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Carbon Capture, Utilisation, and Storage Help to Achieve the Goal of Carbon Neutrality

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To achieve the goal of carbon neutrality within the planned timeline, it is urgent to build a technical system that comprehensively supports the transition from a "high carbon society" to a "carbon neutrality society". Carbon Capture, Utilisation, and Storage (CCUS) are all efficacious means to reduce carbon emissions and strengthen carbon sequestration while also serving as important technical assurances for countries to achieve carbon neutrality. This study provides an overview of the research progress and application cases of CCUS, H transportation, CO_2 network synthesis and integration, and related technical methods. The demonstrations of CCUS technology application and research progress can be summarised from the prism of capture performance assessment, utilisation approach research, environmental suitability inspection, etc. It evaluates the development of CO_2 transportation in relation to the transportation economy, transportation safety, and CO_2 recovery rate. The purpose of this study is to furnish a methodical reference for the construction of a carbon reduction system and promote the gradual realisation of carbon reduction goals in each stage.

1. Introduction

CO_2 is one of the main greenhouse gases. According to the 2021 Global Meteorological Report issued by the World Meteorological Organisation, the emissions of greenhouse gases have reached the highest level in history. According to the annual analysis released by the Global Carbon Project, by 2020, civilisation will have released about 34 Gt of carbon dioxide into the atmosphere (Friedlingstein et al., 2020). This has brought far-reaching impacts on the global ecosystem and human society, including more frequent extreme weather phenomena, sea level rise, species extinction and other issues. In recent years, governments, enterprises and individuals have begun to take action to reduce carbon dioxide emissions, but more efforts and investment are still needed to address this global challenge. The research on Carbon Capture, Utilisation, and Storage (CCUS) is of great significance to the realisation of low-carbon emission reduction and the "carbon peaking and carbon neutrality" goal. CCUS refers to the intricate procedure of isolating CO_2 from industrial processes, energy utilisation or atmosphere and employing it through direct and indirect utilisation, as well as injecting it into the formation to achieve permanent emission reduction of CO_2. CCUS, which is one of the key technologies to deal with global climate change, aims to capture, purify and recycle CO_2 from its source or store it underground so as to balance the negative impact of CO_2 on climate.
At present, many countries and regions in the world have built CCUS projects of different scales, which has a good prospect in solving the carbon emission problem. In their study, Wang et al. (2022) have presented an elaborate framework encompassing system modelling and safety risk assessment for integrated regional CCUS systems. By focusing on the various CCUS modules, Aspen Plus simulation-based regional CCUS system is constructed. They have proposed an integrated inherent safety index system to evaluate the risk characteristics involved in the integrated CCUS setup. CO_2 transportation is a key link that is closely related to CCUS. CO_2 pipeline transportation is one of the ways to transport captured CO_2 to the place of use or storage, and it serves as one of the three indispensable core links of carbon capture and storage technology.

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To enable relevant scientific researchers to efficiently and conveniently understand the above technologies and methods, this paper summarises the study progress and cases of CCUS, CO_2 transportation, CO_2 network synthesis and integration, aiming at reducing CO_2 emissions, promoting green and low-carbon development, and providing a technical reference for the construction of a global carbon reduction system.

2. CCUS research progress and status

Modern industrial production is associated with many sources of CO_2 emissions, including cement, steel, electric power, coal chemical industry and refineries. In response to the CO_2 emission problem, various industries have been conducting research and exploring the options for the capture, utilisation and storage of CO_2. Each industry has formed a variety of technical methods for CCUS according to its own industry characteristics.

