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Applications of Carbon Capture Technologies in Steel and Cement Industries

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Abstract: As problems such as the increase in extreme weather, rising sea levels, and social inequality continue to sharpen with the intensifying climate change, changes are demanded. The cement and iron and steel industries are among the major spheres responsible for the rising global temperature. Carbon reduction methods cannot fully solve the problem and help these industries reach carbon-neutral emissions. Therefore, carbon capture (CC) technology is urgently needed. This article introduces the application of pre-combustion carbon capture (PreCCC), post-combustion carbon capture (PostCCC), and oxyfuel combustion carbon capture in the cement industry and the iron and steel industry. Research has shown that oxyfuel combustion is one of the most assuring pathways to reach carbon neutrality in cement plants since problems of temperature management can be solved by recycling part of the fuel gases, and its cost is relatively lower than the other methods. However, PostCCC is a better solution in the iron and steel industries. Although technological innovations in physical absorption and chemical absorption are still needed, PostCCC can mitigate a large portion of steel plants' carbon footprint. Carbon capture intensity can be increased with further technological development in combining PostCCC and oxygen-rich combustion. The combination of different pathways may be a novel hypothesis, but it has a great possibility of alleviating the carbon emission of the industrial sector.

Keywords: Carbon Capture Technology, Cement Industry, Steel Industry, Net Zero Emission.

1. Introduction

Referring to Earth's natural circle of ice age, the Earth was in the cooling phase starting about 5,000 years ago [1]. However, instead of following the natural trend of falling temperature, the global land-ocean temperature has increased by at least 1.1$°C$ since 1880 (the pre-industrial period). The increase in global temperature demonstrates a rise in the number. It indicates serious ecological degradation and societal conflicts, such as increased extreme weather, animal extinctions, economic decline, and inequality between the rich and the poor. One of the most catastrophic effects of global warming is the rise of water levels, mainly due to the melting of ice sheets that contributed to approximately 20.9 ± 2.8 millimeters of sea level rise from 1992 to 2020 [2]. Although the melting of Arctic sea ice is not the main cause of sea level rise, where the molten ice could replace the place of the former ice, it can accelerate climate change and intensify the melting of sea ice. While sea ice is molten, a larger part of the ocean's surface is covered in a darker color, absorbing more heat from the sun, raising the

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global temperature, and causing more ice to melt. The excessive melting of sea ice can lead to habitat loss and local ecologic decline.

While carbon reduction can mitigate the emission of carbon dioxide (CO_2) and climate change, the CO_2 that already appears in the Earth's atmosphere continues to warm the atmosphere due to its long lifespan (hundreds to thousands of years). Moreover, burning fossil fuels is still the largest sector of the global electricity sector, accounting for about two-thirds of the power generated. Power produced by burning fossil fuels has increased by 70% since 2000. The cement industry and the iron and steel plants have continued to be the leading contributors to the industrial sector of climate change. While cheaper energy storage methods are still needed to reach 100% renewable energy-based consumption, carbon capture (CC) is one of the best ways to achieve net zero emissions. Therefore, carbon removal technology, such as CC, is urgently needed to slow climate change.

The cement industry and the iron and steel plants have continued to be the leading contributors to the industrial sector of climate change. While the carbon footprint of the industrial sector is 14.1 Gt or 24% of global emissions in 2019, 2.428 Mt of CO_2 is emitted in cement plants and 1.41t in the iron and steel industry in 2022. Reducing the clinker-to-cement ratio in cement production and applying scrap-charged electric arc furnaces in the steel plant has been the dominant pathway to carbon reduction. However, CC is still immature in both plants. At present, discussions over CC mainly focus on the technical level, which demands more research in the application realm. Therefore, this article introduces the leading CC technologies and focuses on their application in cement, iron, and steel plants.

2. Conventional Technologies for Carbon Capture

Recognizing the significant role of carbon capture technology, scientists have developed three main pathways to capture CO_2: pre-combustion carbon capture (PreCCC), post-combustion carbon capture (PostCCC), and oxygen-rich combustion carbon capture.

