Opportunities and Potential of CCUS Technology Advancement Under The New Energy and Carbon Neutrality Background

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Abstract. Since the Industrial Revolution, human society has gone through a booming development. Accompanied by roaring machines and towering edifices during industrialization, the expanding ozone hole and rising global temperature all ring the alarm for humans. With the strong crisis awareness of protecting the environment, people weigh more importance on the exploitation and application of CCUS technology. This article aims to perform a comprehensive review of the promising technology. Besides, considering new energy, as a crucial part and developing direction of the energy structure, it also hopes to offer a new perspective of combining CCUS technology with new energy. Carbon capture, storage and utilization, the three critical parts together constitute the CCUS. They are conducive to reducing carbon emissions, responding to climate change and transforming environmentally inefficient industries. Though there are several technical and economic difficulties like demanding reaction conditions and high cost, some pertinent and feasible settlements have emerged, which find creative ways like connecting with new energy. According to some cases and future trends, a coupling of CCUS technology and new energy will offer more probability concerning energy conversion and storage. Based on the exposition of these two subjects, the article put forward this assumption.

Keywords: CCUS technology; new energy; industrial transformation; energy conversion.

1. Introduction

Energy is becoming an increasingly important topic, which is related to several fields such as politics, economy, technology and ecology. The issue of climate change cannot be ignored, and people are gradually developing a more serious awareness of the energy crisis and environmental protection.

Carbon dioxide, as a key component of greenhouse gases, plays a major driving role in exacerbating the global warming. In order to cope with the deterioration of climate, countries are committed to discussing effective measures and putting them into practice. Among the many policies, reducing carbon emissions will be the first. This is not only a requirement for restoring ecosystems, but also an important way to achieve efficient and green development. In many regions, especially developing regions, fossil fuels still dominate the local energy mix and their combustion contributes to significant carbon emissions. Although there is a trend to increase the proportion of renewable energy, fossil fuels cannot be completely replaced. This means that in the short term, atmospheric carbon dioxide concentrations will continue to rise, but probably at a more moderate rate. In addition to controlling carbon emission levels, innovative technologies to capture, store and use this carbon are another logical measure to get out of the dilemma.

CCUS technology has made some breakthroughs in the past few years, but there are still multiple challenges and technical barriers. It has a wide scope for future development due to the urgent need to save energy and reduce carbon emissions. A large body of literature summarizes the concept and development of CCUS technology. However, few studies have linked it to new energy fields and practical utilization cases. This paper aims to combine CCUS technology with the new energy industry to provide a more detailed summary of CCUS and provide more possibilities for carbon reduction methods.

2. CCUS Technology

CCUS technology means cutting down carbon emissions through processes of capturing, storage and utilization. During industrial production, this technology can realize the separation of carbon dioxide and net-zero carbon emissions [1]. It does not affect the manufacturing technique but performs a tail gas treatment. With the premise of not adjusting the energy structure on a large scale and ensuring energy safety, it will be a promising way to promote the transformation of some traditional power plants and the development of decarbonization industry [2].

2.1. Carbon Capture

The term "Carbon capture technology" describes the procedure of extracting, purifying and compressing carbon dioxide from industrial production, energy utilization or the atmosphere [3]. It acts as the initial and fundamental link of CCUS technology. There are three types of capture processes: pre-combustion capture, post-combustion capture and oxygen-rich combustion capture. According to different capture methods, it can mainly be classified as chemical absorption, physical adsorption, membrane separation and so on [3].

2.1.1 Capture process

(1) Pre-combustion capture

Pre-combustion refers to separating carbon from the fuels prior to full combustion. Before combustion, fuels like natural gas should undergo preconditioning like steam reforming and gasification, turning into clean gas energy [4]. During the process, carbon will be eliminated from the fuels in the form of CO_2 so the carbon emissions can be reduced at source [5]. When CO_2 is created, it is under high pressure and can be compressed and liquefied for storage or transit with little power use [6]. Besides, the conversion reaction possibly encourages the generation of H_2, which can be used in fuel cells and manufacture of compounds with added value. The flexibility of the outputs is another significant advantage of the pre-combustion approach, which means we can regulate the product proportion to choose H_2 production or power generation depending on practical need [6].