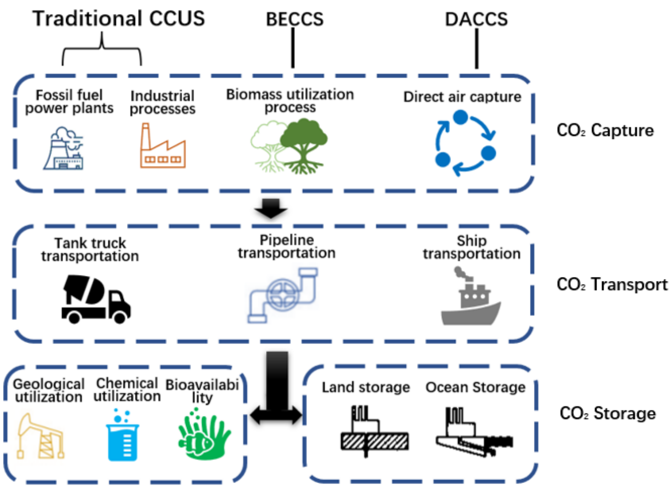

Figure 1: CCUS Technology Link (Luo et al., 2023)

2.1 Carbon capture

The primary source of CO_2 emissions is the use of fossil fuels in power generation and industrial processes. In the power industry, according to the sequence of the carbon capture and combustion process, the traditional carbon capture methods mainly include pre-combustion capture, oxygen-enriched combustion and post-combustion capture. On the basis of traditional carbon capture technology, some carbon capture systems that are still under research and improvement have also been developed. For example, the coal gasification process directly affects the enrichment degree of CO_2 and the energy consumption of capture in the subsequent process. A carbon capture power system that follows a hierarchical transformation of coal hydrocarbon components has been developed, and the concentration of CO_2 before separation can reach about 50 %, providing the possibility of realising the low energy consumption capture of CO_2.

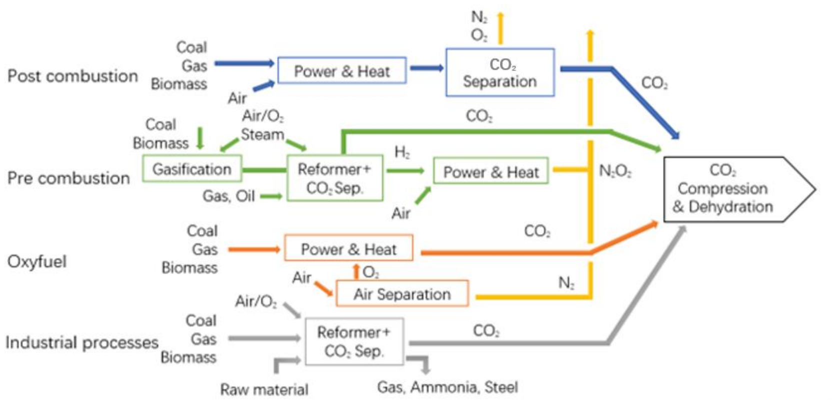

Figure 2: Overview of carbon capture processes and systems (Khan et al., 2023)

Microalgae cultication for carbon capture and utilisation has become a sustainable and effective platform for reducing global greenhouse gas emissions while producing valuable biomass. In a recent study conducted by Oliva et al. (2023), two identical algal photobioreactors (PBRw and PBRp) were compared systematically using white and purple LED lights. The study has achieved a carbon removal rate of up to 98 %, and PBRp provided enhanced culture conditions, higher CO_2 removal rates and increased biomass production (up to 855 mg/d of dry algae biomass). The results proved the potential of this solution as a sustainable strategy to improve the applicability of algal photobioreactors in carbon capture and utilisation.
Indeed, carbon capture technology still has many potential for further development and improvement. With the advancement of science and technology, researchers may be able to invent an efficient, convenient and low-cost carbon capture technology.

2.2 Carbon utilisation

CO_2 utilisation refers to the process of realising resource utilisation of captured CO_2 by means of engineering technology. According to the different engineering technology means, it can be divided into CO_2 geological utilisation, CO_2 chemical utilisation and CO_2 biological utilisation.

