The Research on CO_2 Capture Technology and Its Practical Feasibility

Yue Zhu
School of Architecture, University of Liverpool, Liverpool, L69 7ZG, U.K.

Keywords: CCS, Carbon Dioxide Capture, Fossil Energy, Feasibility.

Abstract: At a time when greenhouse gases (GHG) are increasing rapidly, carbon dioxide is widely recognized as attended as a significant influencing factor. CCS is an important method to achieve the net-zero carbon target, which is effective in slowing down current global warming and mitigating climate changes, and works as a buffer stage for future fully renewable energy sources' usage. This paper mainly focuses on three means of carbon dioxide capture in Carbon Capture and Storage (CCS), pre-combustion, oxyfuel-combustion, and post-combustion. Their features would be explored through comparative analysis to discuss their applicability in the field of fossil energy. Generally, CO_2 Capture is considered to have great potential for practical application in different power station types. Post-combustion can quickly adapt to existing thermal power plants and effectively reduce high carbon emissions, while pre-combustion can suit new stations and synergize with the development of clean energy, such as hydrogen. Oxyfuel combustion, which is still in the developing phase, could possibly reduce current capture costs significantly along with new materials and technologies developed. Although it is undeniable to develop renewable energy sources and promote the energy transition, fossil fuels will still be widely used to guarantee energy security for decades to come, which makes carbon capture technologies required to be emphasized since they can enable its low-carbon use of energy resources.

1 INTRODUCTION

Since sustainable development has become one of the most critical issues in contemporary society, environmental problems, such as global warming and climate change, are receiving widespread attention. If allowed to deteriorate uncontrollably, they would break the balance of the earth's ecosystem and jeopardize social development. Carbon dioxide is considered to as a major factor in greenhouse gas (GHG) that has been largely released into the atmosphere and led to a worsening situation. Since the natural sources remained relatively stable in the pre-industrial era, the increase in CO2 concentration detected is considered to be mainly of anthropogenic origin, from 280 ppm to 390 ppm till 2010 in the last two centuries (Garnier et al., 2011). It comes from multiple sources, including the combustion of fossil fuels, such as coal, natural gas, or petroleum, as well as oil refineries, and industrial production, such as cement and steel (Dantas et al., 2011). Currently, CO2 is still being emitted at high rates, making scientists estimate that its concentrations will rapidly approach thresholds without appropriate mitigation policies, reaching 500 ppm by 2050 (IPCC, 2005). Therefore, the Intergovernmental Panel on Climate Change (IPCC) strongly suggested increasing emissions reductions and deploying technologies to remove carbon emissions from the current atmosphere, which are indispensable means to limit future temperature increases within 1.5° set in the Paris Climate Agreement.

Currently, in order to stabilize the atmospheric concentration of CO2, various ways in different fields are being developed and practically used, mainly centering on energy conservation, emission reduction efficiency enhancement, and carbon fixation increase. Some key technologies include developing hydrogen and solar energy in energy transitions, energy recovery and waste reuse in transforming industrial processes, and Carbon removal and carbon capture in natural carbon sinks such as forests, oceans, and wetlands (Zhang et al., 2021). Among them, Carbon Capture and Storage (CCS) is an important method of Carbon removal, since it is the only way to realize the low carbon utilization of traditional fossil energy in the transition towards net-zero development (Yao et al., 2024). It is considered a process, mainly

Zhu, Y.
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DOI: 10.5220/0013853400004914

In *Proceedings of the 2nd International Conference on Renewable Energy and Ecosystem (ICREE 2024)*, pages 172-178
ISBN: 978-989-758-776-4

consisting of three steps: the separation of CO2 from industrial and energy-related sources, transportation to a storage location, and long-term isolation from the atmosphere. This means is targeted at the anthropogenic sources, especially the large stationary point sources, and helps to reduce emissions by 80-90% effectively (Holloway, 2007). According to the Global CCS Institute report in 2022, its practical usage is under a positive development trend. Currently, there are 194 large-scale facilities located in different regions of the world, of which 61 are new projects added in 2022; while the CO2 capture capacity increased to 244 million tons per year, reaching a 44% year-on-year growth (Global CCS Institute, 2022).

This research aims to explore different types of CO2 capture technology in CCS and analyze its feasibility relating to power stations. Generally, a brief description will be given at first. Then, the three capture methods will be detailly compared to analyze their advantages and disadvantages. Finally, the feasibility of each type will be discussed binding their characteristic when applied in real projects of power energy.