PreCCC turns hydrocarbon into hydrogen, extracting the source in fossil fuels to produce CO_2. First, through processes such as steam reforming, hydrocarbon can be decomposed into hydrogen and carbon monoxide under high temperatures and low pressure. Then, impurities, such as nitrogen, argon, and oxygen, could be removed to avoid other pollutant emissions other than CO_2. Furthermore, in order to maximize hydrogen production, carbon monoxide could be reconverted into carbon dioxide with water, producing more hydrogen that can be used as fuel. Finally, carbon dioxide could be separated from hydrogen through physical or chemical absorption. However, due to the higher carbon tax cost, PreCCC is not widely employed in many industries.

Compared to PreCCC, PostCCC and separates CO_2 from the fuel gases after the fossil fuel is burned, which can usually avoid a greater percentage of CO_2 emission. Similarly, CO_2 could be captured in oxygen-rich burning carbon capture after fossil fuel combustion. On the other hand, oxyfuel combustion requires an additional process before the combustion. Almost pure oxygen could be separated from the atmosphere to prevent the production of multiple impurities after the combustion, simplifying the process of carbon segregation in PostCCC.

3. Application of Carbon Capture Technologies in The Cement Industry

3.1. Background of The Cement Industry

As the primary building material, concrete is used to construct buildings, transportation, and infrastructures, making it the second most consumed worldwide after water. However, cement accounts for around 85% to 90% of concrete production and more than 5% of anthropogenic greenhouse gas emissions. Therefore, concrete has become a large contributor to climate change, intensifying the need to reduce carbon emissions through cement production.

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Cement is mainly composed of gypsum and clinker, produced from limestone calcination or the combustion of limestone and other oxides. Unfortunately, CO_2 is a major byproduct of the chemical reaction between limestone and other oxides when limestone is broken down into calcium oxide (CaO) and CO_2. The carbon emission through limestone calcination contributes to around 60% of the cement's carbon footprint. The output of heat and electricity through the combustion of fossil fuels to support concrete production accounts for the other 40% of carbon emissions.

Considering the significant greenhouse emissions through the production of concrete and its rising demand, especially in middle-income and low-income countries, technological innovation is required. While finding alternate fuels and reducing the concentration of clinker can significantly reduce carbon emissions through cement production, a carbon footprint still exists. Therefore, CCS is the best solution for a completely carbon-neutral cement construction industry.

3.2. Oxyfuel Combustion Carbon Capture Technologies

Although the maturation of CCS technology still needs to overcome the obstacle of high cost and more technical innovation, CCS, such as oxyfuel combustion with carbon capture technology, has great opportunity and potential to reduce carbon emissions in the cement industry.

Unlike the traditional power plant, an oxyfuel-combustion-based power station can capture, compress, and store the fuel gas released by burning the fossil fuel in pure oxygen. While untreated air and the fuel gas it produces contain large amounts of nitrogen, the fuel gas produced by oxygen-rich burning has no nitrogen and a high concentration of CO_2, making the compression process more manageable.

Specifically, first, oxygen is purified via methods such as cryogenic air separation, which uses the dissimilar condensation points of oxygen (-183°C) and nitrogen (-196°C) to separate oxygen from other gases. Second, fossil fuel is burned in the 95% to 97% oxygen gas inside a boiler to produce steam and the byproduct – fuel gases with a high concentration of CO_2 and water [3]. Next, the fuel gases are cooled to the liquid phase to remove the water, leaving the gas with an even higher concentration of CO_2. Finally, the CO_2 sequestrated from the fuel gas can be compressed, transported, and stored. However, not all fuel gases go through the complete process and are stored. Around 80% of fuel gases can be recycled and combined with pure oxygen, making up 3% to 5% of the original gas to react with fossil fuels to cool the boiler's temperature [4]. Fossil fuel combustion within pure oxygen can lead to high flame temperatures of up to 4500°F, surpassing the highest temperature traditional boilers can hold. Fortunately, the reaction can happen suitably with a few additional carbon dioxide-rich fuel gases.

Oxyfuel combustion carbon capture also shows significant cost advantages compared to other carbon capture pathways, including PreCCC and PostCCC. While the costliness index of power stations with PreCCC is 29.64 and power plants with PostCCC is 29.04, the costliness index of power stations with oxyfuel combustion carbon capture technology is only 14.34. It also shows economic potential in its average lifetime levelized cost of electricity (LCOF), capital, and investment costs due to its efficiency in removing CO_2 from the fuel gases without the involvement of physical or chemical solvents [5]. Moreover, to increase energy efficiency and overcome the difficulty of energy penalty, second-generation oxyfuel combustion is developed with a heat integration methodology, which increases the net efficiency from 32.91% to 36.42% and decreases the energy penalty from 10.54 to 7.28 efficiency points. Therefore, oxyfuel combustion has shown great potential in the cement industry.

