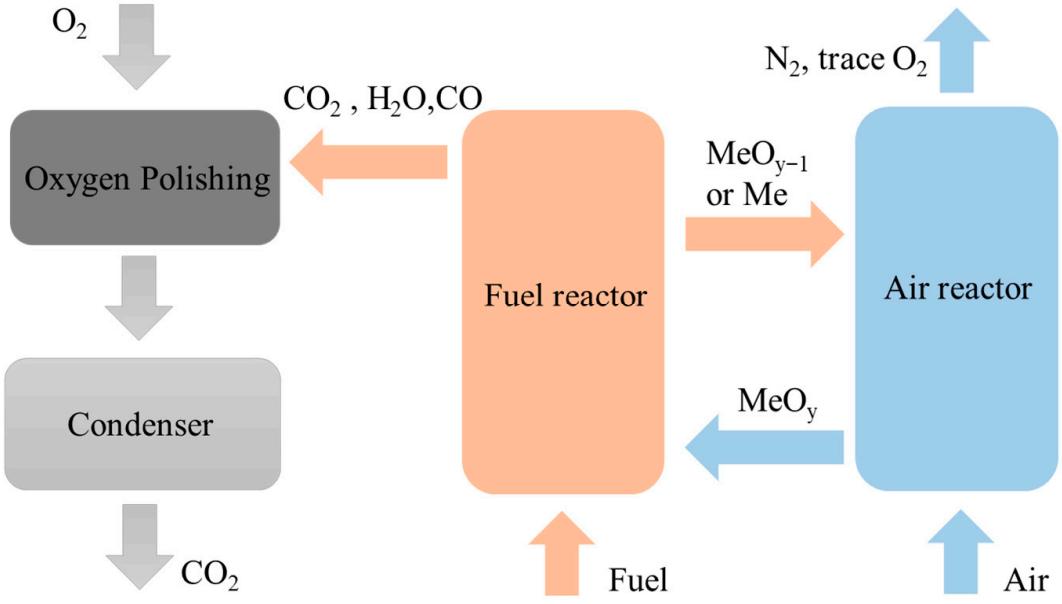


Figure 7. CLC reaction process [19].

It avoids mixing CO_2 from fuel combustion with nitrogen in the air, cutting down on the high energy costs of capturing gases later [69,70]. Additionally, since the fuel does not burn directly in the air within the reactor and the oxygen carrier is reoxidized at a lower temperature in the air, NOx production is reduced [60]. there are still some challenges to the widespread application of this technology, particularly because the oxygen carrier circulates continuously within the system, leading to a decrease in oxygen carrier loading and reaction rates [71].

2.5. Summary

The substantial CO_2 emissions generated during industrial production processes require control through carbon capture technologies. The large-scale industrial application of current carbon capture technologies is constrained by technical maturity and the costs associated with construction and operation. Absorption technology is highly mature and commercially deployed, offering high absorption rates and capacities. However, its regeneration energy consumption is relatively high and requires further reduction to lower operating costs. Adsorption technology features low regeneration energy consumption and no corrosion issues. Yet, its CO_2 selectivity and gas–liquid mass transfer adsorption rates are lower than those of absorption technology, and high-efficiency adsorbents are also costly. Membrane separation technology operates with low energy consumption and requires no chemical additives. However, its technological maturity is insufficient, and stability is poor. Cryogenic technology can produce high-purity CO_2, but it requires cooling flue gas to extremely low temperatures, resulting in high operating costs. Calcium looping and CLC technologies have low operating costs and require no additional energy input, but they suffer from equipment wear and tear, and their CO_2 capture efficiency needs improvement. In summary, absorption technology currently holds a significant advantage, but its regeneration energy consumption must be further reduced to lower operating costs.

The advantages and disadvantages of different carbon capture technologies are shown in Table 1.

Table 1. Comparison of various carbon capture technologies [1,19,72].

Method	Advantages	Disadvantages/Challenges
Absorption	Most mature technology Fast absorption rate Simple, suitable for low CO_2 partial pressure environments	High regeneration energy consumption Equipment corrosion Absorbent volatilization Environmental impact caused by solvent degradation
Adsorption	Easy to use and maintain Adsorbents are reusable Low regeneration energy consumption No corrosion issues	Low CO_2 selectivity and low separation efficiency High cost of high-efficiency adsorbents Adsorbent wear, resulting in poor durability
Membrane separation technology	Low energy consumption during operation Compact equipment, modular operation Not necessary to add other chemicals Simple process, easy maintenance	Low processing capacity, poor stability, and difficulty in maintaining long-term operating performance Blockages caused by impurities in the airflow Low technical maturity
Cryogenic technology	No chemical reagents required Excellent CO_2 purity Suitable for high CO_2 concentrations	High operating costs Not suitable for low CO_2 levels Moisture must be removed in advance
Calcium looping	Low raw material prices Environmentally friendly	Adsorption agent multiple cycles lead to sintering problems, affecting CO_2 absorption Equipment wear issues
Chemical looping combustion	Low gas separation costs No additional energy input required System energy efficiency	Insufficient stability of oxidation carriers Not yet industrialized Equipment wear issues

3. Low-Energy Consumption Recycling Technology Research

Currently, the most widely used industrial capture technology is amine-based chemical absorption, which is mainly due to its advantages of fast reaction speed and large absorption capacity. In addition, it can be integrated with existing production equipment, making it easy for existing companies to adopt based on carbon emission reduction needs [30]. However, in practical application, the regeneration process of amine solvents consumes a large amount of energy. For the 30 wt% MEA benchmark solvent, its regeneration energy consumption reaches 3.80 GJ/t CO_2, accounting for 57% to 70% of total energy demand, which to a certain extent increases the energy consumption and CO_2 treatment costs of enterprises [73,74]. Therefore, many scholars have conducted research on reducing the energy consumption of CO_2 regeneration in the chemical absorption process [35,74,75].

