


Review

Application and Development Countermeasures of CCUS Technology in China's Petroleum Industry

Xingxiang Che ^{1,*} , Xiangyi Yi ¹, Zhaohui Dai ¹, Ziwei Zhang ² and Yun Zhang ³¹ College of Energy, Chengdu University of Technology, Chengdu 610059, China² Chengdu Urban Safety and Emergency Management Research Institute, Chengdu 610023, China³ Shanghai Base, Production Optimization, China Oilfield Services Limited (COSL), Shanghai 200335, China

* Correspondence: chexx@stu.cdut.edu.cn

Abstract: Greenhouse gas emissions cause many global problems. Under the strong promotion of the government's two-carbon goals policy, China's petroleum industry is actively carrying out the application of carbon capture, utilization, and storage (CCUS). The energy consumption and carbon emissions in China are reviewed, and the importance of the petroleum industry in the process of carbon emission reduction is clarified. The applications, advantages, and disadvantages of carbon capture, carbon utilization, and carbon sequestration technologies in China's petroleum industry are summarized, respectively. The current challenges and risks faced by China's petroleum industry in the operation of CCUS projects are analyzed, and corresponding suggestions are provided. This article aims to systematically provide references and help for the application of CCUS in China's petroleum industry.

Keywords: CCUS; carbon emission; petroleum industry; China



Citation: Che, X.; Yi, X.; Dai, Z.; Zhang, Z.; Zhang, Y. Application and Development Countermeasures of CCUS Technology in China's Petroleum Industry. *Atmosphere* **2022**, *13*, 1757. <https://doi.org/10.3390/atmos13111757>

Academic Editors: Liang Huang, Dali Hou, Qian Sun and Yu Yang

Received: 30 September 2022

Accepted: 22 October 2022

Published: 25 October 2022

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1. Introduction

Climate change affects human survival and social development, and is a global issue that has attracted international attention. In September 2020, the Chinese government proposed two-carbon goals at the United Nations General Assembly; that is, the goals of "carbon peaking" in 2030 and "carbon neutrality" in 2060 [1–3]. According to the China Carbon Dioxide Capture, Utilization and Storage (CCUS) Annual Report (2021) issued by the Environmental Planning Institute of the Ministry of Ecology and Environment of the People's Republic of China, by the end of 2020, about 40 CCUS demonstration projects had been put into operation or were under construction in China [4–7]. These mainly focus on small-scale oil capture and displacement demonstrations in petroleum, coal chemicals, and power industries; and on the development of the carbon dioxide-enhanced oil recovery (CO₂-EOR) project. As typical energy-intensive industries, the oil, gas, and coal industries have become the main experimental and research objects of CCUS technology when it was first proposed. The natural storage environment of oil and gas fields also provides new ideas for CO₂ storage. CO₂ injection proved to positively impact the production from near-abandoned oil and gas wells at a lower cost than conventional refract. The research results have also greatly stimulated the enthusiasm of the oil and gas industries to promote the further development of CCUS technology [8]. China's three major state-owned oil companies (PetroChina, Sinopec, and CNOOC), which are the main controllers of China's petroleum industry, are also actively promoting the two-carbon goals.

China attaches great importance to the basic research and technology development of CCUS. In 2003, China funded the first CCUS-related research funded by the National Science and Technology Program through the National Natural Science Foundation. In 2011 alone, 36 studies were supported by the National Science and Technology Program. By the end of the "Twelfth Five-Year Plan" period, more than 140 research projects had been funded by the National Science and Technology Program, mainly in capture and

storage technologies. In 2021, the National Natural Science Foundation of China launched the research on major basic scientific problems and countermeasures for national carbon neutrality; and will carry out special funding work for CCUS theory, technology, database, risk assessment, and other aspects [9–14].

CCUS technology is an internationally recognized carbon emission reduction technology. The early construction and operation costs of carbon capture and storage (CCS) were high, and only capital input had no output benefits, which limited the development of CCS technology. Later, CCUS technology strengthened the research and development of CO₂ utilization. Converting CO₂ into energy or substance has realized carbon cycle rebalancing, increased the economic benefits of CCUS, and made it the most practical and feasible technical solution to reduce carbon emissions on a large scale [15–17]. In China, CCUS still has a large development space and funding gap. According to the technology development roadmap of the Ministry of Science and Technology, it is necessary to realize the extensive deployment of CCUS and new regional formats in 2050, with the carbon dioxide utilization and storage capacity reaching 800 Mt/a [18,19].