Take the European cement industry as an example, fully employing either first-generation or second-generation can bring the most significant possibility in mitigating climate change (around 80%) when compared to other methods, such as applying RDF or bio-fuel on a larger scale and reducing clinker to clinker-to-cement ratio [6]. Furthermore, due to its particular advantage in that its reaction to produce steam is almost pure oxygen and is accompanied by CCS, oxyfuel combustion produces less air pollution and greenhouse gases, reducing harmful chemicals that enter the Earth's atmosphere [7]. Although problems, such as high energy demand for recycling the fuel gas to manage the temperature in the boiler, still exist, second-generation oxyfuel combustion may be a promising solution to enable fossil fuel to burn in pure oxygen without fuel gas recycling by applying excessive oxygen in the boiler. While the excessive oxygen can be reused in the combustion later, fuel gases no longer need to be recycled, and fewer gases can be required to produce the same amount of steam [8].

3.3. Future of Carbon Capture Technology in The Cement Industry

Recognizing the urgent need to eliminate carbon emissions in the cement industry, the Holcim group plans the Go4ECOPLANET project to reach net zero emissions in the cement industry by capturing and liquifying the CO_2 emitted in the plants. This project is expected to be employed at the Lafarge Cement S.A.'s Kujawy Plant in Poland through the Cryocap™ FG technology.

The Cryocap™ FG technology first achieved carbon segregation with high pressure. Then, the CO_2 was condensed into the liquid at a low temperature. Finally, the liquid carbon dioxide could be removed from other impurities or components, where the CO_2 can be stored and the other compounds can be recycled to produce more fuels or energy.

It is predicted that with the implementation of the Cryocap™ FG technology within Lafarge Cement S.A.'s Kujawy Plant, more than 10 Mt could reduce the carbon footprint of that plant and the carbon emnation of the entire cement industry in Poland can be reduced by 10% [9].

4. Application of Carbon Capture Technologies in the Steel Industry

4.1. Background of the Steel Industry

As a versatile and strong alloy, steel is one of the most essential materials in the world widely used in multiple constructions. While 1762.2Mt of steel was used in 2022, 52% is used for building and infrastructures, 16% for mechanical equipment, 12% for automotive, and the others for metal production, transportation, electric equipment, or domestic appliances. However, it is also a great contributor to climate change.

Steel is an alloy that is mainly composed of iron and other metals with the addition of a few carbons to increase its strength. For instance, mild steel contains 99% iron, and stainless steel (304) includes 70%. Although steel is strong, durable, and highly recyclable, the iron and steel industry accounted for 25% of the global industrial sector and 7% of global net direct greenhouse gas emissions in 2018, which is still a continuously increasing trend [10]. While the carbon footprint of steel production is still increasing, each tonne of steel produced releases around 1.9 tonnes of CO_2 in 2010. In 2022, 1885 million tones of crude steel and 1781 million tones of finished steel were produced, which increased a lot when compared to 1563 million tones of crude steel and 1445 million tonnes of finished steel produced a decade ago.

The production of steel can be mainly separated into three processes: raw material preparation, iron making, and steel making. First, coal is burned without the involvement of oxygen to produce coke, a solid carbon fuel. Then, coke is heated again with iron ore in a blast furnace, where coke reduces the iron ore into molten iron and produces a large amount of CO_2. Finally, impurities, such as sulfur and carbon, are removed from the molten iron to produce steel. Nowadays, there are two main pathways to produce steel: the usage of blast furnace-basic oxygen furnace (BF-BOF) and scrap-charged electric arc furnace (EAF). While BF-BOF uses coke to reduce the iron ore to produce molten iron, EAF applies electricity as a replacement for coke to reduce recycled iron, mitigating the carbon emission of steel production. However, the limited amount of recycled iron restricts the development

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and wider application of EAF. Therefore, applying CC in the blast furnace and coking process becomes crucial to reaching net zero emissions in the iron and steel industry.

4.2. Post-Combustion Carbon Capture Technology

The carbon capture technology can be categorized into three groups: PreCCC, PostCCC, and oxyfuel combustion carbon capture. PostCCC and oxyfuel combustion carbon capture are considered the most promising solution to achieve a carbon-neutral steel industry.