2 THE PRINCIPLE OF CCS

As mentioned above, CCS is generally made up of three main steps: capture, transportation, and storage (Figure 1), and the different components are currently at varying levels of technological development and application. The basic principles and features are briefly described in this section.

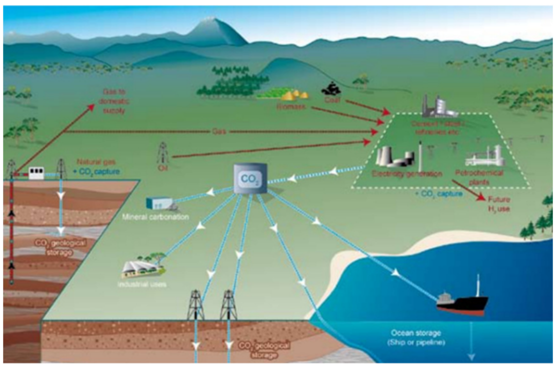

Figure 1: Schematic Diagram of Possible Carbon Capture and Storage Systems (IPCC, 2005).

2.1 Capture

As a first step, capture can remove CO2 emissions at the source before its release, which makes the capture efficiency directly affect the subsequent outcomes. There are three main approaches to capture: pre-combustion, oxyfuel-combustion, and post-combustion. (Details are discussed in the below sector.) Given the cost in practical use, purifying and compression are two procedures required to conduct after capture in order to obtain a high-pressure concentrated liquid for easy transportation and storage.

2.2 Transportation

Since storage methods must meet certain requirements, the captured CO_2 usually needs transportation to reach the selected special locations. The approaches are various, often including pipeline, ship, road, and rail transportation. Among them, pipeline transportation on land is considered the most mature technology in the current market, which has high efficiency and economic advantages, especially in large-scale and long-distance situations (IPCC, 2005). High pressure, typically 10-16 MPa, is needed to avoid convection in the transport pipelines. The IPCC report estimated the cost of a standard pipeline for a distance of 250 km at 1-8 USD/tCO_2 (IPCC, 2005). However, the exact cost is also related to the geographic and environmental characteristics of the pathway.

2.3 Storage

Certain conditions of storage ways or places need to be satisfied, which guarantees CO_2 can be sealed or eliminated for long periods without leaking back into the atmosphere. There are three main means: injection into subsurface geological storage (depleted oil, gas fields, and deep aquifers in porous rock formations), oceanic storage, and solidification in inorganic carbonates through industrial processes. In practice, the suitable storage site is selected based on a combination of factors, mainly including location, geophysical properties, and relationship to densely populated areas. For example, despite the large amount of CO_2 released in the east part of China due to the intensive energy consumption, oceanic storage is a better option since the capacity of the land-based storage is small and easily affected by the dense population distribution (Zhang et al., 2023)

3 THREE MEANS OF THE CARBON DIOXIDE CAPTURE TECHNOLOGY

CO_2 Capture was initially applied in the refining and chemical industries. Now, it is processed maturely in production with relatively low costs and technical difficulty since the emitted carbon dioxide is often in high concentrations and pressures. However, the application in power production requires further exploration, which has much larger energy demands and higher costs but is the largest single category in all stationary CO_2 sources. In some studies, the power station is the main industrial emission source, accounting for more than two-thirds of global emissions, up to nearly 65% (Gür, 2022). Therefore, this section will focus on three capture methods that are highly relevant to fossil fuels, pre-combustion, oxyfuel-combustion, and post-combustion (Figure 2).

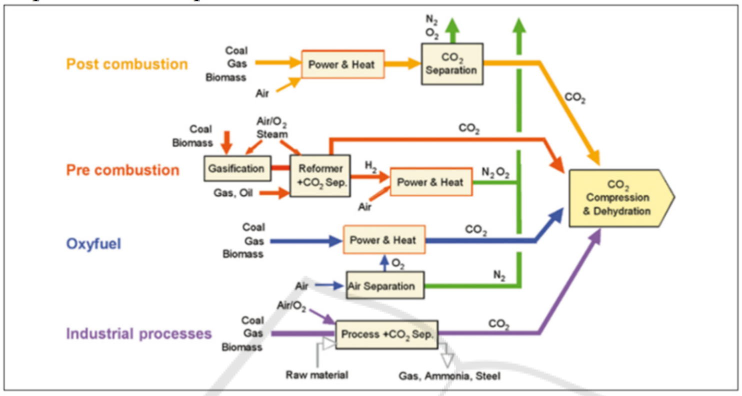

Figure 2: Overview of CO2 Capture Processes and Systems (IPCC, 2005).