This paper will first summarize China's energy consumption and carbon emissions to illustrate the urgency and necessity of developing CCUS technology. Then, we will talk about the application of capture, utilization, and storage in China's petroleum industry at this stage; and analyze the effects, challenges, and policy prospects.

2. Energy Consumption and Carbon Emissions in China

Since China joined the WTO in 2003, as the world factory, it has produced a large number of daily necessities for most countries in the world. However, rapid economic development and extensive industrial production have resulted in large energy use (Figure 1) [20] and a huge amount of carbon emissions (Figure 2) [21–23]. At the same time, it can also be seen that the growth rate of total carbon emissions in recent years has been significantly slower than that of energy consumption, which indicates that the intensity of carbon emissions has decreased significantly. The growth rate of China's energy consumption will slow down further and the elasticity coefficient of energy consumption will also decline, which is lower than the level at the beginning of the 21st century. After 2035, China's energy consumption will enter a low growth period of about 2% [24,25]. Clean, low-carbon, and efficient energy consumption has become an inevitable trend in China [26].

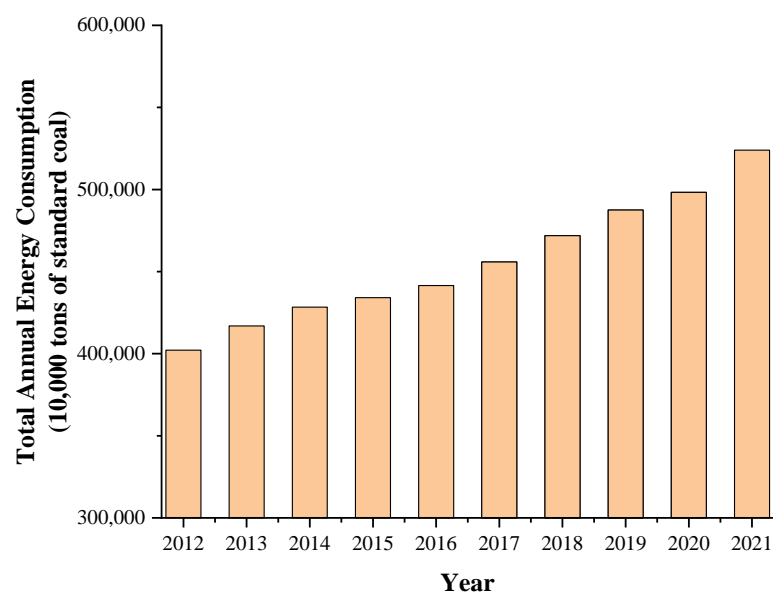


Figure 1. China's energy consumption over the years.

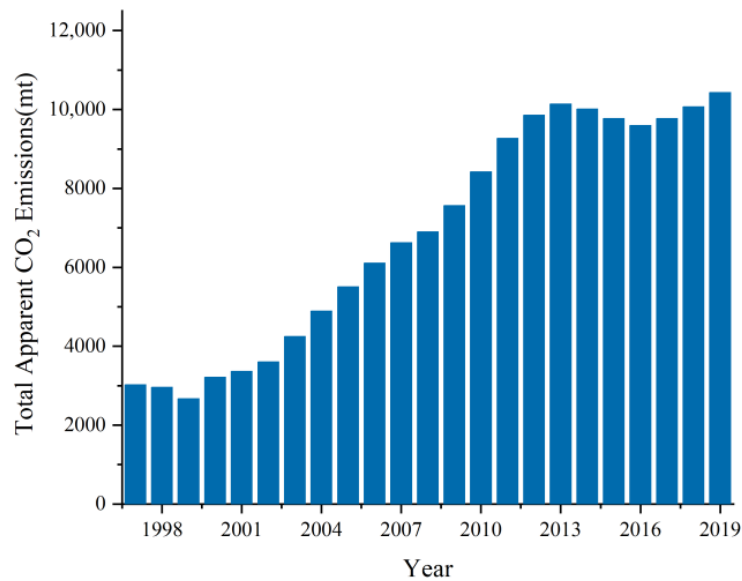


Figure 2. China’s total apparent CO₂ emissions over the years.