3.1. Absorbent Optimization

Absorbent optimization can significantly reduce regeneration energy consumption, thereby reducing regeneration costs. The energy consumption for amine solvent regeneration mainly includes the desorption heat of reaction products (urea, bicarbonate, carbonate), the sensible heat of heating the rich amine solution to the desorption temperature, and the vaporization heat of the solvent [74]. The regeneration process of traditional water-based amine absorbents (such as water-based MEA) not only causes problems such as amine degradation and equipment corrosion, but also results in more than 70% of the water vaporizing into steam, thereby increasing the energy consumption of the regeneration process [35,76]. Therefore, in recent related studies, scholars have optimized the development of new absorbents or mixed different amine solvents to reduce the energy consumption of the desorption process.

Tert-amines have been widely studied due to their high theoretical CO_2 loading capacity and low regeneration energy consumption. Sudkanueng Singto et al. [77] synthesized 5 new tertiary amines and found that at 363 K, the regeneration rate of 2 mol/L 4-(dibutylamino)-2-butanol (DBAB) was more than twice that of MDEA, and the regeneration energy consumption was 29.8% lower than that of MDEA. While tertiary amines lack N-H bonds and cannot react directly with CO_2, their aqueous solutions promote CO_2 hydrolysis while acting as proton acceptors to form protonated amines and generate carbonates. It is not the same as primary or secondary amines, and the reaction heat is also lower, which means that the energy consumption for regeneration during desorption is also lower [78]. Although the synthesis of new tertiary amines can significantly reduce regeneration energy consumption, their reaction rate with CO_2 is relatively slow, making them unsuitable for use alone in post-combustion CO_2 capture [79]. Researchers have therefore proposed investigating the possibility of using mixed amines [35,80].

Mixed amine solutions combine the advantages of different types of amines, can simultaneously meet various requirements for CO_2 absorption and desorption, and have better capture and regeneration effects than single amines, which are gradually being widely used [35,80]. By mixing 2-amino-2-methyl-1-propanol (AMP) with 2- (dimethylamino)ethanol (DMAE) in a 1:1 ratio, it exhibited high CO_2 solubility (0.56 mol CO_2/mol amine) and low regeneration energy consumption (at 363 K, regeneration heat load of 53.81 kJ/mol CO_2) [81]. The regeneration energy consumption is 72.4% lower than that of MEA at the same concentration. Since AMP and DMAE are steric amines, they mainly generate bicarbonates after reacting with CO_2, resulting in low regeneration heat load [82,83]. In addition to binary mixtures, Chikezie Nwaoha et al. [84] mixed AMP, piperazine (PZ), and MEA to form a ternary solvent, which had 42.9% lower regeneration energy consumption than MEA at 363K. Besides saving energy during regeneration, the absorption rate of the mixed amine solution system is also improved. Related research shows that the absorption rate of the mixed amine solution system is higher than the

sum of the absorption rates of the tertiary amine and primary amine systems alone. The reason is that tertiary amines compete with protonated primary amines for protons, allowing more primary amines to react with CO_2 [85].

Poor water/non-water-based absorbents are widely studied because they can reduce the high energy consumption caused by the high specific heat capacity of water-based amine absorbents during regeneration [86,87]. Non-aqueous absorbents are composed of amines and organic solvents, and have low corrosivity, low degradability, and low regeneration energy consumption [88]. Replacing water with organic solvents can direct the products of the reaction between CO_2 and amines toward unstable carbonate compounds, thereby reducing the temperature and energy consumption of the regeneration process [87,89]. Hui Guo et al. [90] replaced water with glycol ethers when mixing with MEA, finding that this significantly reduced thermal load, approximately 55% lower than MEA aqueous solutions. Lv Bihong et al. [88] mixed AMP with 2-(2-aminoethylamino) ethanol (2-(2-aminoethylamino)ethanol, AEEA) and N-methyl pyrrolidone (NMP) to form a non-aqueous absorbent. At 393.15 K, the regeneration thermal load was 91.96 kJ/mol CO_2, which was only half that of a 30 wt% water-based MEA absorbent. Related studies have analyzed that, during the initial stage of the reaction, the primary product is urethane. As the CO_2 loading increases, under the presence of small amounts of water or ethanol, part of the urethane undergoes hydrolysis to form carbonates [88,91]. This phenomenon enables the water-poor/non-aqueous-based absorbent to not only reduce the vaporization heat of the aqueous-based absorbent but also lower the desorption heat of the reaction products, thereby reducing the energy consumption of the system during the regenerative process of the absorbent.

Ionic liquids (ILs) are liquid at room temperature and exhibit low volatility, high thermal stability, high CO_2 solubility, and easily adjustable physicochemical properties, making them promising green solvents for CO_2 capture [92,93]. They are composed of organic cations and anions, and their physical and chemical properties can be altered by modifying the ions or functional groups in the solvent. It can then be designed to enhance its CO_2 absorption rate, capacity, and reduce CO_2 regeneration energy consumption [92,94]. Traditional ILs can selectively capture CO_2 through physical absorption in industrial gas separation processes [93]. However, their CO_2 absorption capacity is not suitable for industrial flue gas CO_2 capture at low pressures [95]. Task-specific ionic liquids (TSIL) are based on traditional ILs with specific functional groups (such as amine groups) introduced to enhance CO_2 absorption capacity [96]. Yingying Zhang et al. [97] screened 76 ionic liquids based on theoretical CO_2 absorption capacity and regeneration heat load. Among them, 1-hexyl-3-methylpyridinium bis(trifluoromethylsulfonyl)imide ([Hmpy][NTf_2]) exhibited the lowest regeneration energy consumption at 323 K, with a value of 44.604 kJ/mol CO_2, which is approximately 24% of that of a 30 wt% MEA solution. In addition to introducing other functional groups, ILs can also be mixed with water, amines, or other compounds to improve their CO_2 capture capacity [93]. Lingdi Cao et al. [94] mixed 1-butyl-3-methylimidazolium nitrate ([Bmim][NO_3]), MEA, and water in a mass ratio of 1:3:6 and found that although the addition of ILs slightly reduced the CO_2 loading, the regeneration energy consumption of the mixture was reduced. Yang Lei et al. [98] customized a 1-methylpyridine trifluoroacetic acid ([C_1Py][CF_3COO])-ethanol mixed solvent and simulated the flue gas of a 600-megawatt coal-fired power plant. They found that the mixed solvent achieved a significant energy saving effect of 72.7% compared to MEA. TSIL's synthesis and purification involve multiple steps, and its increased viscosity and high production costs limit its industrial application [96,99].

