Exploration and Applications of Carbon Utilization and Sequestration Technologies

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Abstract. In recent years, the surge in global energy demand due to rapid technological advances has led to a significant increase in greenhouse gas emissions, resulting in a climate and energy crisis. Against this backdrop, the challenge for the global energy sector is to weigh the advantages and disadvantages of different carbon capture, utilization, and storage (CCUS) technologies in order to select the most appropriate method for each situation. This study focuses on Enhanced oil recovery (EOR) and ocean sequestration technologies and analyzes their theories, advantages, obstacles, and applications. EOR technology improves the efficiency of crude oil extraction by storing carbon dioxide (CO2) in deep strata and reducing the viscosity of the oil. This technology not only helps to reduce greenhouse gas emissions but also increases the rate of extraction of crude oil, providing a double benefit that makes it a commercially viable technology. However, the challenge with enhanced oil recovery technology is the high cost of facilities, which may limit its development prospects. Ocean sequestration refers to the storage of CO2 in the deep seabed to delay its contact with the atmosphere. The delay in the time of CO2 emissions brings a huge time value. However, ocean storage also has negative impacts, such as excessive CO2 in the ocean leading to acidification of seawater, disrupting the stability of ocean pH values, and ultimately leading to the extinction of deep-sea organisms.

Keywords: Carbon capture and storage, Enhanced oil recovery, Ocean sequestration.

1. Introduction

In recent years, the global demand for energy has increased as a result of the high level of human scientific and technological development. At the same time, environmental and energy crises have become increasingly visible, leading to various extreme weather events and the intensification of climate change. Against this backdrop, it has become a challenge for the global energy sector to realize sustainable energy development while reducing the impact on the environment. One of the key issues is the reduction of greenhouse gas emissions, in particular carbon dioxide (CO2). Its emissions have a serious impact on the global climate. To address this issue, carbon capture, utilization, and storage (CCUS) technologies have turned out to be an area of great interest. These technologies allow CO2 to be captured by various methods and sequestered underground or in other facilities. CCUS technologies include a variety of methods. Carbon capture technologies are categorized as pre-combustion capture, oxygen-enriched combustion, and post-combustion capture. Carbon sequestration can be achieved by land-based sequestration or ocean-based sequestration. The development of these technologies not only helps to reduce greenhouse gas emissions but also helps the world to achieve the goal of sustainable development. In addition, CCUS technology can also be combined with other clean energy technologies to achieve a more integrated energy solution while addressing the singularity of this technology's performance.

In this paper, two of the more cutting-edge practical value technologies discussed today are selected for in-depth study: EOR technology and ocean sequestration technologies, exploring their working principles, application cases, potential impacts on carbon collection and storage, barriers to the technology, and economic costs, respectively. By analyzing these two technologies comprehensively, we can better understand the role of these two technologies and provide a new path for sustainable energy development in the future. Therefore, CCUS technology is considered a key technology in the context of global energy challenges. It can provide a future for sustainable global energy development while minimizing negative impacts on the environment.

2. Enhanced oil recovery technology

2.1. Principles

CCUS technology is capable of capturing carbon dioxide from combustion or industrial processes, transporting it through pipelines, and storing it in depleted reservoirs and deep saline formations to enhance oil recovery [1]. Enhanced oil recovery (EOR) technology injects CO2 into the reservoir where it mixes with the oil causing it to expand, lighten and separate from the rock surface due to the viscosity of the oil. These changes allow the oil to flow more freely within the underground reservoir [2]. This technique can utilize Carbon dioxide to cut oil that cannot be extracted by current waterflooding techniques, and it is the lone of the CCUS methods that can produce valuable merchandise whose vitality partially offsets the cost of capturing CO2 [3]. EOR techniques can also extend the profitable life of an oil field and add extra income [4].

2.2. The advantages of EOR

EOR projects have significant potential to reduce CO2 emissions. The data cited earlier amply demonstrates its remarkable contribution. This is because when EOR is carried out, CO2 captured from the atmosphere is injected in an orderly manner and safely stored underground, thus effectively reducing total greenhouse gas emissions. At the same time, the implementation of EOR significantly improves crude oil recovery, optimizes energy output and results in greater field production. This further improves the efficiency of oilfield development and utilization, thereby reducing the GHG emissions generated during the extraction process. Finally, the technology also allows for the use of underground carbon reservoirs as long-term carbon sequestration banks, which contributes to global greenhouse gas emission reduction targets.