As China’s economic development has gradually entered a new normal stage, the optimization and adjustment of the industrial structure, the demand for energy, and the environmental protection requirements have promoted the development of China’s energy in a cleaner, more efficient, more intensive, lower carbon, and more diversified direction. At this stage, China is in an important period of energy transformation. The substitution effect of low-carbon and clean energy on coal has been significantly enhanced, and the policy of energy conservation and consumption reduction will continue to be promoted. In the past, China’s economic development relied too much on the consumption of carbon energy. Coal is a major component of China’s energy consumption [27]. Overall, the proportion of coal consumption has gradually decreased, while the proportion of natural gas, primary electricity, and other energy sources has gradually increased (Figure 3) [20]. Economic development plays a leading role in the growth of natural gas consumption demand. According to this trend, natural gas use will continue to grow steadily. While the total amount of carbon emissions increases and the emission intensity gradually decreases, carbon capture, utilization, and storage of CO₂ are important means to achieve carbon neutrality [7,28,29].

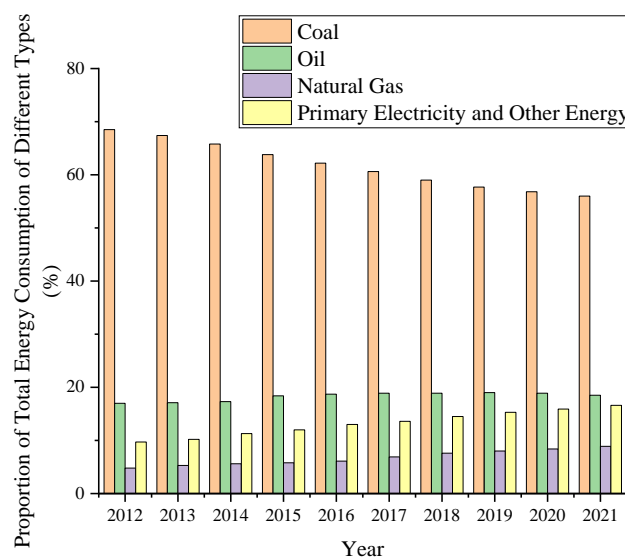


Figure 3. The proportion of total energy consumption of different types.

3. Progress of CCUS Technology in China's Petroleum Industry

In recent years, international oil companies have actively announced the carbon peak and carbon neutral targets under the national level of vigorously promoting greenhouse gas emission reduction measures. Among them, the oil company alliance represented by the Oil and Gas Industry Climate Initiative (OGCI) has set an example, and actively set emission reduction targets and scope [30]. Some well-known international oilfield technology service companies, such as Schlumberger, Halliburton, Baker Hughes, and National Oilwell Varco, have carried out corresponding new energy business [31], setting 2050 as the deadline for achieving net zero carbon emissions. Chinese oil companies are also vigorously promoting the application of CCUS.

3.1. Carbon Capture

From the perspective of the capture process, it mainly includes capture after combustion, capture before combustion, and capture by oxygen-enriched combustion. In terms of capture methods, they mainly include the chemical absorption method, physical adsorption method, membrane separation method, low-temperature distillation method, etc. [32–34]. Among them, the chemical absorption method is the most commonly used capture method for Chinese oil companies. For example, chemical absorption method is used for CO₂ capture in the refinery tail gas capture project of Zhongyuan Oilfield and the high carbon natural gas capture project of Songnan Gas Field.

The main reason for the high cost of carbon capture is a large amount of energy consumption in the capture process. Therefore, reducing the energy demand in the process of carbon capture is the main research direction of carbon capture development at this stage [35].

3.2. Carbon Utilization

In the petroleum industry, it is mainly divided into two aspects: geological utilization and geological storage. CO₂ geological utilization refers to the technology of injecting CO₂ into the reservoir to improve the recovery efficiency. It can be subdivided into the following categories: CO₂ enhanced oil recovery (CO₂-EOR), CO₂ enhanced coalbed methane recovery (CO₂-ECBM), CO₂ enhanced natural gas recovery (CO₂-ENGR), CO₂ enhanced shale gas recovery (CO₂-ESGR), CO₂ enhanced saline water recovery (CO₂-ESWR), and CO₂ storage in a depleted reservoir (CO₂-SDR) [36–38]. CO₂ geological utilization technology can reduce the CO₂ utilization cost by replacing CO₂ with formation resources, which is conducive to large-scale industrial promotion and application.

