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Research on the Development of CCUS Full Process Technology

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Abstract

At present, China's CCUS has made a leap forward development in policy, technology, demonstration projects and commercial operation. However, from the perspective of the entire energy system, CCUS can play its role in reducing CO_2 only when it is combined with the process of resource exploitation, energy production, energy storage and transportation and energy utilization, which requires the research of the whole process technology of CCUS. This paper studies the source sink matching and technology integration matching in the whole process of CCUS technology, studies the application of existing coal-fired power plants + CCUS, steel plants + CCUS, cement plants + CCUS technology and the future application of BECCS technology and hydrogen energy + CCUS technology, and puts forward relevant suggestions on improving the laws, regulations and policy system for the development of CCUS, establishing a cross sectoral and cross industry cooperation platform and improving the carbon trading system.

Keywords

CCUS, CCUS, Full Process Technology, Emission Reduction

1. Introduction

As the progress towards "Carbon Peaking and Carbon Neutrality" further advances, China has enacted a series of incentive policies for green and low-carbon industries, and the accelerated development of domestic CCUS industry, the fast growth in maturity of relevant technologies, the implementation of demonstration projects… all showing a development trend characterized by ever-emerging technologies, continuously efficiency growth and gradual reduction of energy costs [1]. The first 1 million-ton CCUS project in service, the 3 million-ton CCUS project under planning, the 10-million-ton offshore storage project for which the pre-feasibility study is underway… according to the inexhaustive statistics of the Administrative Center for China's Agenda 21, by July 2022, China has nearly 100 existing or planned CCUS projects, doubling that in the same period of 2021. Among these projects, there are 40 CCUS demonstration projects already in service or under construction across 19 provinces, including 13 projects in coal-fired power plants with a limited overall capture capacity of about 600,000 tons. Large-scale CCUS projects are most commonly seen in the petrochemical industry, as evidenced by the 6 existing, ongoing or planned million-ton CCUS projects.

At present, China's CCUS has made a leap forward development in policy, technology, demonstration projects and commercial operation. However, from the perspective of the entire energy system, CCUS can play its role in reducing CO_2 emission only when it is combined with processes such as resource exploitation, energy production, storage, transportation and utilization [2], which requires the research of CCUS whole process technology.

2. Characteristics of CCUS Whole Process Technology

CCUS whole process technology refers to the systematic CCUS integration technology developed by scientifically bridging key CCUS technical processes through source-sink matching and technology integration matching and the application modes of such technology [3], which aims to realize the integrated, large-scale, industrial cluster deployment of the whole process of CCUS, and relies on large-scale and energy-saving capture, effective transportation, industrialized utilization of CO_2 in the industrial sources of intense emission and safe, cost-effective geosequestration techonologies as its basis and key connotation. CCUS whole process technology is a major trend in the future, a key to realize applications at the industrial-scale, and more important, an urgent need for China to deploy its CCUS decarbonization industrial clusters.

In addition to key technical processes and key system factors such as CO_2 capture, transportation, utilization and storage, CCUS whole process technology also involves factor relation-for example between source-sink matching and integrated deployment of technologies for key processes-and technologies in risk monitor, assessment and alarming for the system operation [4].

For the purpose of the "Carbon Peaking and Carbon Neutrality" goals, key processes of CCUS whole-process technology include mainly carbon emission source investigation, CO_2 geosequestration potential assessment, technology integration and matching for key processes, CCUS system optimization and risk assessment, as shown in **Figure 1** [5].

3. Research Emphases of CCUS Whole Process Technology

1) Source-sink matching

In essence, CCUS source-sink matching means the overall planning and transportation network layout of CCUS cluster system, which is one of the key