Developing new amine absorbents or mixed amine solvents can significantly reduce regeneration energy consumption. Water-based amine absorbents require high vaporization

heat during regeneration, so water-poor/non-aqueous absorbents have been developed to further reduce regeneration energy consumption. In addition, ILs have been extensively studied due to their high CO_2 solubility, low volatility, and easily adjustable physical and chemical properties. However, while reducing regeneration energy consumption, the viscosity of the absorbent often increases, leading to a decrease in absorption rate. Therefore, further research is needed on the corrosion resistance, absorption rate, and economic feasibility of new absorbents.

3.2. Adding Catalysts or Other Materials

Catalytic regeneration of CO_2 amine solutions can improve desorption performance, lower desorption temperatures, and accelerate desorption rates, thereby reducing the thermal load of CO_2 regeneration [100]. Currently, commonly used catalysts include metal oxides [101], zeolite molecular sieves [100,102], and MOF-based catalysts [103,104]. Yanni Guo et al. [101] prepared aluminum-modified SAPO-34 composite catalysts using the impregnation method, and reduced the energy consumption of CO_2-rich amine solution regeneration by loading different mass ratios of Al_2O_3. It was found that at 361 K, the catalyst performed best when loaded with 15 wt% Al_2O_3, with a 78.4% increase in CO_2 desorption rate and a 37% reduction in regeneration heat load. Zhan Tan et al. [105] synthesized two catalysts (1/2-SnO_2/ATP and 1/4-SnO_2/ATP) using the precipitation-impregnation method, with attapulgite (ATP) as the carrier and weight ratios of $SnCl_2 \cdot 6H_2O$ to ATP of 1:2 and 1:4, respectively. At 361 K, the desorption rate of 1/2-SnO_2/ATP increased by 265%, and the regeneration heat load decreased by approximately 52%. Through mechanistic studies, it was found that the enhancement of MEA regeneration depends on Brønsted acid sites (BAS) and Lewis acid sites (LAS) on the catalyst. The catalyst provides acid sites that transfer protons to the urethane group, while the conjugate base of the acid site acts as a proton acceptor to accelerate the deprotonation process of protonated MEA, thereby reducing the high energy consumption associated with proton transfer [106].

Zeolite molecular sieves are often used as catalysts or carriers due to their large specific surface area and good thermal stability [102]. Gwan Hong Min et al. [100] used mesoporous silica SBA-15 as a carrier and loaded it with NiO to study its desorption heat load in a CO_2-rich MEA solution at 86 °C. They found that SBA-15 loaded with 10 wt% NiO could reduce the desorption heat load by 19.9%. The composite catalyst SO_4^{2-}/ZrO_2/SBA-15, also using SBA-15 as the carrier, reduced regeneration energy consumption by up to 26.5% compared to the reference aqueous MEA solution at 370.15 K [107]. Xitong Yang et al. [108] synthesized MnOOH/HZSM-5 catalyst by loading MnOOH onto HZSM-5. It takes full advantage of the acidity of HZSM-5 and the synergistic ability of MnOOH for proton transfer, thereby promoting the process of protonated amine regeneration. When the catalyst concentration was 0.2 wt% in the amine solution, the regeneration thermal load was reduced by 31.8%.

MOFs have a high specific surface area, adjustable pore size, and diverse structures, allowing specific functional groups to be incorporated to meet functional requirements, thereby improving CO_2 capture and regeneration capabilities [39]. It is a porous material composed of metal ions or metal clusters and organic ligands. Applying it to the desorption process has been found to increase the CO_2 desorption rate [103]. ZIF-8 and Zeolitic Imidazolate Framework-67 (ZIF-67) materials formed by the coordination of metal ions with dimethylimidazole are widely used as amine solution regeneration carrier materials due to their high thermal stability, adjustable pore size, and broader functionality [104]. Muhammad Waseem et al. [109] loaded MoO_3 onto ZIF-67 and further treated it with phosphotungstic acid to regulate the acidic sites of the catalyst. Under conditions where only 0.1 wt% of the catalyst was added as MEA, the regeneration heat load was reduced

by 32% compared to the reference solution. Characterization analysis revealed that the activation by phosphotungstic acid further enriched the LAS and BAS sites on the MoO_3 surface. The synergistic effect of these sites significantly reduced the thermal energy required for urethane decomposition and accelerated the CO_2 desorption rate.

Catalysts primarily accelerate proton transfer processes by providing acidic sites, which reduces regeneration energy consumption and accelerates desorption rates. Since amine solutions are primarily alkaline, this results in a lack of proton participation during the decomposition of urethanes. The addition of a catalyst provides more acidic sites for CO_2-rich amine solutions, accelerating the deprotonation of protonated amines and thereby reducing the high energy consumption required for the proton transfer process. However, catalysts face issues such as insufficient surface area, reduced activity, and agglomeration during operation, necessitating further exploration.