CO₂-EOR can be used and stored synchronously. At present, a large number of projects have been applied and certain economic benefits can be achieved [39]. As of 7 August 2022, PetroChina Jidong Oilfield has applied CO₂ huff and puff, and CO₂ oil displacement technology in the reservoir; in addition, it has achieved a significant production increase. The accumulated comprehensive utilization of CO₂ exceeds 108×10^4 t; a cumulative oil increase of 98×10^4 t. On 29 August 2022, Sinopec announced that the “Qilu Petrochemical Shengli Oilfield Million ton CCUS Project”, China’s largest demonstration base for carbon capture, utilization, and storage of the whole industrial chain, was officially put into operation. This marks that China’s CCUS industry has entered the middle and late stage of technology demonstration—mature commercial operation. The project covers more than 25 million tons of ultra-low permeability reservoir reserves and 73 injection wells are deployed. It is estimated that the cumulative injection of more than 10 million tons in 2015 will increase oil by nearly 3 million tons and the recovery factor will increase by more than 12%. The primary storage rate of CO₂ can reach 60% to 70%.

3.3. Carbon Storage

With the significant reduction of CCUS technology cost and energy consumption, CO₂ storage technology is used as a supplement to CO₂ geological utilization. Carbon storage technology is mainly used to inject captured CO₂ into deep salt water layers, deep coal

seams and oilfields without commercial exploitation value, depleted natural gas fields, etc. [40–42]. The deep salt water layer is widely distributed in the inland and marine sedimentary basins of China. Because of its huge CO₂ storage space and long CO₂ injection duration, it is conducive to the implementation of large capacity CO₂ geological storage projects. Therefore, CO₂ deep salt water layer storage technology is considered as one of the technologies with the most CO₂ storage potential.

The China Shenhua Coal to Liquid Deep Salt Water Layer CO₂ Capture and Storage (CCS) Demonstration Project has accumulatively injected 3×10^5 t CO₂; it is currently the largest CO₂ saline water layer storage project in Asia [43]. However, in order to ensure the feasibility and safety of geological storage, and prevent potential environmental risks, such as fault activation and earthquake events that may be induced, the pollution of freshwater aquifers caused by carbon dioxide escape, and leakage endangering human health and local ecosystems nearby, a large number of geological surveys, sampling, and analysis have been carried out in the early stages of the project, as well as multiple fracturing treatments [44]. After injection, several sets of detection systems were installed for continuous monitoring. These have greatly increased the project cost. China's oil companies have also carried out CO₂ storage for many years. The storage area varies from 1.2 km² to 60.8 km². The total injection amount also ranges from 1×10^4 t to 30×10^4 t.

4. Challenges and Development Countermeasures

4.1. Challenges Faced by Large-Scale Applications

China's CCUS technology started later than that in Europe and the United States. Capture technology: the pre-combustion capture technology is relatively mature and some of them have commercial capabilities. The post-combustion capture technology is at the primary application stage; especially, the post-combustion chemical absorption method has a large gap with its international leading commercial application. The second generation capture technology is still in the development stage [45–47]. Transportation: land transportation and inland ship transportation technologies have been relatively mature. However, the design of the supporting land transmission pipeline and pipe network is still in the early stage. For the development of submarine pipeline transportation technology, it is still in the conceptual design stage [48,49]. Utilization: CCUS-EOR and other projects are still in the stage of industrial demonstration research and development. Storage: the demonstration project of seabed CO₂ storage has not been carried out yet. The volume of other storage projects is significantly different from that of Europe, America, and other regions [35].

At present, local governments and oil enterprises have shown high enthusiasm for CCUS; however, once the project is approved or implemented, it is difficult to promote it. The large-scale application of CCUS in China's petroleum industry faces many challenges, including technology, environment, capital, and policy [50–53]:

(1) High investment cost. The investment subjects of CCUS technology are basically state-owned energy enterprises. The initial investment and maintenance costs of the whole process are high, and the payback period is long. The high investment cost is the main reason hindering the large-scale industrialization of CCUS.

(2) Lack of CO₂ gas sources. The scale of available CO₂ sources in major Chinese oil companies is small and scattered. The lack of matching bridges between oil fields and carbon sources also makes it difficult for oil companies to start large-scale CO₂ flooding and storage projects.

(3) The technical level of CCUS still needs to be developed. Generally speaking, China's CCUS technology is in the stage of industrialization and testing; and there is still a gap between it and the international advanced level. At present, there are still a lot of technical problems that need to be solved or improved in the application of CCUS technology in China's petroleum industry.

(4) Environmental safety. There are certain environmental risks in the process of CO₂ capture, transportation, utilization, and storage.