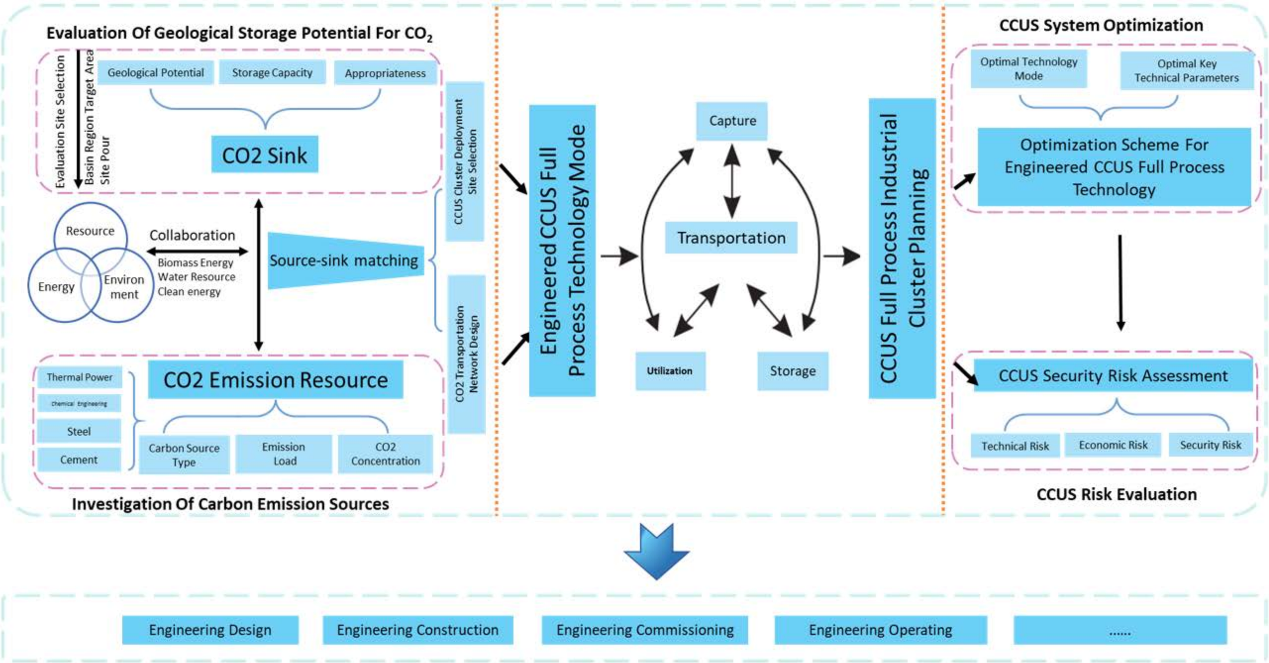

Figure 1. CCUS whole process technology.

mechanisms of CCUS whole process technology. The implication of CCUS source-sink matching: the CO_2 emission sources in a region are geographically dispersed, with different emissions, and the CO_2 utilization and geological storage sinks have different carbon removal potentials and methods. CO_2 transport modes and transport costs between sources and sinks are affected by factors such as regional geographical conditions, land use types, rivers, traffic and crowd density [6]. It can reduce CO_2 transport costs and maximize CO_2 utilization and geological storage by constructing the source-sink matching relationship of CCUS scientifically.

European and American countries have carried out in-depth research on the mathematical model of CCUS cluster transportation pipeline network, developed a number of source-sink matching decision support systems with their own characteristics and realized engineering applications [7]. The research of CCUS cluster source-sink matching and transportation network planning is relatively rare in China, which does not meet the development of CCUS whole process technology industry cluster.

2) Technology integration & matching

The CCUS whole process technology is limited by factors such as carbon source (CO_2 volume fraction, pressure, temperature, etc.), capture process, utilization target, and storage geological body. It is very important to scientifically connect and integrate the technical links of capture, transport, utilization and storage [8] [9] (see **Figure 2**).

For industrial carbon sources with different CO_2 volume fractions, a scientific matching of capture technology and removal technology (utilization or storage) will be adopted to form an integrated capture-utilization-storage collaborative