3.1 Pre-Combustion Technology

This system aims to pre-treat fossil fuels before combustion. It usually contains three steps:

1) processing the water steam and air into a mixture of carbon monoxide and hydrogen in a high-temperature reactor first,
2) conducting the second reaction of carbon monoxide with the water steam to achieve Hydrogen and carbon dioxide through a shift reaction,
3) finally separating the carbon dioxide from the gas mixture through physical or chemical processes, such as cryogenic fractional distillation and solution absorption.

This technology has been widely used in industrial production but is still under development for power plants. Because of the bad adaptability to existing equipment, the Retrofitting investment is often very high at the early stage (Yang, 2024). Thus, this approach is mainly suitable for new plants considering carbon capture, especially under linkage with Integrated Gasification Combined Cycle (IGCC) plants, which could improve efficiency (IPCC, 2005). The main workflow in the factory is shown in the following diagram (Figure 3), mainly containing Gasification - Shift reaction - Carbon Capture – Hydrogen Utilization.

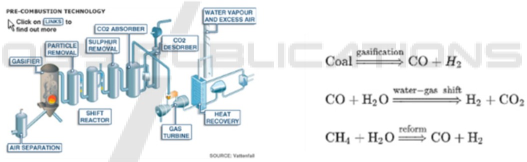

Figure 3: Pre-combustion System (Arshad, 2009).

Greengen located in Tianjin (China) is a typical project that adopts this capture system in practical operation, which works with the IGCC system and the annual capture capacity reaches 100,000 tons. The purity of the recovered CO_2 reaches 98% and the capture rate is up to 90%, while the energy consumption for removal is less than 1.6GJ/t (Yang, 2024). The most outstanding advantage of this technology is that hydrogen as a by-product can be used as a carbon-free clean energy for power generation. However, although its operating cost is relatively low, the complexity of the paired IGCC system is an important negative factor that cannot be ignored as well as the large upfront construction cost and capital investment. Some practical projects, such as The Kemper County Energy Facility in Mississippi, have been indeed shut down. Besides, some experts pointed out low efficiency, theoretical capture rates of which may be as low as 10% in some projects (Li and Qiao, 2008).

3.2 Oxyfuel-Combustion Technology

This system mainly focuses on the combustion process, improving complete combustion efficiency. It mainly has three steps:

1) using high-purity oxygen to replace air to make reactions with fossil fuels under a pressurized condition firstly,
2) then separates and collects CO_2 from the flue gas, which is mainly a by-product of water vapor, by means of low-temperature condensation,
3) finally dry CO_2 collected from the condensate water to prevent corrosion of the subsequent transportation piping.

Figure 4 shows the main factory workflow below: Oxygen Generation - Combustion - Cooling and Water Removal - CO_2 Capture.

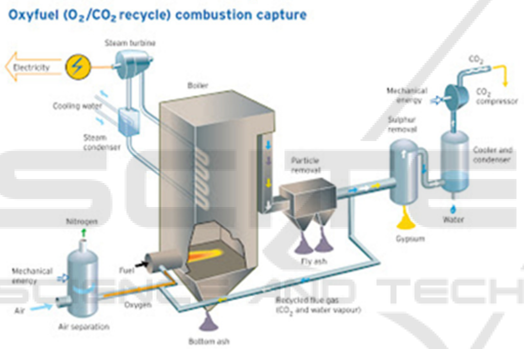

Figure 4: Oxyfuel-combustion System (Arshad, 2009).