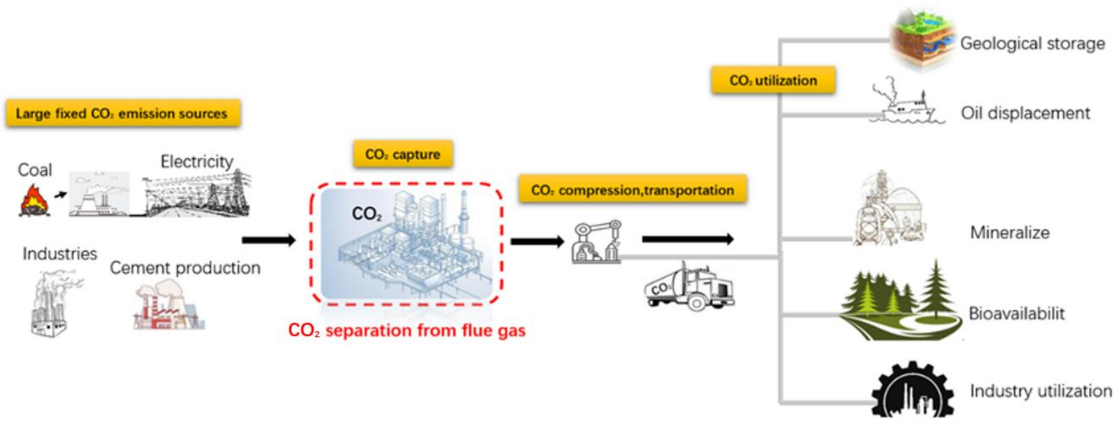

Figure 3: Carbon Capture, Utilisation and Storage (CCUS)

Methanol is becoming a carbon dioxide utilisation technology and hydrogen carrier, which can use captured carbon dioxide and hydrogen to produce methanol. Kim et al. (2022) conducted a comprehensive study to find the best way from the perspective of economy and environment, cost estimation, sensitivity analysis, uncertainty analysis and carbon footprint analysis for four methanol production situations with methanol production capacity of 1, 10, 20 and 50 t/d. The results show that compared with the unit methanol production cost of fossil fuel production (0.396 USD/kg), direct methanol production is more feasible than other situations.
Marra et al. (2022) employed the ASPEN PLUS® software to carry out simulations of the catalytic conversion of CO_2, and they utilised the composition of the CO_2 absorption column solvent to perform the equilibrium calculation for enzymatic hydroxylation. To objective of their investigation was to assess the potential use of this solvent, enriched with bicarbonate, as a carbon vector in the enzymatic CCU process.
Using various carbon resources for mixed nutrient microalgae cultivation is a promising strategy that can increase biomass. Ma et al. (2023) characterised IC and OC consumption, chlorophyll fluorescence parameters, intracellular nicotinamide adenine dinucleotide phosphate content, and transcription changes of related genes. The results showed that IC was preferentially used, with 76 % of IC being consumed within 8 h. Subsequently, OC is the main carbon resource for fermentation. At 24 h, the cell density of IC group was 100 % higher than that of the group without IC. Real-Time Quantitative Polymerase Chain Reaction analysis confirmed this finding. These results clarify the carbon utilisation mechanism under mixed nutrition conditions, and provide clues for promoting the growth of microalgae by regulating carbon utilisation.

2.3 Carbon sequestration

Carbon sequestration, also known as carbon storage, is the process of capturing carbon dioxide formed in fossil fuel power generation and industrial processes, and then storing these carbon so that it will not be discharged into the atmosphere. Carbon sequestration has strong potential in reducing carbon dioxide emissions in energy systems.