(5) Low market participation. At present, China's CCUS applications are mainly government-driven projects; and private enterprises are less involved in the research and development, and promotion of this technology. Therefore, Chinese oil companies should effectively promote diversified market players to enter the CCUS cooperation and competition.

(6) Lack of collaborative cooperation. The application and promotion of CCUS requires the joint cooperation of multiple industries and multiple parts. Except for a small amount of cooperation in the power and oil industries, there is currently less cross-industry cooperation.

(7) The standards and specifications are not clear. Due to the small number of operating projects, there is a lack of clear industry standards and operating specifications, which in turn limits the large-scale application of CCUS.

(8) Insufficient policy coordination. The advancement of the CCUS project depends on the government's financial and policy support. Support should highlight not only economic benefits, but also social benefits. At present, the policies introduced by various departments are relatively independent and lack corresponding coordination.

4.2. Development Strategy

The development of technology is not achieved overnight. The government, society, and enterprises need to coordinate and cooperate from various aspects. In the face of these challenges, the following development strategies are proposed [54–56]:

(1) Strengthen key technology research. It is suggested that the government should coordinate enterprises and research institutions to jointly tackle key problems and promote collaborative innovation. Focusing on key links, such as carbon dioxide capture, industrial utilization, sequestration, and carbon sink measurement, we will tackle key problems in core technology and promote the technological upgrading of CCUS's entire industrial chain.

(2) Methods and standard system construction. This is an important link to realize the standardization of CCUS industrial development. CCUS standard specification systems and management systems need to be established; establish a series of standards and specifications covering CO₂ capture, transmission, storage, monitoring and evaluation, emission reduction verification, etc.

(3) Establish a good CCUS financial ecology. CCUS is a technology with a high investment risk. Reasonable and effective CCUS investment and financing channels play a vital role in industrial development. Building a good CCUS financial ecology can accelerate the sound development of its industry.

(4) Accelerate CCUS pipeline network layout and cluster infrastructure construction; increase the investment in relevant infrastructure and strengthen the construction of a transport network; to form a CCUS industrial center based on pipe network facilities and storage sites.

(5) Incorporate CCUS into the carbon emission trading system; formulate supporting systems and methods; reasonably allocate quotas; and clarify emission reduction throughout the life cycle. Thus, it will bring certain economic income to enterprises applying CCUS technology and absorb some carbon sequestration costs.

(6) The government should improve the fiscal and tax incentive policies, and laws and regulations system. CCUS should enjoy the same supporting policy support as renewable energy and other low-carbon clean energy technologies. Industry norms, the system and regulatory framework, and technical specifications should also be improved.

5. Summary and Recommendations

Chinese oil companies mainly use the most promising chemical absorption method for CO₂ capture. CO₂ oil displacement technology can realize storage and utilization simultaneously; and Sinopec and PetroChina have both carried out large-scale application. CO₂ storage technology has greatly improved the CO₂ emission reduction capacity, which has been carried out by Chinese oil companies for many years and has achieved good results.

The large-scale application of CCUS in China's petroleum industry is facing many challenges. These include technology, environment, capital, market, standards, policies, and other aspects. The government, enterprises, and research institutions shall make overall plans for development and collaborative innovation; promote the development of CCUS core technology; establish a good ecology, reasonable standards, and norms; accelerate the construction of a CCUS pipeline network and infrastructure; incorporate CCUS into the carbon emission trading system; improve the fiscal and tax incentive policies, and laws and regulations system; improve the core competitiveness of CCUS technology in an all-round way; control greenhouse gas emissions; and improve energy and resource utilization efficiency.