Spremberg had operated a small pilot project equipped with oxyfuel-combustion Technology, Schwarze Pumpe Power Station in Germany (has been shut down). It had an installed capacity of 30 MW and captured about 30,000 tons of CO_2 per year (Kreutz et al., 2005). In China, a 35 MW industrial demonstration plant is applied with this system as well, which was built recently in Hubei by Huazhong University of Science and Technology with China Oriental Electric Corporation. (Yang, 2024). It uses a compatible program that allows air and oxygen in combustion reactions and achieves a capture rate of up to 82.7%, which can be applied to new and existing facilities. This technology can have several advantages, including achieving high concentrations of CO_2 directly, being easy to capture, and having the potential to be applied in retrofitting existing power plants. However, there are two main negative factors for further development: the difficulty of temperature control in oxyfuel combustion and the extra effort required to develop materials and equipment with high fire resistance, such as CO_2 compressors and ion transport membranes (IPCC, 2005). In addition, there is a view that the high cost of oxygen production makes it less economically advantageous in practical usage (Li and Qiao, 2008). However, according to calculations by the IPCC, although the cost and energy required for an oxyfuel-combustion system may significantly increase the overall cost of power generation, the costs can be offset by the technology's potential to capture more than 90% of the emissions (IPCC, 2005).

3.3 Post-Combustion Technology

This system usually captures CO_2 after the combustion in the flue gas, which generally contains two steps:

1) utilizing a liquid solvent to absorb CO_2 gas from the combustion of fossil fuels or biomass,
2) separating CO_2 from the solvent and compressing it for transportation or usage, while releasing the purified flue gases back into the atmosphere.

This technology has several different separation principles, including absorption, adsorption, and membrane separation (Yang, 2024). Currently, the process of monoethanolamine (MEA) is widely used as a proven chemical adsorbent in factories (IPCC, 2005). Since it is highly compatible with current flue gas systems, post-combustion technology is particularly suitable to retrofit existing facilities, such as modern pulverized coal (PC) power plants or natural gas combined cycle (NGCC) power plants. Atypical workflow is illustrated below (Figure 5), consisting of Flue Gas Generation - Flue Gas Treatment - CO_2 Capture - CO_2 Separation, Regeneration, and Compression.

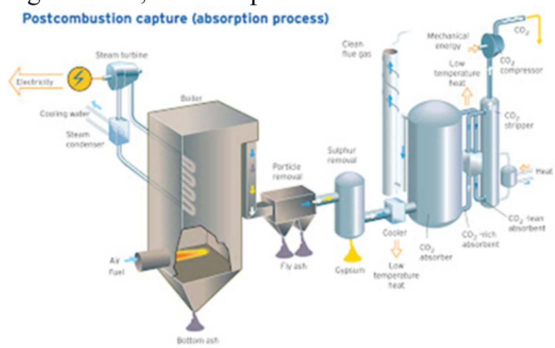

Figure 5: Post-combustion System (Arshad, 2009).

As one of the most mature technologies in CCS, post-combustion capture has been applied in many projects worldwide. Huaneng Beijing Thermal Power Plant in Beijing (China) is a typical example, which can achieve an average annual carbon capture scale of 3000 tons, and the capture rate is more than 85 with a purity of 99.99%. Besides, the captured CO_2 achieves source reutilization, which is produced as refined food-grade carbon dioxide and supplied to the carbonated beverage market (Wang, Zhang and Kuang, 2010). The outstanding advantage of post-combustion technology is its great flexibility in being well adapted to various facilities, which allows direct application in existing traditional power plants with relatively low-cost investment. Besides, this technology can especially be targeted at low concentrations of CO_2 and applied to large, centralized emission sources. However, high energy consumption and equipment operation costs are also inevitable results. Since the low CO_2 concentration in the flue gas, generally accounting for 3-15%, small airflow pressure, and large volume could result in a high capture cost price. In addition, the corrosion caused by liquid solvents can a decline in the service life of the equipment, which is also considered a negative factor in increasing the running cost (Yang, 2024).

Thus, the selection of a capture system requires balancing all the positive and negative factors of each technology and making the decision generally according to different features of the practical project, such as the CO_2 concentration in the gas stream, the gas stream pressure, and the fuel type (solid or gas).

4 DISCUSSION

Based on the analysis above, this part will shortly summarize the major negative factors that limit carbon capture technology and emphasize its importance first, followed by a discussion of the practical feasibility and adaptability of the three specific methods.