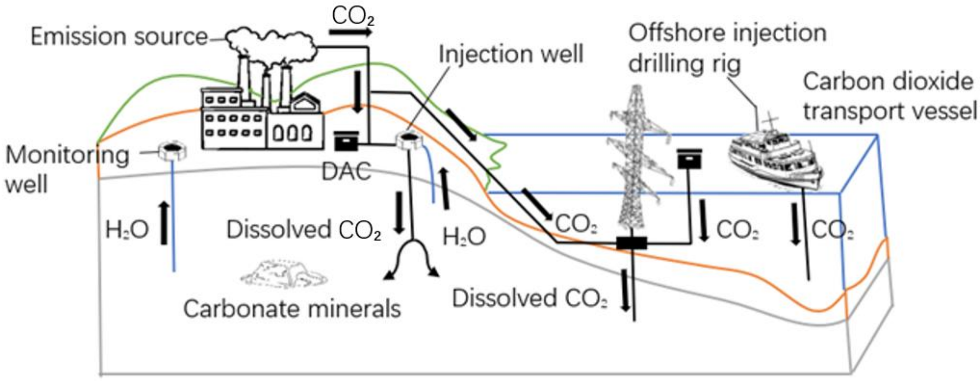

Figure 4: Carbon dioxide sequestration through mineral carbonisation

Carbon storage in geological structures is considered to be an important technology that can reduce the carbon intensity of industrial processes based on fossil fuels. Oyenowo et al. (2023) introduced a case study of geological carbon storage using formate solution as carbon-bearing water. The simulation results show that formate injection leads to a more stable oil-water displacement front. This is a significant advantage of using formate as a carbon carrier to control CCS risks associated with permeability heterogeneity and its impact on underground flow conditions.

The ideal non-collapse heated oil shale reservoir can maximise the preservation of pores and fractures. Niu et al. (2023) conducted an open thermal system experiment to combined with multi-scale visual statistics and quantitative testing. It is concluded that the displacement pressure, fracture pressure and overburden pressure of the surrounding rock determine the CO_2 injection pressure. With regard to adsorption and free state, through the improved carbon storage potential formula, the maximum theoretical CO_2 storage per unit volume of the depleted oil shale reservoir is estimated to be about 0.261×10^9 t/km^3. Therefore, the depleted oil shale reservoir is a suitable place to store carbon dioxide due to its huge storage potential.

Gathering carbon dioxide sources and sinks through hubs is a way to achieve large-scale deployment of CCS and extensive decarbonisation in the energy sector. A key factor for the success of the hub project is to find a suitable storage site to store these integrated emissions. Callas et al. (2022) developed a quantitative and standard-driven method to evaluate the potential applicability of depleted oil and gas reservoirs to carbon storage. The purpose of this study is to gain an in-depth understanding of the applicability of depleted reservoirs in various geological environments, match project specifications, and evaluate many potential sites to determine the most suitable place for safe storage.

3. CO_2 network integration

Many examples of CCUS technologies are generally based on the CO_2 network comprehensive utilisation system, and the "bridge" connecting this comprehensive utilisation system - CO_2 transportation plays a vital role in it (Lu et al., 2020). The following summarises the transport details and optimisation cases of CO_2 transport.

3.1 CO_2 transportation

The transportation of CO_2 refers to the process of transporting captured CO_2 to usable or storage sites. The modes of transportation include tank cars, ships, pipelines, etc. Generally, tank trucks are considered for small-scale and short-distance transportation, and pipeline transportation is preferred for long-distance large-scale transportation or CCUS industrial cluster. The selection of a specific transportation mode requires comprehensive consideration of the location and distance between the starting point and the end point of transportation, CO_2 transportation volume, CO_2 quality, CO_2 temperature and pressure, transportation process cost, transportation equipment, etc.

For CO_2 transportation, Cao et al. (2021) proposed a CO_2 hydrate slurry transportation mode with the aim of the study of CO_2 transportation in order to further reduce costs and improve transportability, a CO_2 hydrate slurry transportation mode was proposed. A multiphase flow model combining the kinetic model of hydrate dissociation and the population balance model is established. The influence of hydrate dissociation on CO_2 transport capacity is analysed, and it is concluded that hydrate dissociation can reduce the average viscosity of CO_2 hydrate slurry flow, pressure drop and energy loss. The bubbles generated can accelerate the flow of CO_2 hydrate slurry, increase transportability, and reduce the risk of hydrate blockage due to agglomeration in the pipeline. In the study of Wang et al. (2023), X70 steel was selected, and the environment during supercritical CO_2 transportation was simulated with different O_2 and SO_2 contents by using high- temperature high- pressure slow strain rate tensile test (SSRT) and high -temperature high -pressure electrochemical test equipment. The research shows that the SCC sensitivity increases with the increase of SO_2 concentration, but the increased amplitude decreases. Based on the characteristics of hydrogen embrittlement fracture, the stress corrosion mechanism of supercritical CO_2 pipelines containing SO_2 and O_2 impurities was studied. Pantoleontos et al. (2021) established a CO_2 transportation network optimisation method, which is to develop a transportation level cost function for CO_2: N_2 (96 %: 4 %) mixture within the range of 25-2,000 kg/s and 50-2,000 km, determine the best solar city to receive CO_2 and further convert it into fine chemicals, and draw the best route to present the minimum transportation and utilisation costs.