Author Contributions: Conceptualization, X.C. and X.Y.; methodology, X.Y.; investigation, X.C. and Z.Z.; writing—original draft preparation, X.C.; writing—review and editing, X.C.; visualization, Y.Z.; supervision, X.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Publicly available datasets were analyzed in this study. This data can be found here: [<https://data.stats.gov.cn/easyquery.htm?cn=C01>; <https://www.ceads.net.cn/>], accessed on 29 September 2022.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Xie, H.; Wu, L.; Zheng, D. Prediction on The Energy Consumption and Coal Demand of China in 2025. *J. China Coal Soc.* **2019**, *44*, 1949–1960.
2. Zhao, M.; Li, L.; Zhang, B.; Luo, H. Dynamic Relationship Among Energy Consumption. *Econ. Growth Carbon Emiss. China* **2021**, *34*, 1509–1522.
3. Ming, Z. *Research on the Spatial and Temporal Evolution of Coupling Degree and Optimization of Decoupling Economic Growth from Energy Consumption in China*; China University of Geosciences: Wuhan, China, 2019.
4. Wu, Z.; Wang, Q.; Pang, X.; Li, J.; Han, Z.; Lu, Y.; Zhang, B.; Wang, J. Progress and Trends of Carbon Capture Utilization and Storage Technology. *Ecol. Environ. Monit. Three Gorges* **2022**, *36*, 2213–2232, *in press*.
5. Qin, J.; Li, Y.; Wu, D.; Weng, H.; Wang, G. CCUS Global Progress and China's Policy Suggestions. *Pet. Geol. Recovery Effic.* **2020**, *27*, 20–28.
6. Liu, Y.; Chen, L. Inter-connection between Hydrogen Energy and CCUS Technology Targeting Goal of Carbon Neutrality. *Energy Energy Conserv.* **2022**, *02*, 15–17.
7. Li, Y.; Zhao, Q.; Xue, Z. CCUS Technological and Industrialization Development Path under the Target of Carbon Peaking and Carbon Neutrality. *Oil Drill. Prod. Technol.* **2022**, *18*, 1837–1846, *in press*.
8. Xue, H. Strategic Study on “Carbon Neutrality” Targeted CCUS Development in China Petroleum Industry. *Pet. Energy* **2021**, *33*, 67–70.
9. Zhao, Z.; Yao, S.; Yang, S.; Wang, X. Under Goals of Carbon Peaking and Carbon Neutrality: Status, Problems and Suggestions of CCUS in China. *Environ. Sci.* **2022**, *in press*. [[CrossRef](#)]
10. Huang, J.; Mao, Q.; Shi, M.; Peng, X.; Zhang, X. Process and Suggestions of CCUS Technology Development from the Perspective of Carbon Neutrality. *Environ. Impact Assess.* **2022**, *44*, 42–47.
11. Dong, R.; Gao, L.; He, S.; Yang, D. Significance and Challenges of CCUS Technology for Low-carbon Transformation of China's Power Industry. *Power Gener. Technol.* **2022**, *43*, 523–532.
12. Wu, Y. Advances and Application of CCUS Technology. *Mod. Chem. Res.* **2022**, *11*, 118–120.
13. Xiang, Y.; Hou, L.; Du, M.; Jia, N.; Lu, W. Research Progress and Development Prospect of CCUS-EOR Technologies in China. *Pet. Geol. Recovery Effic.* **2022**, *31*, 1716–1732, *in press*.
14. Xu, M.; Zhang, X.; Fan, J.; Gao, L.; Xu, D. Status Quo, Opportunities and Challenges of Integrated Application of Coal-to-hydrogen and CCUS Technology in China. *J. Min. Sci. Technol.* **2021**, *6*, 659–666.
15. Xie, H.; Wang, Y.; Chu, W.; Ju, Y. Mineralization of flue gas CO₂ with coproduction of valuable magnesium carbonate by means of magnesium chloride. *Chin. Sci. Bull.* **2014**, *59*, 2882–2889. [[CrossRef](#)]
16. Xie, H.; Liu, T.; Hou, Z. Using electrochemical process to mineralize CO₂ and separate Ca²⁺/Mg²⁺ ions from hard water to produce high value-added carbonates. *Environ. Earth Sci.* **2015**, *73*, 6881–6890. [[CrossRef](#)]