(2) Post-combustion capture

Post-combustion capture acts as a last link and can be installed into existing power plants with little infrastructure modification [7]. It describes the process of treating fuel gases, separating them into different components and extracting rarefied CO_2 in an oxidizing atmosphere. Low concentrations of CO_2 in the tail gas makes the collection step technically difficult and energy-demanding [4]. Typically, the extracted CO_2 will be transformed into supercritical fluid through compression, and transferred to get stored in the reservoirs [6].

(3) Oxygen-rich combustion capture

It is a new combustion technology with high efficiency and energy conservation, which uses the separation equipment to obtain high purity oxygen from air as oxidative of burning coal [8]. It has primary benefits of cheap CO_2 recovery costs, high combustion efficiency, little pollutant emissions and low smoke exhaust loss [8]. There are several types such as chemical chain combustion and pressured oxygen-rich combustion, among which the usage of latter has been popular in American and European regions [2]. Besides, the pressured oxygen-rich combustion cycle outperformed the conventional atmospheric cycle and might boost efficiency [6].

2.1.2 Capture method

(1) Chemical absorption

Chemical absorption is a method that uses the CO_2 property of acidic gas to make chemical reaction with weak alkaline substances and finally remove it by heating and desorption [8]. Absorption can be classified as either a physical process or a chemical process depending on the characteristics of the solvent [4]. For chemical absorption, under atmospheric pressure, strong chemical bonds form betweenthe solvent and CO_2 [4]. With a relatively long research and utilization

period, chemical absorption has been acknowledged as the most feasible and popular post-combustion capture [8].

(2) Physical adsorption

Adsorption is a process using special adsorbents to selectively adsorb CO_2 to their surface through necessary processes like temperature rise or pressure reduction [8]. The adsorption capacity depends on the surface areas of adsorbents and differences in temperature or pressure during operation [8]. Significant interest is drawn by adsorption because of its low costs, operation simplicity, low energy requirements, simplicity of handling, and overall stability [4]. The primary factors for choosing a novel adsorbent are high permeability, good CO_2 selectivity, large specific surface area and strong renewability [4].

(3) Membrane separation

Membrane technology is a more innovative strategy that has been investigated for CO_2 extraction in recent years compared to the two approaches mentioned above. Membranes refer to extremely thin layers of some porous inorganic materials, such as silica or organic materials, such as cellulose acetate, with a pore diameter range of 0.1 to 2 μm [4]. While constructing membranes suitable for CO_2 separation, two main factors of selectivity and permeability should be taken into account [4]. Moreover, polymeric membranes perform greater effectiveness at capturing CO_2 for their high selectivity [4].

2.2. Carbon Storage

In order to permanently separate captured carbon dioxide from the environment and reduce emissions, carbon storage technology is the technique of pumping it into geological repository storage. The primary sealing techniques include sealing depleted natural gas fields, sealing deep coal seams and oil fields without economic mining potential and others [3]. By storing CO_2 in gas reservoirs, it can greatly boost natural gas output while reducing CO_2 emissions [9]. CO_2 storage offers an effective and operational solution for the captured CO_2, by sequestrating them in suitable geological structures worldwide [6]. When a certain amount of CO_2 is permanently sequestrated in the reservoirs, carbon emissions can achieve negative [10].

2.3. Carbon Utilization

Carbon utilization means torealize the resourceful utilization of CO_2 through multiple methods. The two types of used modes are transformation and non-transformation. To reduce emissions, transformation entails converting carbon dioxide into other useful compounds through mineralization, biology, chemistry, and other processes [3]. CO_2 can be directly used as dry ice, refrigerant and component of carbonated beverages [11]. This method only achieves a covert reduction in emissions with no effect on overall emissions [3]. It not only significantly raises the economic worth of CCUS but also gives CCUS the chance to be commercialized [1].