PostCCC refers to segregating CO2 from the fuel gas after the burning process, which usually involves physical and chemical absorption technology.

Physical absorption means directly absorbing CO_2 in the liquid solvent. After dissolving in the high-pressure and low-temperature liquid solvent, CO_2 is separated from the other fuel gases and is further separated from the solvent by flash tanks. The greatest advantage of physical absorption is its relatively low capital and process costs compared to other carbon capture technologies [6]. However, while both thermal management and pressure reduction require lower energy consumption than other operations, a large amount of energy is needed to raise the pressure to compress the original fuel gases. Physical absorption also demands high CO_2 concentration in the fuel gases, which demands the technology to remove the impurities. Moreover, challenges such as high-pressure loss, large equipment size, and complex systems further block the development of physical carbon capture.

Like physical carbon capture, fuel gases must pass through a liquid solvent. However, a chemical reaction happens between CO_2 and other compounds, such as potassium hydroxide (KOH), to selectively separate CO_2 from the other gases, forming carbonates, such as potassium carbonate (K_2CO_3) and water. Following the segregation of CO_2, pure CO_2 can be obtained by replacing the carbonate group with the hydroxide group. For instance, through the reaction between potassium carbonate (K_2CO_3), calcium hydroxide ($Ca(OH)_2$), calcium carbonate ($CaCO_3$), and potassium hydroxide (KOH) are produced. While potassium hydroxide (KOH) can be reused to capture more CO_2, calcium carbonate ($CaCO_3$) can be broken down to produce pure CO_2. However, this process requires large amounts of energy, mainly generated from fossil fuels, such as coal and natural gas, to separate CO_2 from potassium carbonate (K2CO3) and calcium carbonate ($CaCO_3$) at high temperatures. The involvement of fossil fuel combustion leads to carbon dioxide emission, opposing the primary aim of CC.

Nevertheless, PostCCC is a technically realizable method to mitigate climate change and is expected to reduce steel plants' carbon footprint by 40%. Furthermore, combining oxyfuel combustion with PostCCC is a promising pathway to increase carbon capture intensity. Like the oxyfuel combustion in cement plants, pure oxygen can replace the original air in traditional blast furnaces, and part of the fuel gases can be recycled to maintain the combustion temperature. Moreover, recycling fuel gases can even increase the efficiency of coke use.

5. Conclusions

This article introduces the different types of carbon capture technology and discusses its application in the cement and iron industries.

Over the past centuries, climate change has continued to cause serious problems, such as extreme weather and animal and social inequality. More catastrophic disasters may happen, such as rising water levels due to melting ice sheets, if the global temperature keeps increasing. While cement plants and steel plants are the main contributors to the industrial sector of global climate change, carbon reduction processes cannot fully eliminate their carbon footprint, underscoring the significance of implementing carbon capture technology in the cement and iron and steel industries.

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The carbon capture technology can be separated into three categories: pre-combustion carbon CO_2 production by turning hydrocarbon in the fossil fuels into hydrogens. PostCCC separates CO_2 from the fuel gases with absorption. Oxyfuel combustion involves preparing almost pure oxygen before the combustion and treating the CO_2 emitted after the combustion.

Oxyfuel combustion carbon capture is the most promising pathway in the cement industry. It is not only cheaper in cost when compared to PostCCC but also more environmentally friendly. The Go4ECOPLANET project may provide a plausible solution to carbon-neutral cement plants in the future. PostCCC may be a reliable approach to net zero emissions in the iron and steel industry. Despite the unmatured technology in physical and energy consumption in chemical absorption, PostCCC can mitigate the CO_2 emanation of the iron and steel industry at a much larger scale than the other two pathways.

This article introduces the three plausible pathways of carbon capture technologies and analyzes their possibilities and challenges in the cement and iron industries. This article can foster further study and research in the employment of CCS in the industrial sector, alleviating the problem of climate change from one of the major sectors that demands more attention. In conclusion, admitting the absence of real-life application of all three carbon capture technologies in the cement and iron industries, this article lacks direct proof and data analysis from relevant experiments. Therefore, in order to consolidate the hypothetical ways of applying PostCCC and oxyfuel combustion carbon capture in the cement and steel plant, projects, such as the Go4ECOPLANET project, that can unite theory with practice are needed.

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