3.3. Technology Enhancement

Besides just lowering the heat load, a lot of research is looking at how to modify process equipment to cut down on regeneration energy use or overall carbon capture costs. Traditional tower-based capture systems have been studied a lot, and there has been a bunch of research on changing the reaction conditions in the system or adding different equipment for absorption and desorption [110]. In the context of process optimization, many studies utilize process simulators to simulate and determine optimal operating conditions [111]. Se-Young Oh et al. [110] simulated traditional amine-based CO_2 capture configurations and 4 different types of modified structures using the UniSim® process simulator. They found that flue gas separation alone could reduce total energy consumption by 7.4% compared to the baseline process. Zhiwei Zhang et al. [112] optimized the scrubbing columns of the absorption and desorption towers, which could further reduce thermal load and capture costs. New process equipment has also been proposed to optimize the high energy consumption of the regeneration process. To address the high energy consumption required for solvent regeneration at the reboiler during desorption, Jaeheum Jung et al. [111] proposed a new desorption configuration, namely a combination of rich vapor recompression (RVR) and cold solvent split (CSS). RVR is a newly developed device to minimize preheating energy losses caused by cold solvent splitting. Cold solvent segmentation eliminates the reflux ratio in the aspirator. This combination improves RVR's ability to evaporate cold solvents in heat exchangers, reducing the heat demand of the reboiler by 20%. Won-Hee Lee et al. [113] developed a process for CO_2 capture utilizing an absorption tower and subsequent absorbent regeneration via reverse electrodialysis (RED). This system achieves energy and absorbent recovery during the desorption stage through RED. However, for primary and secondary amines, carbamates react with H_2O as intermediate products through the ion exchange membrane of RED, and are replaced by amines and protonated amines, resulting in absorbent loss. Because tertiary amines do not produce charged intermediate products, they will not cause the loss of absorbents during the regeneration process, and the regeneration efficiency can reach 99.96%, which is more suitable for the application of this system. Therefore, selecting the optimal absorbent for the system can significantly save energy and have a good regeneration effect.

Waste heat utilization and new types of heat pumps are being researched to reduce the energy consumption of CO_2 capture systems. Te Tu et al. [114] designed a novel CO_2 regeneration process that combines gas-assisted desorption with waste heat recovery from the desorption gas. it enhances the driving force for CO_2 regeneration by introducing auxiliary gas into the bottom or side of the desorption tower and utilizing the waste heat from the desorption gas (primarily water vapor). Compared to traditional thermal regeneration processes, the new regeneration process can reduce the thermal load of the

regenerator by 7.9%. However, since auxiliary gas must be introduced into the system, there is still the issue of separating it from the CO_2 gas. Therefore, it still requires some time before this process can be applied in practice. Ting Lei et al. [115] developed a novel heat exchanger to reduce efficiency losses. The cooling heat from flue gas, the steam at the top of the desorber, the condensate from the reboiler, and the cooling heat from compressed CO_2 are recovered to reheat the heat exchanger, which is then used for solvent regeneration. Compared to traditional carbon capture processes, the energy consumption for regeneration was reduced by 18.03%.

In terms of reducing regenerative energy consumption, researchers have achieved certain results through the renovation of traditional process equipment, the development of new equipment, and the utilization of waste heat and new heat pump applications, such as reducing total energy consumption and regenerator heat load; nevertheless, some new processes face practical application challenges such as gas separation, and further research and optimization are needed in the future to achieve the widespread application of efficient and economical carbon capture technology.

3.4. Chemical Desorption

Chemical desorption, also known as CO_2 mineralization, uses inexpensive calcium-based compounds (such as CaO [116], $CaCl_2$ [117], and $Ca(OH)_2$ [118]) to react with HCO_3^- in alcoholamine-rich liquid at room temperature to form carbonate precipitates. Protonated amines react with alkalis in calcium-based compounds to complete regeneration. Besides calcium-based compounds, some researchers have also studied magnesium-based compounds [119,120]. It simulates the natural weathering process of rocks, where CO_2 dissolves in the atmosphere to form carbonic acid, which reacts with alkaline minerals to produce carbonates, and can permanently and safely capture and store CO_2 [116,121]. Long Ji et al. [116] developed an integrated CO_2 absorption-mineralization process in which the amine absorbent is regenerated chemically rather than by conventional thermal regeneration, significantly reducing regeneration energy consumption. Furthermore, the resulting $CaCO_3$ is a non-toxic and stable compound that can be widely used as a filler in paper, rubber, and paint [122].

Chemical desorption can significantly reduce regeneration energy consumption and do not require further treatment of CO_2. Weifeng Zhang et al. [118] studied the desorption rate and regeneration energy consumption of 5 CO_2-rich solutions, including MEA and MDEA, by adding $Ca(OH)_2$. Under optimal reaction conditions, the MEA solution exhibited the highest desorption rate of 85.31%, and the MEA-poor solution still had excellent absorption capacity after multiple cycles. Compared with thermal desorption, chemical desorption can be carried out at a lower temperature (40 °C), and the energy consumption for regeneration is only 21.28% of the thermal desorption. Long Ji et al. [116] added CaO to 5 common CO_2-rich amine solutions and found that PZ exhibited the highest regeneration efficiency of 91%. Compared with traditional thermal desorption, chemical desorption does not require equipment for further treatment of regenerated CO_2, such as desorbers, heat exchangers, and CO_2 compressors, which significantly reduces equipment costs and operating costs.

In order to further reduce costs, many scholars have used industrial waste materials such as incineration fly ash and coal ash to chemically desorb CO_2-rich amine solutions [116,123,124]. Long Ji et al. [116] added coal ash to a CO_2-rich PZ solution and found that PZ undergoes regeneration after the reaction, but its regeneration efficiency is lower than that of CaO solution with the same calcium dosage. It is mainly due to the high heterogeneity of coal ash, which results in a lower theoretical CO_2 loading capacity. Yan Wang et al. [125] used semi-dry desulfurization slag to mineralize 4 typical CO_2-rich amine solutions, with AMP showing the highest desorption efficiency of 98%. Furthermore, chemical desorption using semi-dry

desulfurization slag resulted in lower desorption energy consumption and CO_2 capture costs than thermal desorption. Although the use of industrial waste for CO_2 mineralization helps reduce CO_2 emissions and promote the comprehensive utilization of industrial waste, its large-scale application still faces issues such as low mineralization efficiency and insufficient mass and heat transfer [124].

Compared with thermal desorption, chemical desorption can directly sequester CO_2 and significantly reduce regeneration energy consumption, equipment and operating costs. The $CaCO_3$ generated by the reaction also has certain commercial value. In addition, in order to further reduce the cost of desorbents, industrial waste can be used for CO_2 regeneration. However, its large-scale application still faces problems such as low mineralization efficiency and insufficient mass and heat transfer. In the future, further in-depth research on its reaction kinetics is needed.