17. Xie, H.; Wang, J.; Hou, Z. CO₂ sequestration through mineral carbonation of waste phosphogypsum using the technique of membrane electrolysis. *Environ. Earth Sci.* **2016**, *75*, 1–11. [[CrossRef](#)]
18. China Agenda 21 Management Center, Department of Science and Technology for Social Development, Ministry of Science and Technology. *China's Roadmap for Carbon Capture, Utilization and Storage Technology Development*; Science Press: Beijing, China, 2019.
19. Cai, B.; Li, Q.; Zhang, X.; Cao, C.; Chen, W.; Dong, J. *China Carbon Dioxide Capture, Utilization and Storage (CCUS) Annual Report (2021)-China CCUS Path Study*; Institute of Environmental Planning, Ministry of Ecology and Environment, Wuhan Institute of Geotechnical Mechanics, Chinese Academy of Sciences, China Agenda 21 Management Center: Beijing, China, 2021.
20. China National Bureau of Statistics. Available online: <https://data.stats.gov.cn/easyquery.htm?cn=C01> (accessed on 30 September 2022).
21. Shan, Y.; Guan, D.; Zheng, H. China CO₂ emission accounts 1997–2015. *Sci. Data* **2018**, *5*, 170201. [[CrossRef](#)]
22. Shan, Y.; Huang, Q.; Guan, D.; Hubacek, K. China CO₂ emission accounts 2016–2017. *Sci. Data* **2020**, *7*, 54. [[CrossRef](#)]
23. Guan, Y.; Shan, Y.; Huang, Q.; Chen, H.; Wang, D.; Hubacek, K. Assessment to China's recent emission pattern shifts. *Earth's Future* **2021**, *9*, e2021EF002241. [[CrossRef](#)]
24. Yu, W.; Wang, A.; Wang, G. A prediction on the time of realizing zero growth of energy consumption in China. *Diqiu Xuebao (Acta Geosci. Sin.)* **2010**, *31*, 635–644.
25. Fan, J.; Li, P. Analysis on the future energy consumption and preliminary discussion on carbon emission of China from the perspective urbanization. *Adv. Earth Sci.* **2011**, *26*, 57–65.
26. Li, H.; Zhang, J. China's Energy Consumption Structure and Forecast on Natural Gas Demand. *Ecol. Econ.* **2021**, *37*, 71–78.
27. Sang, S.; Yuan, L.; Liu, S.; Han, S.; Zheng, S.; Liu, T.; Zhou, X.; Wang, R. Geological Technology for Carbon Neutrality and its Application Prospect for Low Carbon Coal Exploitation and Utilization. *J. China Coal Soc.* **2022**, *47*, 1430–1451.
28. Guo, Y. Analysis of Carbon Capture, Utilization and Storage in Oil and Gas Industry. *J. Test Meas. Technol.* **2022**, *36*, 86–92.
29. Ma, S.; Fan, S.; Wu, K.; Yang, P.; Chen, L. CCUS Technology Development of Coal-Fired Power Plant under the Background of Dual Carbon Strategy: Challenges and Countermeasures. *Clean Coal Technol.* **2022**, *28*, 1–13.
30. Zhao, Z.; Dou, L.; Gao, F.; Wang, X.; Yan, W.; Wang, Z.; He, X.; Peng, Y. Strategies of IOCs to Cope with the Challenge of “Dual Carbon” Goal and Enlightenment. *Int. Pet. Econ.* **2022**, *30*, 8–22.
31. Ding, G. Current Situation and Prospects of Carbon Capture, Utilization and Sequestration Business of International Oilfield Services Companies. *World Pet. Ind.* **2022**, *29*, 28–33.
32. Sang, S.; Liu, S.; Lu, S.; Zhu, Q.; Wang, M.; Han, S.; Liu, T.; Zheng, S. Engineered Full Flowsheet Technology of CCUS and Tts Research Progress. *Pet. Reserv. Eval. Dev.* **2022**, *12*, 711–725+733.
33. Nie, L.; Jiang, D.; Li, X. Relationship between CCUS Technology and Low Carbon Development of China Coal-Based Energy. *Coal Econ. Res.* **2015**, *35*, 16–20.
34. Zhang, X. The Application Prospect of CCUS in China under the Target of Carbon Neutrality. *China Sustain. Trib.* **2020**, *12*, 22–24.
35. Miao, J.; Yang, G. Status and Prospect of CO₂ Capture and Oil Displacement in China. *Pet. Petrochem. Today* **2020**, *28*, 32–37.
36. Li, X.; Mei, K.; Cai, Y.; Zhang, L. Improvement of CO₂ Sequestration Intension with Collaborative Pumping-injection Technologies in Multi-formations. *Adv. Eng. Sci.* **2022**, *54*, 167–176.
37. Li, H.; Wang, Q. Study of CO₂ Utilization and Geological Storage in CCUS. *Mod. Chem. Ind.* **2022**, *15*, 783–791, *in press*.
38. Zhang, L.; Wang, Y.; Miao, X.; Gan, M.; Li, X. Geochemistry in Geologic CO₂ Utilization and Storage: A Brief Review. *Adv. Geo-Energy Res.* **2019**, *3*, 304–313. [[CrossRef](#)]
39. Wei, Z.; Li, Y.; Omambia, A.N. Reactive Transport Modeling of Effects of Convective Mixing on Long-term CO₂ Geological Storage in Deep Saline Formations. *Int. J. Greenh. Gas Control.* **2011**, *5*, 241–256.
40. Gan, M.; Miao, X.; Zhang, L.; Wang, Y.; Li, X. Review on Applications of CT Scanning Technique in the Field of CO₂ Geological Utilization and Storage. *Water Resour. Hydropower Eng.* **2019**, *50*, 174–184.
41. Xia, Y.; Xu, T.; Yang, Z. Factors Influencing Amount of CO₂ Leakage through a Fault Zone in Deep Storage Aquifer. *Res. Environ. Sci.* **2017**, *30*, 1533–1541.
42. Li, Q.; Cai, B.; Chen, F.; Liu, G.; Liu, L. Review of Environmental Risk Assessment Methods for Carbon Dioxide Geological Storage. *Environ. Eng.* **2019**, *37*, 13–21.
43. Li, X.; Li, Q.; Bai, B.; Wei, N.; Yuan, W. The Geomechanics of Shenhua Carbon Dioxide Capture and Storage(CCS) Demonstration Project in Ordos Basin, China. *J. Rock Mech. Geotech. Eng.* **2016**, *8*, 948–966. [[CrossRef](#)]
44. Ma, J.; Yang, Y.; Cai, B.; Cao, L.B.; Zhou, Y.; Li, Q. Environmental Monitoring Range for Different Types of CO₂ Geologic Sequestration Projects and Its Related Issues. *Environ. Eng.* **2018**, *36*, 10–14.
45. Lu, S.; Zhang, J.; Liu, L.; Kang, G.; Zhu, J.; Li, Q. Progress and development trend of industrial carbon dioxide capture technology. *Mod. Chem. Ind.* **2022**, *13*, 1371–1378, *in press*.
46. Lei, T.; Yu, S.; Zhou, C.; Song, L.; Ma, K.; Yue, H. Research progress on the shaping technology of solid amine adsorbents for CO₂ capture by adsorption method. *Chem. Ind. Eng. Progress* **2022**, *in press*. [[CrossRef](#)]
47. Zhao, R.; Ma, W.; Xu, X.; Li, C.; Ma, G.; Zhang, Q. Research progress of carbon dioxide capture chemical absorbents. *Fine Chem.* **2022**, *in press*. [[CrossRef](#)]
48. Wang, T.; Bai, D.; Jiang, Y. On Establishment of Supervision of Carbon Dioxide Transport in China. *Sci. Decis. Mak.* **2022**, *03*, 112–122.