EOR technology presents a more significant commercial value than traditional carbon sequestration and capture technologies. This technology combines the processes of carbon sequestration and oil recovery, as dual benefits are realized. The technology helps in maximizing the extraction of oil resources. EOR Technology allows oil reserves to be extracted more efficiently by improving the flow of oil and reducing the amount of residual crude oil. EOR reduces the concentration of CO2 in the environment while increasing oil production, a feature that has a positive impact on attracting investment and commercial implementation. The resulting economic advantages make it more attractive in the commercial sector and give it the ability to provide economic incentives. EOR technology also allows for the combined use of different energy sources, combining oil resources and clean technologies, thus presenting a merged energy profile, which distinguishes it from the performance homogeneity problem faced by traditional CCS technologies.

There is a strong correlation between EOR technology and the global economy, and this technology could impact the global energy market. Through commercialization, EOR technology may increase the supply of crude oil in the market, thereby affecting the balance between supply and demand in the global energy market. This regulation may have an impact on oil prices and energy market stability, because unstable energy supplies may lead to price volatility and production disruptions. The development and application of this technology requires extensive research, engineering and technological innovation, which provides new business and employment opportunities and promotes economic growth worldwide. In addition, EOR technology contributes to the competitiveness of global economies. In the context of environmentally sustainable development, the adoption of cleaner technologies for crude oil extraction is gradually become mainstream, thereby giving economies a significant advantage in international competition.

2.3. Obstacles of EOR technologies and how to overcome them

In the field of EOR technology, the issue of high cost has been identified as one of the most significant constraints, especially when it comes to EOR projects. The core of an EOR project is a stable supply of CO_2, however, the cost of installing and operating carbon capture equipment is estimated to be in the hundreds of millions of dollars [3], which is a significant expense. The cost of CCUS technology accounts for two-thirds of the total cost of the entire EOR technology [1]. The high economic pressure can limit the widespread use of EOR technology in oil extraction. In the context of low return on investment, shareholders lack economic incentives to invest in CCS technology projects [3]. In addition, a stable and low-cost supply of CO_2 is one of the barriers constraining carbon sequestration-EOR technology. If CO_2 suppliers are profit-driven, the commercial value of CO_2 may be adversely affected, leading to an increase in the cost of CO_2 for EOR, which may also hinder the development of this technology [5]. Finally, carbon sequestration-EOR technology, as an emerging clean technology, has a low level of technological maturity compared to conventional oil recovery technologies. The unstable technology may lead to multiple problems in the oil recovery process, which may harm the environment. The government can encourage investors to participate by implementing carbon incentives to reduce the cost of CO_2 and increase the research and development of carbon sequestration-EOR technologies.

2.4. Feasibility of EOR Technology

EOR technology requires the feasibility of geological conditions, economics and policy. EOR technology enhances crude oil recovery by injecting CO_2 into deep geological formations, and therefore the sealing conditions of the geological formations are critical to prevent CO_2 leakage. However, its high cost and relatively low maturity have constrained the development of carbon capture and storage infrastructure technologies [5]. Mining companies need to calculate costs and profits to assess the feasibility of this technology. Government support is essential for clean technology research and development, and the positive effects of the policy are expected to reduce the cost of CCUS infrastructure technology, thereby increasing the feasibility of EOR.

2.5. Application Cases of EOR Technology

There are many places where carbon sequestration EOR technology is used, with approximately 98 commercial EOR projects in North America alone [3]. For example, the largest EOR project in Canada is located in Weyburn, Saskatchewan. This project uses 325 km of pipeline to transport 95% pure CO_2. In 2000, this project injected 5,000 tons of CO_2/day, and now it is about 6,500 tons of CO_2/day. Since the start of the EOR program, production levels at the Weyburn field have increased by 60%. To date, more than 10 million tons of CO_2 have also been sequestered in this field, and the total sequestration capacity of the field is estimated to be approximately 55 million tons. The project has added billions of dollars to the Saskatchewan economy. In addition, China's EOR technology has also had an impressive track record. By 2022, China's EOR technology had sequestered more than 6.6 million tons of CO_2 and increased recovery by 1 million tons. PetroChina has made outstanding achievements in CO_2 flooding and emission reduction, with 2.12 million tons of CO_2 injected into five CO_2 flooding storage demonstration areas in the Jilin Oilfield. Whether in China or Canada, EOR technology has become mature through the practice of these projects [6].