3.5. Summary

Traditional amine-based absorbents suffer from high regeneration energy consumption and high volatility issues. Therefore, researchers have analyzed CO_2 regeneration energy consumption and sought to reduce it by lowering desorption heat or vaporization heat. This paper summarizes the methods used in recent years to reduce regeneration energy consumption, including adsorbent optimization, adding catalysts or other materials, technology enhancement, and chemical desorption. The advantages and disadvantages of different methods are summarized in Table 2. The high energy consumption during regeneration primarily stems from the regeneration of the CO_2-rich absorbent—a 30 wt% MEA solution (benchmark solvent). Therefore, researchers first focused on optimizing the absorbent. This optimization is achieved by simultaneously or individually reducing the desorption heat and vaporization heat, which can significantly lower regeneration energy consumption. However, other issues associated with changing the absorbent must also be considered, including the high viscosity of saturated solvents, reduced absorption rates, and concerns regarding corrosion and thermal stability. Rich-amine regeneration is also a chemical reaction process; it can be optimized by adding catalysts or other materials to reduce regeneration energy consumption and temperature. Common issues with catalysts, such as insufficient surface area, deactivation, and agglomeration, require further resolution. Technology enhancement involves maximizing utilization of internal waste heat to reduce additional energy demands on the regeneration system. This requires modifying existing processes to optimize waste heat utilization. Consequently, it is more suitable for facilities not yet equipped with carbon capture units, where waste heat utilization modifications can be incorporated during design to save construction costs. Chemical desorption significantly reduces regeneration energy consumption while saving equipment costs and operational expenses. However, it necessitates continuous calcium source replenishment. Additionally, the disposal of generated $CaCO_3$ after regeneration—including storage and transportation—requires thorough consideration. In summary, by optimizing regeneration energy consumption, CO_2 regeneration energy consumption can be significantly reduced. However, in practical applications, factors such as actual flue gas conditions, regeneration temperature, and regeneration costs must be fully considered.

Table 2. Advantages and disadvantages of different low-energy regeneration methods.

Method	Advantages	Disadvantages	Regeneration Energy Consumption (GJ/t CO_2)	Reduction in Regeneration Energy Consumption Compared to MEA (%)	References
Absorbent Optimization	1. Reduces regeneration energy consumption by lowering desorption heat or vaporization heat 2. Fast reaction rate 3. Mature technology 4. Low corrosion	1. Absorption of CO_2 increases viscosity, affecting reaction rate. 2. Poor thermal stability.	1.01~2.85	25~75%	[35,87,126]
Adding catalysts or other materials	1. Reduces regeneration energy consumption by lowering desorption heat 2. Fast desorption rate 3. Desorption can occur at lower temperatures	Catalysts face issues such as deactivation and agglomeration.	2.28~2.85	25~40%	[105,127]
Technology enhancement	1. Make full use of system waste heat 2. Reduce total energy consumption	1. Need to make certain modifications to existing processes 2. Gas separation issues	3.05~3.60	5~20%	[110,114]
Chemical desorption	1. Significantly reduce renewable energy consumption 2. Achieve CO_2 sequestration 3. Save equipment costs and operating costs	1. Low mineralization efficiency 2. Insufficient mass and heat transfer 3. Need for constant supply of calcium source	-	No regeneration required	[118,120,124]

4. Iron and Steel Industry Carbon Capture Development

Iron and steel production heavily relies on fossil fuels to generate heat and act as a reducing agent to convert iron ore into iron, making it one of the world's largest industrial sources of CO_2 emissions [22]. Over 70% of steel production relies on the BF-BOF process. Given that steel production facilities typically have a long service life, existing plants are unlikely to be replaced by new technologies, and achieving industry-wide emissions reduction targets through measures such as improving production systems alone is not feasible [24]. Therefore, implementing carbon capture technology is the only viable method for achieving large-scale carbon emissions reductions in the steel industry. This section analyzes the current state of research and commercial application of carbon capture technologies in the steel industry.

The feasibility of applying different combustion carbon capture technologies in the steel industry has been studied. Navid Khallaghi et al. [128] used a model to simulate the technical feasibility of pre-combustion carbon capture using MDEA, finding that the CO_2 capture rate from blast furnace gas ranged from 27% to 65%. Jorge Perpiñán et al. [23] considered using oxygen-enriched air as hot air for the combustion of coke and auxiliary fuels, with part of the exhaust gas recirculated back into the furnace. However, this may affect the reduction of iron oxides, and the high costs of modifying the blast furnace and pipelines limit the application of oxy-fuel combustion technology. Both pre-combustion and oxy-fuel combustion require modifications to existing production equipment or pipelines, which may disrupt normal production operations. In contrast, post-combustion carbon capture only requires minimal modifications to existing facilities, making it widely studied and applied in the steel industry [129].

Researchers are conducting studies on the application of post-combustion capture technologies such as absorption, adsorption, and membrane separation in the steel industry

to verify the feasibility of these technologies. Yuhang Yang et al. [129] conducted a study on carbon capture using chemical absorption methods at a long-process (BF-BOF) steel plant with an annual crude steel production capacity of 9.7 Mt and CO_2 emissions of 21 Mt/a. Using Aspen Plus v12® software for simulation, they investigated CO_2 capture using MEA absorbents for blast furnace gas (BFG), coke oven gas (COG), Linz-Donawitz process gas (LDG), and lime kiln flue gas (LKG) using MEA absorbent, achieving a maximum annual CO_2 reduction of 7.65 Mt. Mengxiang Fang et al. [130] studied the carbon capture capacity of MDEA and 2-(piperazin-1-yl) ethanamine (AEP) in a laboratory-scale study. They found that the mixed absorbent not only had a higher absorption rate but also had 28.5% lower regeneration energy consumption than MEA. Ying Xie et al. [27] also conducted pilot-scale testing of carbon capture from simulated blast furnace gas using a mixture of MDEA and AEP. After more than 200 h of stable operation, the energy consumption for regenerating the mixed solvent was only 2.47 GJ/t CO_2, which is 34.66% lower than that of MEA solution. This demonstrates the feasibility of chemical absorption for carbon capture in the steel industry. Seokwon Yun et al. [131] conducted an economic assessment of the application of absorption and membrane separation technologies in the steel industry through modeling and simulation using Unisim® and MATLAB®. An increase in CO_2 concentration reduces capture costs, with membrane separation technology showing a greater reduction. Therefore, at higher CO_2 concentrations, membrane separation is more cost-effective and energy-efficient than absorption. Calin-Cristian Cormos [132] evaluated calcium looping and absorption technology for decarbonization in the steel industry and found that calcium looping technology has significant advantages in terms of CO_2 emission reduction capacity and investment costs. In addition, calcium looping has the advantage of requiring fewer modifications to the steel manufacturing process and auxiliary facilities. For solid wastes such as steel slag, Kailun Chen et al. [123] proposed a leaching-mineralization-regeneration process to regenerate solvents with low energy consumption while comprehensively utilizing solid wastes and producing $CaCO_3$, as shown in Figure 8. However, it still requires consideration of multiple factors before achieving true commercial application, as laboratory-scale and demonstration-scale operations often exhibit differences in flue gas composition, reaction temperature, degradation products, and operating conditions [133].