49. Zhai, M.; Lin, Q.; Wang, X.; Gao, R.; Tao, H.; Jiang, S.; Wang, H.; Liang, K. Development of an optimization model for planning carbon dioxide pipeline transportation system and its application. *J. Harbin Inst. Technol.* **2017**, *49*, 116–122.
50. Liu, B. Challenges and Countermeasures for Oil and Gas Fields to Promote Application of CCUS Technology. *Pet. Sci. Technol. Forum* **2022**, *41*, 34–42.
51. Mi, J.; Ma, X. Development Trend Analysis of Carbon Capture, Utilization and Storage Technology in China. *Proc. CSEE* **2019**, *39*, 2537–2544.
52. Zhang, F. Challenges, Countermeasures and Development Direction of CCUS Industrialization Mode Under ‘Carbon emission peaking’ and ‘carbon Neutrality’ Goals. *Mod. Chem. Ind.* **2022**, *42*, 13–17.
53. Wu, Q.; Shen, J.; Du, X.; Li, Y.; Zhang, J.; Ai, Y. Analysis on the Pressurization in Supercritical Carbon Dioxide Transport. *Pet. New Energy* **2022**, *34*, 68–74.
54. Qin, Z.; Xiao, G.; Wang, J.; Liu, Y. A Review of CO₂ Storage Technology and Perspective of CO₂ Storage in the Nearshore Area of South China. *Mar. Geol. Front.* **2012**, *28*, 40–45.
55. Ma, B.; Jia, L.; Yu, Y.; Wang, H.; Chen, J.; Zhong, S.; Zhu, J. Geoscience and Carbon Neutralization: Current Status and Development Direction. *Geol. China* **2021**, *48*, 347–358.
56. Huang, J.; Sun, X.; Zhang, X. Construction and Prospect of the Typological Framework of Technologies for Carbon Neutrality in China. *China Popul. Resour. Environ.* **2021**, *31*, 24–28.