EOR technology focuses on increasing the efficiency of oil extraction while permanently sequestering CO_2 underground. This process not only helps to reduce greenhouse gas emissions but also promotes sustainable energy. However, the high cost of implementation can lead to some energy consumption issues. This is where we can turn our focus to ocean storage technology. Unlike land-based storage, ocean storage does not require long-distance transportation of CO_2 and facilities, making it a more cost-effective and environmentally friendly option in some cases.

3. Ocean Storage

3.1. Basic principles and technologies of ocean storage

Coastal wetland blue carbon. In the coastal wetland ecosystem, ocean plants represented by mangroves fix CO2 through photosynthesis [7]. with most of it stored in the roots, stems, leaves, and coastal sediments of the plants. Ocean storage is mainly achieved through four types of pumps. Biological Carbon Pump (BP) mainly utilizes the photosynthesis of ocean phytoplankton to fix CO2; Micro Carbon Pump (MCP) uses ocean microorganisms to convert active organic carbon that is difficult to degrade in the ocean into low activity or inert organic carbon; Carbonate Pump (CP), which dissolves CO2 in the ocean and forms calcium carbonate by combining it with calcium ions; The solubility pump (SP) transports CO2 absorbed under low temperature and high salinity conditions from the surface to the deep sea through a series of water body movements such as ocean circulation and flipping [8]. The ocean fertilization method of adding nutrients to a large area of a sea area for a long time to increase the number of plankton in the shallow layer of the ocean to enhance the absorption of CO2 in the atmosphere, and the technology of injecting a large amount of CO2 into the low-lying areas 4000 meters deep in the sea to form a CO2 Lake (referred to as "carbon lake") [8].

Seabed sealing is the technology of injecting CO2 into the pores of sediments such as seafloor peridotite to form carbonates for storage, utilizing oil and gas reservoirs or deep saltwater layers on the seafloor to inject supercritical CO2 for storage, converting CO2 into solid hydrates or mineralized CO2 and burying it in the seafloor (Figure 1) [9].

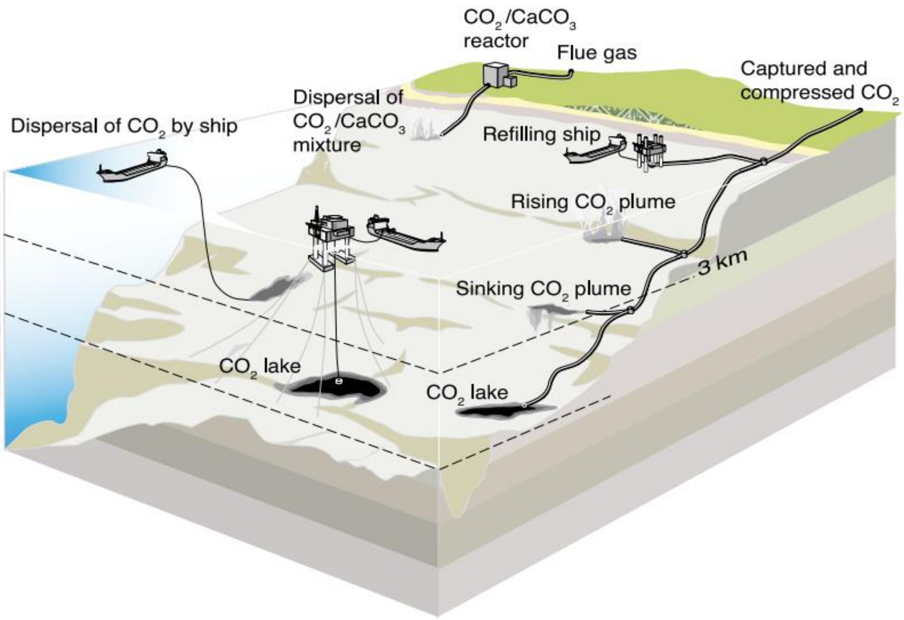

Figure 1. Some of the ocean storage strategies (Artwork courtesy Sean Goddard, University of Exeter)