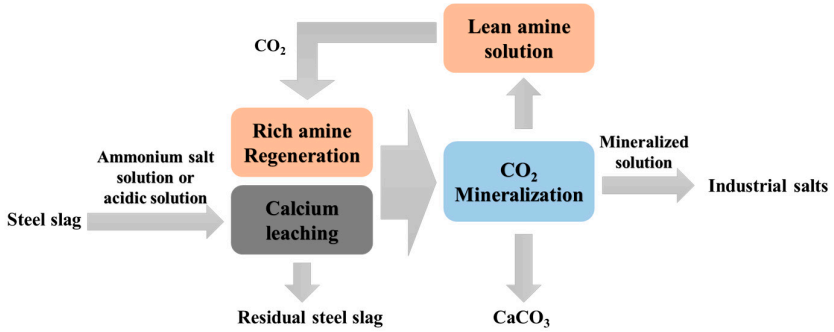


Figure 8. Steel slag leaching-mineralization-regeneration process.

Commercial carbon capture projects in the steel industry are still in developing stages. In 1972, Occidental Terrell in the United States launched its first carbon capture project, which was applied to the natural gas/liquid natural gas industry [19]. However, it was not until 2016 that the first carbon capture project in the steel industry using the MEA amine process and with an annual CO_2 capture capacity of 0.8 Mt was completed and put into operation [25]. In 2019, CO_2 capture technology for lime kiln exhaust gas developed by Chinese steel companies was put into use, and the project has been operating smoothly. Related research has found that using pressure swing adsorption after oxy-fuel combustion

in converters results in lower carbon emissions than chemical absorption [134]. In 2025, China Baotou Iron and Steel's CCUS demonstration project successfully achieved full process integration. Using steel slag (SS) and CO_2 as raw materials, the project produces high-purity negative-carbon calcium carbonate and sintering flux products, effectively utilizing approximately 30,000 t of CO_2 annually. SS is a major byproduct of steel production, characterized by high production volumes and low utilization rates. Its primary components include CaO, SiO_2, Fe_2O_3, and MgO, among others [124]. Shu-Yuan Pan et al. [135] conducted a comprehensive assessment of the potential of mineralization technology to reduce CO_2 emissions, and the results showed that SS mineralization could reduce global CO_2 emissions by 134.85 Mt. The use of steel slag for CO_2 mineralization capture not only solves the problem of steel slag disposal, but also solves the problem of CO_2 emissions and reduces the costs of CO_2 capture, compression, and transportation [136]. Aside from the above-mentioned carbon capture projects currently in operation in the steel industry, there are 5 other projects under construction or evaluation globally [137]. Table 3 shows the current commercial carbon capture application projects in the steel industry.

Table 3. Global carbon capture projects in the steel industry [16,25,137].

Facility Name	Country	Operational Year	Carbon Capture Methods	Capture Capacity (Mtpa CO_2)
ADNOC Al-Reyadah	United Arab Emirates	2016	MEA	0.8
Baotou Steel	China	2025	Steel slag carbonization	0.5
Nucor Steel DRI	United States	2026	_	0.8
Indiana Burns Habor Capture	United States	Under Evaluation	Solvents	2.8
ArcelorMittal Texas (formerly voestalpine Texas)	United States	Under Evaluation	Air Liquide's pressure swing adsorption-assisted Cryocap™ technology	Under Evaluation
ArcelorMittal Sestao CCS	Spain	2025	–	Under Evaluation
Japan Malaysia steel CCS	Japan, Malaysia	Under Evaluation	–	Under Evaluation

In considering the current commercial application of CCUS technology in the steel industry, the cost of carbon capture is a critical factor. Its costs primarily stem from initial construction investment, capture expenses, and transportation and storage fees. Research indicates that a carbon capture project with an annual capture capacity of 0.1 Mt requires an investment of approximately USD 2.7 billion [24]. Operational costs for carbon capture are influenced not only by the capture technology itself but also by capture efficiency and the CO_2 concentration in flue gas. Table 4 summarizes the costs of various carbon capture technologies for steel industry flue gas. The table demonstrates that flue gas CO_2 concentration significantly impacts capture costs. Given the relatively low CO_2 concentration emitted by the steel industry, capture costs are higher compared to those with higher CO_2 concentrations. Therefore, the steel industry should select low-cost capture technologies based on its actual CO_2 emission concentration when implementing carbon capture. In the future, as the energy consumption for regenerating chemical absorption technologies continues to decrease, further reductions in carbon capture costs are anticipated.

Table 4. Cost of carbon capture technology for flue gas in the iron and steel industry [129,132].