At present, this research direction is faced with such problems as improving the CO_2 transportation safety monitoring system, reducing the ecological impact of transportation projects, and monitoring the safety and efficiency of transportation. New CO_2 transport media and CO_2 transport modes are emerging all over the world. The Americas initially formed a land transport network, and the offshore pipelines are mainly concentrated in the Nordic region. China's CO_2 pipeline demonstration is still in its infancy. CO_2 pipeline transport is mainly in the gas phase, and there is no long-distance CO_2 supercritical phase transport pipeline. It is expected that research on large-scale supercritical transportation will be carried out in the future.

3.2 CO_2 network integration

Based on the rapid development and wide application of CO_2 transportation, the CO_2 network integration that has been constructed using it has played an outstanding role in carbon reduction, energy conservation and other aspects.

The environmental benefits of a carbon reduction system for a bioethanol distillery were investigated, considering both the geological viability and economic feasibility (Bonijoly et al., 2009). Through conducting CO_2 balance calculations, it has been demonstrated that the introduction of carbon capture and storage in the biomass energy system can significantly improve the CO_2 emission reduction potential for reducing CO_2 emission of the system and even achieve negative carbon emissions. Silva et al. (2018) developed and applied a method to design the best sugarcane B-BACCS-CO_2 network and two alternative concepts: one considers the multi-modal transport network of road and pipeline transportation, and the other considers multiple hub systems. The emission reduction cost results of the system include sensitivity analysis in the best and worst case between 32 and 87 USD/t of carbon dioxide. Yin et al. (2023) employed a distributed ground source heat pump heat storage system as a part of an integrated energy system to improve the utilisation efficiency of wind and solar energy. A balanced generalised learning prediction model considering various heterogeneous data is established for load forecasting, and the prediction accuracy is 96.12 %. Under the four conditions of low or high wind and solar power generation curves, carbon emissions will be reduced to at least 82.02 % of the original emissions.

The above case shows that the CO_2 network comprehensive utilisation system focuses on improving the energy utilisation rate and taking into account the overall rationality of the system. In the development process of the CO_2 network comprehensive utilisation system, it is developing towards multi-dimensional participation factors and detailed evaluation standards.

4. Conclusions

This study reviewed the research status of CCUS and CO_2 network review. The findings indicate that CCUS technology has gained widespread application across various domains and has developed rapidly. CCUS technology represents an exceedingly efficacious way of man-made carbon sequestration. This article recommends that the worldwide carbon capture system is widely studied to achieve low energy consumption and efficient carbon capture, enriching and developing the use of methods and technologies of CO_2. At the same time, the construction of carbon fixing facilities is popularised in coastal and other regions. And by optimising the CO_2 transportation method, the CO_2 comprehensive utilisation system is constructed. The application and development of various methods and technologies have regional characteristics. Therefore, in the carbon reduction work, localities need to be continuously trying to find the most suitable method to apply. This study believes that the CO_2 comprehensive utilisation system built with CCUS and CO_2 transportation has great potential for development. It is believed that in the forthcoming era, nations shall embrace the application of CCUS technology with greater magnitude, employing a more systematic approach to establish the required carbon reduction system. Through this progressive undertaking, the objectives of four distinct stages encompassing carbon control, carbon reduction, low-carbon, and neutralisation shall gradually come to fruition.

Acknowledgments

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