3.2. The advantages of ocean storage

3.2.1. The Potential of Ocean Storage

Compared to the 750 Gt of carbon stored in the atmosphere, the ocean, as the largest carbon storage site on Earth, can store at least 40000 Gt. According to statistics, the carbon emissions caused by human activities can reach 87 Gt. Most of the 9 Gt of carbon is stored in the ocean in physical form, and only 38 Gt of carbon is emitted into the atmosphere. It is estimated that in the past two centuries, the ocean has absorbed nearly 500 Gt of CO2 caused by human activities. The acidity, alkalinity, and stable concentration of seawater determine the storage capacity of the ocean. After the reaction between CO2 and seawater reaches a chemical equilibrium, shallow CO2 in the ocean could be exchanged with CO2 in the atmosphere. So, depending on the long-term CO2 balance process between the atmosphere and the ocean, a portion of the CO_2 directly injected into the ocean could still appear in the atmosphere. The release of CO_2 directly injected into seawater into the atmosphere does not necessarily mean that the ocean does not have the capacity for large-scale carbon sequestration. However, regardless of whether CO_2 is initially emitted into the atmosphere or the ocean, a significant portion of CO_2 remains stable at concentrations ranging from 350 to 1000 in the atmosphere. After reaching equilibrium, stored in the ocean. In addition, as the alkalinity of the ocean increases (such as carbonate rocks dissolved after weathering), the ability of the ocean to store CO_2 also increases.

3.2.2. The Economy of Ocean Storage

In terms of economy, according to the Net Present Value (NPV) method [10], ocean storage is equivalent to delaying the release of CO_2 into the atmosphere. Its value depends on the cost and economic discount rate of future carbon emissions. If the cost of carbon emissions is lower than the rate of increase in the discount rate, then delayed emissions are considered to have economic value. Overall, the degree of utilization of ocean carbon sequestration reserves depends on various factors such as cost, equilibrium partial pressure p (CO_2), and the environment.

3.3. Application Cases of Ocean Storage

In 1996, Norway launched the Sleipner Oilfield CCS project, which separated the CO_2 generated during oil and gas extraction and injected it back into the saltwater layer through an inclined well, using the airtightness of the geological structure of the seabed saltwater layer to store CO_2. This is the world's first commercial-scale saltwater layer carbon sequestration project, which has been in operation for more than 20 years and stores 1 million tons of CO_2 annually. The stored CO_2 has no abnormal activity or leakage. Denmark has recently launched the "Greensand" carbon storage project, which stores CO_2 from countries such as Denmark under the North Sea seabed to cope with climate change. This is the world's first cross-border carbon sequestration project, and Denmark has become the first country in the world to sequester "imported CO_2". The report states that after the trial operation phase of the project, 1.5 million tons of CO_2 are stored annually. By 2030, it will have the ability to store 8 million tons of CO_2 annually. On August 28, 2021, CNOOC announced that it would begin to demonstrate China's first carbon undersea storage project in the Pearl River Mouth Basin, becoming the fourth country to carry out carbon undersea storage after Norway, Brazil and Australia.

3.4. Obstacles and detection measures of ocean storage technology

Although ocean carbon sequestration is a new CCS technology with great storage potential. However, the risks of this technology cannot be ignored. For example, the injection of CO_2 into water bodies leads to ocean acidification; If carbon sequestration is adopted in the seabed formation, it may lead to leakage due to changes in pressure during injection or an increase in the temperature of water compounds.

Ocean acidification can also increase the concentration of heavy metal ions in the ocean. The principle is that the acidified seawater releases heavy metal ions from sediment, which pollutes the seawater. The acidified seawater can also enhance the toxicity of heavy metal ions, affecting the safety of local ocean organisms. The physiological adaptability of ocean organisms may have reached its limit within a regional range, therefore, the increase in CO_2 content in the ocean caused by CO_2 leakage and the resulting pH changes have a huge impact on ocean species.

At present, remote-controlled underwater robots equipped with high-resolution cameras can be used to directly observe and detect the leakage of CO_2 in the ocean. CO_2 leakage leads to an increase in the CO_2 content in the ocean, resulting in changes in pH values, as well as an increase in the concentration of heavy metal ions in the ocean caused by ocean acidification, which has a significant impact on the ocean environment. Therefore, attention should be paid to studying the changes in pH values and metal ion concentrations in the sea area at all times. At the same time, technologies such as pH sensors and high-precision in-situ and airborne metal ion concentration sensors are used to quickly detect the amount of CO2 leakage in water bodies. μ Meson tomography technology, as a low-cost, efficient, and high-definition technology, can detect density changes in oil and gas reservoirs and determine whether there is a CO2 leak based on this, thus conducting preventive interventions.