Carbon Capture Technology	Materials	CO_2 Concentration	Carbon Capture Efficiency	Carbon Capture Cost (USD/t CO_2)
Absorption	30 wt% MEA	24 vol%	90%	41.92
	30 wt% MEA	6 vol%	90%	65.08
	50 wt% MDEA	-	90.24%	-
	30 wt% MEA	4.8 mol%	90%	73.5
	30 wt% MEA	27.3 mol%	90%	55.3
Membrane	Polyimide membrane	4.8 mol%	90%	271.7
	Polyimide membrane	27.3 mol%	90%	41.7
Calcium looping	Calcium-based sorbent	-	95.44%	-
	Steel slag	-	-	8~104 (No costs for CO_2 transportation or storage)

In summary, the steel industry faces a severe emissions reduction challenge as a high-carbon emitting point source, and carbon capture technology is a feasible method for large-scale emissions reduction. Among various combustion carbon capture technologies, post-combustion carbon capture has been widely studied due to its minimal requirements for retrofitting existing facilities. Post-combustion capture technologies such as absorption, adsorption, and membrane separation have demonstrated feasibility in laboratory and pilot-scale studies, but they remain some distance from commercial application. Currently, commercial carbon capture projects in the steel industry are in the development phase, with some projects already operational, such as the Baotou Steel CCUS Demonstration Project in China, which incorporates steel slag mineralization technology that combines SS disposal with CO_2 emissions reduction. Further efforts are needed to promote the industrialization of these technologies to achieve deep decarbonization in the steel industry.

5. Future Directions and Challenges

5.1. Direction of Technological Innovation

In recent years, the development of high-efficiency, low-regeneration energy consumption absorbents has become a hot topic in the field of carbon capture technology research. In order to further improve absorption rates and absorption capacity while reducing regeneration energy consumption, current approaches primarily involve modifying the composition of the absorbent or developing phase-change absorbents that only regenerate the rich-phase solvent, thereby reducing reaction heat and regeneration heat [138]. Zhen Wang et al. [139] developed a low-viscosity non-aqueous absorbent and introduced MDEA as a regulator and dimethyl sulfoxide (DMSO) as a co-solvent. The study found that the lowest viscosity of the non-aqueous absorbent after CO_2 absorption was 13.12 mPa·s, and the energy consumption for regeneration was also significantly reduced, 53% lower than that of MEA. Yujing Zhang et al. [140] introduced ethylene glycol (EG) into a polyamine/organic ether system prone to precipitation, developing a novel non-aqueous homogeneous absorbent based on polyamine/composite solvents. The study found that the absorbent reduced the sensible and latent heat during desorption, with regeneration energy consumption 42.8% lower than that of MEA. Non-aqueous absorbents can achieve relatively low regeneration energy consumption to a certain extent, but the increase in

viscosity after absorbing CO_2 leads to a decrease in reaction rate. Therefore, it is necessary to develop low-cost, low-viscosity non-aqueous absorbents that can be regenerated with low energy consumption.

Biphasic absorbents have attracted widespread attention due to their ability to significantly reduce regeneration energy consumption [141]. Yanlong Hu et al. [142] developed a novel phase change absorbent by adding n-butanol to MEA aqueous solution. At 120 °C, the regeneration energy consumption of the novel absorbent was approximately 35% lower than that of MEA aqueous solution, and the desorption volume was reduced by approximately 50%. Rui-Qi Jia et al. [143] used the ionic liquid 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim][BF_4]) as a promoter, adding it to AEEA and DEEA aqueous solutions to improve phase separation ability and absorption/desorption performance. The study found that the addition of [Bmim][BF_4] not only enhanced the solvent's CO_2 absorption performance but also reduced regeneration energy consumption by approximately 44% compared to MEA aqueous solutions, achieved by lowering specific heat capacity and reducing water evaporation. Xinling Zhong et al. [144] synthesized a novel non-aqueous ionic liquid biphasic absorbent, which has a regeneration energy consumption approximately 51% lower than that of MEA aqueous solutions. Yao Shen et al. [141] analyzed the relationship between the properties and performance of amines in two-phase solvents and thermal load. They found that the alkalinity of tertiary amines determines the absorption capacity of two-phase solvents, while the hydrophobicity of primary amines primarily affects phase separation behavior. Therefore, two-phase solvents can be tailored by adding appropriate amines to achieve high absorption capacity, good phase separation performance, and low regeneration energy consumption. Sihong Cheng et al. [126] conducted a comprehensive review of the research progress on phase change absorbents. The high viscosity of phase change absorbents requires high regeneration energy consumption during the regeneration process, thereby increasing the capture cost. Thus, choosing a low-viscosity solvent is conducive to further reducing regeneration energy consumption.

Currently, carbon capture technology focuses on developing high-efficiency, low-regeneration energy consumption absorbents. Both non-aqueous absorbents and two-phase absorbents can significantly reduce regeneration energy consumption, but the viscosity increases after absorbing CO_2, which affects the reaction rate and also causes an increase in regeneration energy consumption. Further exploration of new absorbents or additives can be conducted to reduce the viscosity of the rich liquid and promote the transition of experimental research to industrial applications.

5.2. Challenges of Large-Scale Application

Although there are currently a variety of carbon capture technologies available, they are all based on laboratory-scale or system simulations. Emerging technologies need to undergo a series of scaling steps before they can be commercialized, and therefore face many challenges [16]. Primarily, the carbon capture process requires a certain amount of energy consumption, which imposes additional energy and material demands on factories. It increases operating costs for enterprises and also results in additional carbon emissions [26]. Carbon emissions avoided is commonly used as an effective indicator of carbon emission reduction to measure the difference in total carbon emissions released into the atmosphere [26]. Taking the steel industry as an example, the cost of carbon capture using MEA aqueous solutions is 52.6–73.5 USD/t CO_2 [131]. Solomon Aforkoghene Aromada et al. [145] analyzed the costs of CO_2 capture and CO_2 avoidance in the cement industry, with CO_2 capture costs ranging from 62.1 to 69.3 USD/t CO_2, while the costs of avoided CO_2 ranged from 74.3 to 88.9 USD/t CO_2. Therefore, the implementation of carbon capture can actually reduce carbon emission costs for businesses. However, chemical absorption using organic amine solvents can result in energy consumption

as high as 3.7–4.0 GJ/t CO_2 during the regeneration process, leading to an increase in overall carbon capture costs and, consequently, higher production costs for the product [126].