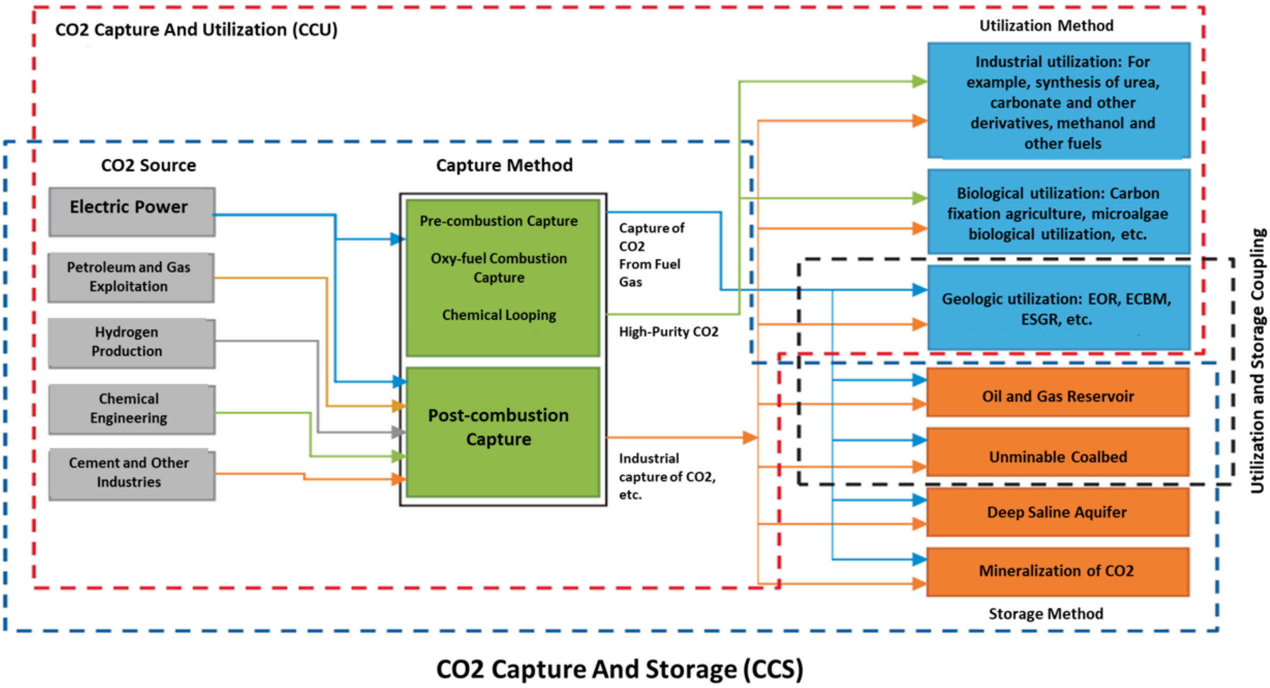

Figure 2. CCUS technology integration & matching flow.

emission reduction technology mode. It is necessary for maximizing CO_2 capture, utilization and storage, and ensuring the efficient implementation of CCUS, and also reduces the cost of CCUS system and the implementation risk of CCUS. At present, the existing CO_2 capture technologies apply to the main types of carbon sources, the technology of CO_2 utilization and storage has been demonstrated and explored in the fields of electric power, oil and gas exploitation, hydrogen and chemical industry [10].

According to the types of carbon emission sources with different volume fractions of CO_2, various CCUS technology matching modes can be formed by using different capture technologies [5]. In coal-fired power plants, natural gas mining, steel, cement and other industrial fields with low CO_2 volume fraction flue gas emission, chemical absorption method is used to capture CO_2 (capture after combustion). The main method is absorption with alkanolamine solution. In the chemical field of high CO_2 volume fraction flue gas or tail gas emission, the physical absorption method or adsorption method is mostly adopted to capture CO_2, and the low temperature methanol method and pressure swing adsorption method are mainly adopted. With the development of pre-combustion capture, oxygen-enriched combustion, BECCS and DACCS, CCUS technology matching model becomes more and more abundant.

4. Application of CCUS Whole Process Technology

Under the scenario of scale-based deployment of CCUS industry clusters, the CCUS whole process technology is selected according to their application scenarios and technologies. There are a variety of technology application modes: first, technology application modes for achieving substantial emission reduction and low-carbon transformation of major carbon emission industrial sources; for example, "coal-fired power plants + CCUS", "iron and steel plants + CCUS", "cement plants + CCUS", and "energy chemicals + CCUS", etc. Second, the technology application mode for the low-carbon development and utilization of fossil energy; for example, underground coal gasification (UCG)—coal hydrogen production CCS integrated zero carbon emission technology, integrated gasification combined cycle power generation system (IGCC)—CCS technology, etc. Third, the technology application mode for high-carbon emission industries and specific regions to achieve carbon emission reduction, such as "coal energy base + CCUS", "oil and gas energy base + CCUS", and "coal-oil and gas multi-energy base + CCUS" [11].

1) Application of "coal-fired power plant + CCUS"

Coal-fired power plants are vital to China's electricity supply. As of August 2022, the installed capacity of China's active coal-fired power generation units was about 1.18 billion kilowatts, accounting for about 50% of global coal-fired power generation capacity [12]. China has the most efficient coal-fired generating sets in the world, and the million-kilowatt ultra-supercritical high-efficiency power generation technology currently accounts for more than 26% of the total installed coal-fired power capacity. The average power consumption of coal-fired power generation units is 302.7 g/kWh, lower than the world average, but the average service life is only about 12 years, less than half of the global average service life. Overall, it is characterized by "large stock, new unit and high efficiency" [13]. Given China's vast and young coal-fired cluster and power-system architecture, it is unrealistic to phase out coal power quickly at this time without the support of economically reliable large-scale energy storage technology. In response to "Carbon Peaking and Carbon Neutrality", the pressure of low-carbon transformation of coal-fired power generation is increasingly prominent, and advanced coal-fired power generation units urgently need to realize low-carbon utilization in combination with CCUS technology to balance China's needs of affordable energy supply and environmental sustainable development for the future development.