2.3.1 Biological utilization

In the natural carbon cycle, CO_2 can be transformed into organic matter through photosynthesis. Therefore, it is safe and economical to absorb and fix CO_2 biologically using autotrophs [12]. With the characteristics of the tiny volume, good adaptation to the environment, high photosynthetic efficiency, quick replication, and simplicity of coupling with other techniques, autotrophic microorganisms like microalgae are a good choice [12]. The dissolved inorganic carbon in water serves as the major source of carbon for them [12]. The actual engineering applications of the carbon fixing oraganisms are determined by concrete demands.. Though natural biological carbon fixation has contributed much to the carbon cycle, artificial biological carbon fixation is playing an increasingly significant role, with itslow energy consumption, highproduction efficiency, as well as wonderful economic and environmental benefits [2].

2.3.2 Electrocatalytic conversion

In addition to getting sequestrated, CO_2 can also be converted into other valuable compounds, which can be utilized in construction and chemical industries. For example, hydrocarbon fuels like carbon monoxide, alcohol and formic acid are common products resultants from electroreduction of CO_2. With the advantages of mild reaction condition and controllable products, this technology has a wide application prospect.. Besides, the consideration of economic viability is crucial for competing with products by fossil fuels and potential market risks brought by government policies should be taken into account [12].

Table 1. Comparisons between Steps of CCUS Technology [3]

CCUS Steps	Carbon Capture		Carbon Storage	Carbon Utilization
Technical Modes	Capture process	Pre-combustion capture Post-combustion capture Oxygen-rich combustion capture	Geological storage Ocean storage Carbon dioxide flooding	Transformation Non-transformation
	Capture Method	Chemical absorption Physical adsorption Membrane separation		
Technical Maturity	The technology is relatively mature, and the post-combustion capture is the most widely used		The technology is relatively mature, and gradually achieves transformation towards large-scale. The oil extraction technology has been basically mature.	Transformation technology needs technical breakthrough while non-transformation technology is mature but contributes little to actual carbon emissions reduction
Principal Problems	High cost and energy consumption		Mainly affected by the geological conditions	Limited contribution to carbon emissions reduction

3. Combination of CCUS and Energy Industry

It is important to optimize the impact of CO_2 collection, storage and utilization and guarantee the effective application of CCUS technology in energy industries targeting at industrial carbon sources with various CO_2 volume fractions [2]. It also aids in lowering the danger of implementation and the expense of the CCUS system. Now the major categories of carbon emission sources have been covered by developed carbon capture techniques. Additionally, carbon storage and utilization technologies have undergone technical proof and practical application in the electricity, chemical, hydrogen production and other energy industries [2].

3.1. Thermal Power

Given the difficulty in altering thermal power's dominant position in the near future and the high demand of industrial carbon emissions, CCUS technology has emerged as a crucial tool for significant

pollution reduction in the thermal power sector. The present capture technology is reasonably mature from the standpoint of the operation economy, and the expense can be decreased. The main issue is a dearth of efficient storing and utilizing methods. Oil extraction is more practical if an oil field is close to coal-fired electricity facilities [3].

Geological factors have a significant influence on carbon sequestration, and there might not be appropriate storing sites nearby [3]. Besides, the carbon capture ability is limited at present and the high investment of corresponding equipment might be a burden for the factory, which needs an extended period to gain the expected returns [3].

3.2. Fossil Energy

Carbon dioxide flooding is an established technology with an application period of decades and has been perceived as one of the feasible carbon emissions reduction techniques by realizing carbon storage [3]. It should be mentioned that carbon dioxide is not produced by the oil business itself. The majority of the carbon dioxide used in oil extraction is produced locally in the chemical thermal power and other industrial sectors. Currently, approximately 70% of the CCUS projects worldwide involve carbon dioxide flooding technology [3].

3.3. Hydrogen Energy

Although the carbon emission reduction scale of CCUS is presently inferior to that of hydrogen energy, it still has promoting implications for the energy's green and clean use. Additionally, hydrogen generation also have problems of safety, high cost and carbon emissions. Therefore, to realize the comprehensive utilization of CCUS and hydrogen energy is a practicable solution. For example, the high concentration of CO2 produced during the manufacture of coal acts as a good and cheap carbon source for CCUS application. Though the adjunction of the CCUS equipment partly increases the cost of manufacturing H2 using fossil fuels, the resource usage of CO2 will allow for the achievement of economic and ecological benefits [13].