Large-scale application of existing low-energy technologies is currently the main issue. In laboratory research, various types of absorbents have been studied. However, there has been little research on the industrial feasibility of these technologies, and most pilot-scale studies have focused on amine-based absorbents [146]. Yuli Artanto et al. [147] conducted a pilot-scale comparative study of a mixture of AMP and PZ solutions with MEA solutions. They found that when capturing higher concentrations of CO_2, the energy consumption for regenerating the two absorbent liquids was similar. They further found that increasing the concentration of the absorbent increased the reaction rate with CO_2, but the increase in concentration was limited by viscosity or solubility. Markus Rabensteiner et al. [148] investigated the suitability of glycine hydrate as a CO_2 absorption solvent. Using real flue gas from a coal-fired power plant, they analyzed the carbon capture performance of sodium glycine hydrate at different concentrations under industrial conditions. They found that the regeneration energy consumption of 25 wt% sodium glycine hydrate was higher than that of MEA aqueous solution, with energy demand increasing by approximately 40%. In addition to assessing the overall benefits of carbon capture units, various characteristics should also be considered, including corrosiveness, degradation rate, by-products generated during the degradation process, environmental impact, and manufacturing costs [149]. Yi Ye et al. [146] developed a new type of high-load absorbent and conducted pilot-scale research. Through continuous optimization of the absorbent's performance, the minimum regeneration energy consumption was 2.85 GJ/t CO_2. Meanwhile, the low liquid-to-gas ratio demonstrated excellent potential for industrial application. However, it did not analyze the corrosion of the absorbent or the emission of by-products, so it is still some distance away from actual industrial application.

Carbon capture technology still faces challenges in terms of large-scale application. Future research needs to focus on solving the problem of large-scale application of low-energy consumption technology and thoroughly investigate the feasibility of laboratory results on an industrial scale in order to promote the practical industrial application of low-energy consumption carbon capture technology.

5.3. Policy-Driven

Policy intervention can accelerate the implementation of low-energy-consumption regenerative carbon capture projects in a variety of ways. CCUS technology is crucial to achieving carbon neutrality goals. Due to the enormous costs associated with industrial carbon capture, large-scale CCUS projects have progressed slowly. Therefore, it is necessary to drive progress through the implementation of appropriate policies. To encourage high-emission industries to adopt carbon capture technology, various policy incentives have been proposed and implemented globally. These mainly include: financial support, carbon pricing mechanisms (carbon taxes, carbon trading, and cap-and-trade systems), as well as regulatory and standard measures [150]. Countries and regions such as the United States and the United Kingdom have implemented a series of policy incentives, including direct financial support, carbon emission reduction tax credits, and carbon tax reverse incentives, to encourage industrial carbon capture projects [150]. For example, Section 45Q of the U.S. Inflation Reduction Act provides a tax credit of 85 USD/t of permanently stored carbon dioxide, offering financial incentives for businesses to capture and store carbon dioxide emissions [151]. China has also established a "1 + N" policy framework for carbon peaking and carbon neutrality, but CCUS-related policies remain primarily focused on encouragement and guidance, with no fiscal or tax incentives yet in place to support the scaled-up development of the industry. Additionally, current legal and policy frameworks

are not conducive to the further development of CCUS technology [152]. Due to the current lack of CCUS demonstration projects in the steel industry, there is a gap in relevant technical standards, which has hindered technical exchanges between industries. Hence, it is necessary to further improve the legal and policy framework and expand government financial support to accelerate the widespread implementation of CCUS technology.

In the future, the global community should strengthen communication and cooperation in the formulation of CCUS policies, learn from advanced experiences, and establish a more comprehensive and targeted policy framework. On the one hand, investment in the research and development of low-energy carbon capture technologies should be increased to reduce the cost of applying these technologies. On the other hand, unified technical standards and specifications should be established as soon as possible to promote the widespread application of CCUS technologies.

6. Conclusions

Driven by both global sustainable development strategies and carbon neutrality goals, CCUS has become a core approach for reducing industrial carbon emissions and mitigating climate change. This study provides a comprehensive review of carbon dioxide capture technologies. Among these, chemical absorption technology based on amines has been widely researched and adopted due to its advantages of simple process flow, high absorption efficiency, high maturity, and high adaptability. Nevertheless, high regeneration energy consumption increases the cost of carbon capture, limiting its further commercial application. This study analyzes the main advances in current low-energy regeneration technologies. New absorbents have been synthesized to reduce regeneration energy consumption, including novel amines, mixed amine solutions, water-poor/non-aqueous-based absorbents, and ionic liquids. These primarily reduce the thermal load of the regeneration process by lowering the desorption heat and vaporization heat required for regeneration. Catalysts accelerate proton transfer processes by providing acidic sites, thereby reducing regeneration energy consumption and enhancing desorption rates. By retrofitting traditional equipment, developing new equipment, utilizing waste heat, and applying new heat pump technologies, the overall energy consumption of capture technologies can be reduced. However, practical application still faces certain challenges. Chemical desorption involves reacting calcium-based compounds with amine-rich solutions to directly sequester CO_2. It can significantly reduce regeneration energy consumption, save equipment and operational costs, and the generated $CaCO_3$ also has commercial value, offering a new pathway for sustainable development.

As one of the largest industrial sources of carbon emissions, the steel industry can reduce emissions through the implementation of carbon capture technology. Researchers have conducted simulation analyses of various carbon capture technologies for steel industry flue gas. Although these technologies have demonstrated feasibility at the laboratory and pilot scale, they are still some distance from commercialization. Therefore, commercial carbon capture in the global steel industry is still in its developmental stage, with very few operational projects currently in place. In the future, it will be necessary to further develop absorbents with high absorption rates, low regeneration energy consumption, and low costs to promote their large-scale application. At the same time, policy incentives should be used to increase investment in the research and development of low-energy carbon capture technologies, and relevant technical standards and regulations should be established to promote the implementation of CCUS technologies in the steel industry. Hence, it helps the industry achieve a balance between economic and environmental benefits during its low-carbon transition, fully unlocking its potential for sustainable development.

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