4.1 Technical Feasibility

Carbon capture technology is the first step of CCS, the capture rate of which is the basis for the whole. However, at this stage, several key reasons may influence its wide application negatively. Firstly, carbon capture technologies correlated with fossil fuels still have not reached a mature market-oriented stage. The optimization room does exist for varying components, especially those linked to oxyfuel combustion technology. Secondly, this technology generally requires additional investments, especially the capture technology that accounts for 70-80% of the whole capital cost and should be responsible for 10-40% of extra energy consumption (Blomen, Hendriks and Neele, 2009). Thirdly, it sometimes raises questions among the public during practical applications, especially environmentalists. The Schwarze Pumpe power station is an example that has been forced to shut down. Some viewpoints argue that funds are fully invested in the development of clean energy and resist the development of capture technologies applied to traditional thermal power stations. However, fossil fuels are an important source of global energy supply, currently up to 80% of the energy mix, and are also predicted to account for more than 60% by 2050 (IEA, 2022). Since fossil energy is indispensable to ensure energy security in the coming decades, it is important to promote the development of carbon capture technology, which offers the possibility to continuously use it in a more climate-friendly approach with a low-carbon footprint. Besides, it can mitigate the high rates of CO_2 emissions from the current stations and facilitate the development of clean energy technologies such as hydrogen. Furthermore, though capture is considered to be energy-intensive, the net removal of CO_2 can be reduced by 80-90% through this technology (IPCC, 2005).

4.2 Economic Feasibility

Currently, three carbon capture systems are developed at various stages with distinct features that can be applied to different types of fossil fuel stations. In practical usage, existing technologies can theoretically reach technical feasibility, while economic viability becomes an important concern due to the financing issue (Holloway, 2007). It mainly includes the efficiency, the upfront investment in the equipment, the cost of running the system, and the energy loss. In pre-combustion technology, the capture efficiency can be achieved by 85-92% with 81-88% CO_2 removal level of the emissions. Correspondingly, energy demand would increase by 16-25%. However, in combination with an IGCC system, the incremental costs can be reduced by about 20%, since the average energy demand and equipment size are reduced due to the reduced volume of gas being processed (IEA, 2022). For post-combustion technology, the capture efficiency is about 85-95% while the emissions reduction rate is around 80-90%. It often requires an extra 24-42% energy consumption, which is mainly used for solvent regeneration and carbon dioxide compression. Meanwhile, for oxyfuel-combustion technology, there is a lack of data on the practical application. Compared to the energy mainly spent on CO_2 separation in the last two adsorption-separation approaches, the extra energy would be used in oxygen purification.

4.3 Applicability

As the features of the three capture technologies described above, they have their own unique advantages for a typical scope of application. The pre-combustion technology is characterized by low operating costs, but has large upfront investment and construction difficulty, which suits new plants, especially for projects considering the development of hydrogen energy; the oxyfuel-combustion has received lots of attention in recent decades due to its high decarbonization capacity, but is still in the development stage and small-scale demonstration; the post-combustion technology is currently the most mature carbon capture technology with great flexibility in applying to the existing equipment and low upfront costs, while the daily operation of the capture cost is relatively high and its optimization is largely dependent on the research and development of new materials

Generally, it is necessary to choose the appropriate capture method according to the characteristics of the combustion reactions and equipment of the power plants for specific plants. In addition, national law-making and related policy framework-building can be positive enablers to encourage its development under a long-term stable financial incentive, such as carbon taxes and subsidies (Coninck and Benson, 2014). Besides, the establishment of a suitable testing system and regulatory system is essential.

5 CONCLUSION

This paper mainly focuses on exploring the three carbon capture technologies in CCS, pre-combustion, oxyfuel-combustion, and post-combustion. The features of the three systems are discussed through comparative analysis for their feasibility and applicability.

The research finds that carbon capture technology types have different features that suit different types of power stations, which generally gives it a high potential for application in the field of fossil fuels. In detail, as a mature technology with great flexibility and many successful precedents, the post-combustion system can focus on the present, quickly and effectively changing the high carbon emission from the existing traditional power plants. Meanwhile, pre-combustion technology is more suitable for newly built plants that are being prepared, especially the ones that are synergizing with the development of hydrogen energy. Besides, although oxyfuel combustion is considered to have great potential to reduce capture costs along with the development of new materials and technologies, it is still under the research and development stage in the laboratory, and its actual potential for practical application requires more data feedback. In general, this study considers that CCS has great feasibility due to its broad usage ranges in a wide range of sources. Thus, this paper suggests the promotion of further development and wide application of this technology in practical projects, which can not only quickly change the current high emissions condition but also help achieve deep decarbonization of the entire economy in the future.

In addition, further research could be carried out by involving more annual reports about actual production processes from different factories to gain a broader perspective on the feasibility analysis.

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