4. Conclusion

This article discusses two cutting-edge and practical technologies, namely EOR and ocean storage. At present, carbon sequestration technology has become a major concern of the international community. Under the measures of energy conservation and emission reduction, it is still impossible to limit the temperature rise to within 1.5°C compared to pre-industrial levels. However, in today's era, fossil energy consumption still accounts for a large proportion, so a large amount of carbon emissions is inevitable. Nowadays, EOR technology realizes CCUS in the environment while crude oil is being extracted, reducing the pressure of greenhouse gas emissions. After considering the advantages and disadvantages of the technology, certain feasibility and uniqueness can be observed. However, the commercial application of the technology still faces a series of challenges, such as high cost, technology maturity and stable CO2 supply. Nevertheless, it is possible to overcome these obstacles through policy incentives and the promotion of international cooperation. With such measures, carbon sequestration EOR technology is gradually mature and show significant feasibility as one of the important solutions to reduce greenhouse gas emissions.

The existence of ocean storage technology has also effectively alleviated the harm of CO2 direct emissions to the atmosphere. Meanwhile, the main technologies for ocean storage include ocean sediment storage, biological pump ocean storage, and seabed sealing. Although ocean storage technology is a recently proposed technology that poses risks of leakage, high costs, and incomplete laws, it still has great potential. As the world's largest carbon emitter, China is facing huge emission reduction tasks every year. Ocean storage technology could effectively utilize the potential of ocean storage and ocean geological conditions, and use ocean carbon storage as a new path. At the same time, enhanced solidification measures could be taken to improve the efficiency of the carbon sequestration process.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Adu, E., Zhang, Y., & Liu, D. Current situation of carbon dioxide capture, storage, and enhanced oil recovery in the oil and gas industry. Canadian Journal of Chemical Engineering, 2019, 97 (5), 1048 – 1076.

[2] Azzolina, N. A., Peck, W. D., Hamling, J. A., Gorecki, C. D., Ayash, S. C., Doll, T., Nakles, D. V., & Melzer, L. S. How green is my oil? A detailed look at greenhouse gas accounting for Carbon dioxide-enhanced oil recovery (Carbon dioxide-EOR) sites. International Journal of Greenhouse Gas Control, 2016, 51, 369 – 379.

[3] Brawn, B., & Lewis, I. Enhanced oil recovery through carbon capture and storage an opportunity for Alberta. Alberta Economic Development Authority, 2009.

[4] Roefs, P., Moretti, M., Welkenhuysen, K., Piessens, K., & Compernolle, T. Carbon dioxide-enhanced oil recovery and Carbon dioxide capture and storage: An environmental economic trade-off analysis. Journal of Environmental Management, 2019, 239, 167 – 177.

[5] Zhu, L., Yao, X., & Zhang, X. Evaluation of cooperative mitigation: captured carbon dioxide for enhanced oil recovery. Mitigation and Adaptation Strategies for Global Change, 2020, 25 (7), 1261 – 1285.

[6] Yuan, S., Ma, D., Li, J., Zhou, T., Ji, Z., & Han, H. Progress and prospects of carbon dioxide capture, EOR-utilization and storage industrialization. Petroleum Exploration and Development, 2022, 49 (4), 955 – 962.

[7] Wang Faming, Tang Jianwu, Ye Siyuan, et al The Blue Carbon Sink Function and Carbon Neutralization Strategies of Coastal Wetlands in China [J]. Journal of the Chinese Academy of Sciences, 2021, 36 (3): 241 - 251.

[8] Sun Yujing, Zhou Lifa, Li Yue. Development Status of Carbon dioxide Marine Storage in 2018. Geological Science and Technology Intelligence. 2018.

[9] Liu bo, Gao Shuo, Xu Zhenqiang, Fu Xiaofei, Erfan Mohammadian, Lu Hongfeng, Yan Baiquan, Shi Weiguang, Yang Zhen, Xu Chenlu, PAN Zhejun. Overview of Direct Injection Carbon dioxide Storage Technology and Methods into the Ocean. Geological Review. 2023.

[10] Kheshgi H S, Archer D. A nonlinear convolution model for the evasion of Carbon dioxide injected into the deep ocean. Journal of Geophysical Research: Oceans, 2004. 109 (C2): C02007.