In comparison to producing hydrogen using renewable energy, the combination of CCUS technology and hydrogen energy has a cost advantage. There are fewer carbon emissions produced, which is a crucial step toward achieving low-carbon conversion of fossil fuels, and advantageous for effective use of carbon resources [13].

4. Application Cases

In different countries and regions, the developing degree of existing CCUS projects varies. Chemicals, mineralization, and polycarbonate polymers are three CO2 usage methods in the United States that are intended to expand the CO2 commodity market [12]. By 2030, there should be extensive testing of these techniques, and by 2035, there should be broad commercial usages. Since 2003, seven RCSP (Regional Carbon Sequestration Partnership) regions have been established to promote the growth of the regional infrastructure for CCS(Carbon Capture and Storage) [12].

The UK government has been announcing new initiatives since 2017 to assist improvement in carbon capture, storage and utilization, such as the Clean Growth Strategy [12]. The creation of novel technologies, the growth of international cooperation on CCUS, and cost-cutting research in CCUS projects are the encouraged three avenues=. Besides, in the next two or three decades, substantial CCUS implementation projects are anticipated to get underway [12]. Since 2011, more than £130 million has been spent to support the research, development, and innovation of CCUS [12]. The first to utilize carbon capture, transportation, storage and usage whole-process technology, and CCUS cluster deployment project in the world, for instance, is the ALIGN-CCUS project [2].

China National Petroleum Corporation started up the first significant CCS plant in 2018 [12]. Moreover, the Chinese government is actively involved in some international forums like the Clean Energy Ministerial (CEM) conference and also offer substantial support to domestic research

institutions and businesses engaged in bilateral or multilateral joint projects [12]. Now there are the most operational, under construction, and planned pilot and demonstration factories of CCS [12].

5. Challenges

Owing to high costs and significant business uncertainties, the extensive utilization of CCUS technology is still restricted since it is still in the early stages of demonstration [1]. As a result, in order to achieve carbon neutrality, it is essential to explore the viable and steady operating model of CCUS and provide appropriate government encouraging measures to motivate its application in traditional power plants [1]. From a technical standpoint, carbon capture technology has been relatively developed, but still hindered by high cost and energy consumption. Though with many development programs, the application scope of carbon storage technology is strongly influenced by geological conditions. As for carbon utilization technology, fundamental breakthroughs are lacking, especially in economy and application scale [3].

5.1. Carbon Capture

After CO_2 has been gathered, it needs to be purified to concentrations above 95% before it can be compressed, transported, and stored in an acceptable condition [4]. Thus, to extract CO_2 from large quantities of exhaust gas with complex components and low CO_2 concentrations, effective carbon capture technologies are required. Absorption has a number of flaws, including a high energy demand of solvent regeneration, the breakdown of key substance, and caustic corrosion on equipment [4]. The low selectivity and adsorption capability of adsorbents under low CO_2 pressure is one of the key challenges. Another challenge in CO_2 adsorption is the moisture effect on the saturation of active sites on the adsorbents' surface [4]. Although CO_2 may be separated from syngas, flue gas, or natural gas using membrane technology, the collection tactics have a substantial impact on the operational cost [4].

5.2. Carbon Storage

The fundamental obstacle to the current large-scale commercial CO_2 geological usage and storage is the absence of effective, affordable, and safe CO_2 geological utilization and storage technologies [2]. Another major worry with CCUS techniques is CO_2 leakage from subterranean geological storage [4]. For example, the possibility of ocean acidification due to CO_2 leakage is a current critique of deep ocean storage. Furthermore, there is a direct correlation between the carbon storage technologies' high operational costs and the various challenges facing their commercial deployment [4].

5.3. Carbon Utilization

Regardless of the specific utilization pattern, they are all confronted with challenges of high economic costs and inadequate implementation scale. Breakthrough of key techniques are necessary for some utilization modes to realize their potential [3]. In general, the present utilization technologies can only reduce a limited amount of carbon emissions. To transform CO_2 into high added value products, both chemical and photochemical reactions have demanding requirements of high CO_2 purity, high pressure and temperature [4]. As for electroreduction, the poor selectivity and conversion rate restrict its application. Now these approaches also have problems of unsustainable energetic and financial investment. Mineralization of CO_2 is composed of the grinding of feedstock, process heating, and slurry stirring, which all consume extensive energy [4]. Hence, to make the process commercially feasible in an industrial setting, technical improvement is required and the energy expenditure should be offset by other exothermal processes [4].

6. Future Improvement

6.1. Carbon Capture

The emphasis of carbon capture's researching direction is on exploiting the novel capture methods, such as the low-temperature separation technique, and conquering the technical deficiency in cost, stability and application scale [2]. For example, microalgal carbon capture is a revolutionary method of providing more possibilities for lowering carbon emissions and finally realizing the sustainability by turning extracted CO_2 into valuable products [4]. CO_2 should go through a series of biochemical reactions in the biological framework of these micro algae, thus realizing the carbon fixation. The method is a coupling with two steps of carbon capture and utilization which can be should be widely used for its profitability and environmental friendliness.

6.2. Carbon Storage

Nowadays, researches on the gas reservoirs on account of the complicated conditions like heterogeneity and inflow water, are still rare [9]. More researches are required to explore the reservoirs' geological characteristics and use the simulation technique to effectively evaluate their feasibility [9]. Geological storage essential technology should achieve the advancement of geological adaptability, safety, efficiency, and industrialization in line with the complexity of geological circumstances and the various geological storage types [2]. Furthermore, technical issues relating to subterraneous closed salt and mine cavity storage safety should be resolved [2].

6.3. Carbon Utilization

The scale of CO_2 utilization should be expanded by upgrading the market size and production capability when applied to commercial facilities [12]. The carbon utilization solutions will be investigated and constructed with low energy consumption, high conversion efficiency and moderate reaction conditions for industrialization [12]. It has been established that the solar thermochemical technique is a cutting-edge and practicable method for converting CO_2 using solar power. The extra solar energy in summer can be used to produce sustainable fuels that can be utilized in the winter [12]. Besides, electroreduction of CO_2 can be driven by new energy power, serving as an ideal solution for abandonment of electricity. The commodities produced from conversion processes should be highly demanded and economically feasible in order to achieve sustainability of large-scale CO_2 consumption [12]. The energy balance and economic viability of the conversion processes should also be assessed.

Future priority research can focus on the integration of CO_2 mineralization with other ideas and techniques, including comprehensive air pollution management or water reutilization [12]. Energy, engineering, environmental, and economic domains should cooperate to optimize the system and create a waste-to-resource supply chain [12].

7. Conclusion

With the aim of promoting carbon emissions reduction and preventing environmental deterioration, the high-quality development of CCUS technology is urgent to accelerate the transformation of industrial production and alleviate the extreme climate change. CCUS technology is composed with three key steps, carbon capture, storage and utilization. Each aspect has come through technical iteration and extent to multiple industrial areas, adaptive to varieties of application demands. They cooperate to help with timely extracting carbon dioxide from industrial production or atmosphere, storing it safely and consuming it efficiently. Besides, such a complete procedure contributes to sustainability of carbon cycle. However, there still existing some problems during technical innovation, such as severe reaction conditions, conversion efficiency to be improved, energy consumption and potential additional pollution. Targeting at these technical defects, solutions with high feasibility have been researched and proposed. For example, characteristics of some special

microorganisms can be applied to improve carbon capture process, geological conditions should be valued when selecting the storage sites and new technology like solar and hydro power can be associated closely with carbon utilization.

This article gives a complete overview of CCUS technology, ranging from the background, definition to shortcomings and future improvement. Besides, it is related to the new energy, offering a new perspective and stressing the importance of joint development. It can be foreseen that in the next decade, the progress of human society will not bog down and continuously require large amount of energy sources as drive forces. To satisfy this demand, the energy structure needs to change and the carbon emission should be reducing extensively, which demonstrate the future direction of new energy and CCUS technology. Besides, the two elements cannot be separated, but combined to play a significant role in recovering the ecological environment and boosting economic improvement. Given that there are few cases of combing new energy with CCUS technology currently, the analysis part is concise, not providing a detailed demonstration. In the future, it can be believed that the coupling application of new energy and CCUS technology will meet its prosperous development and then more meaningful researches can be conducted to explore the mystery behind energy conversion and utilization.

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