Compared with wind power and photovoltaic power generation, which are currently developing on a large scale, have high technical maturity and have greatly reduced power generation costs, the coal-fired power plants that implement the CCUS technology do not have an advantage in cost per kilowatt hour of the electricity generated by WTGS. However, considering that CCUS technology is the only way to achieve deep emission reduction in the coal-fired power industry, the development of integrated technology of coal-fired power plants and CCUS will be a key measure to ensure low-carbon and continuous operation of coal-fired power plants in the future, and promote the low-carbon transformation of China's energy system. If CCUS technology cannot be commercialized in coal-fired power plants, China's coal-fired power industry will face severe challenges in reducing emissions in the future, and the supply pattern of the power industry will undergo profound changes.

2) Application of "Steel Plant + CCUS"

In 2021, China's steel industry emits 1.79 billion tons of CO_2, accounting for 17.5% of the country's total carbon emissions; China's crude steel output is 1.03 billion tons, accounting for 54% of the global total [14]. China's steel industry faces huge pressure to reduce emissions. Achieving indirect emission reduction by reducing energy consumption is a universal measure to cope with climate change in China's steel industry. Energy saving and emission reduction are highly effective for small and medium-sized steel enterprises with relatively low technology level, but for large enterprises with relatively high technology level, energy saving not only means facing the challenge of rebalancing enterprise energy system. Moreover, with the improvement of energy efficiency of enterprises, the space for energy saving becomes gradually smaller, and the cost of emission reduction becomes higher accordingly, which makes it difficult to meet the long-term emission reduction demand of the steel industry. Applying CCUS technology to the steel industry can effectively reduce CO_2 emissions in the steel production process and make the steel production process cleaner.

Compared with the carbon emissions in coal-fired power plants, the carbon emission is available in multiple processes (coke furnaces, blast furnaces, energy centers, etc.) of steel plant [15]. Since the CO_2 produced in iron and steel production is mainly contained in the flue gas, a variety of post-combustion carbon capture technologies including absorption extraction, adsorption and separation, membrane separation, low temperature separation can be adopted. The absorption extraction is the most mature technology, adsorption and separation technology has been sophisticatedly applied in carbon capture and storage; membrane separation technology is widely used in the gas separation industry; the currently-used CO_2 capture technology mainly involves chemical absorption method and physical adsorption method.

The integration of steel plant and CCUS technology is supposed to relieve the pressure on carbon emission reduction in China's steel industry. CCUS technology is able to effectively minimize the carbon intensity and total carbon emissions of steel industry and reduce carbon emission as specified, so as to address energy sustainability and environmental issues such as climate change caused by energy consumption. Since a large amount of steel will be needed in China's rapid urbanization and large-scale infrastructure construction, the CO_2 emission, by reason of irreplaceability of raw material, cannot be avoided in steel and iron production, and may only be captured and stored through CCUS technology. Therefore, CCUS technology has a valuable function in the transformation of steel industry towards low-carbon emission.

3) Application of "cement plant + CCUS"

China is a big producer of cement. Since 2009, China has produced more than 50% of the world's cement, and both cement output and carbon emissions from cement production have continued to rise. In 2021, China produced 2.36 billion tons of cement, accounting for 55% of the world's total cement output. The carbon emission of cement production is about 1.466 billion tons, accounting for 14.3% of the total carbon emission in China [16]. Therefore, the emission reduction of China's cement industry plays a decisive role in achieving emission reduction target of the global cement industry. Emission reduction measures in the cement industry mainly involve energy efficiency promotion, the use of alternative fuels, the reduction of clinker content in cement, and the application of CCUS technology. 60% of carbon emissions in the cement industry are from the carbonate decomposition in raw material. In the case that CO_2 emissions are unavoidable and difficult to reduce, the advantages of CCUS technology are gradually shown in emission reduction. Capturing CO_2 during cement production will be a key measure to reduce emissions in this industry.

As a major industry of difficult-to-emission reduction in China, cement plant can be equipped with CCUS technology to effectively reduce carbon emissions in the global cement industry and promote the green transformation of the cement industry. With the increasing demand for cement and the increasing urgency of low-carbon transition, CCUS technology applied in cement plants, can both reduce CO_2 and SO_2 emissions through CO_2 capture and minimize resource waste and environmental damage in the traditional limestone mining and production through CO_2 utilization, plays a crucial role in ensuring China's energy security and low-carbon transformation of the cement industry.

5. Development Trend of CCUS Whole Process Technology

In terms of how CCUS whole process technology relates to a diversified energy system of the future, CCUS whole process technology can not only address the carbon emission problem of high-carbon fossil energy system, but also combine with renewable energy and hydrogen energy technology to reduce system carbon emission or even achieve negative carbon emission, and ensure the security and stability and other significant features of diversified energy system in the future.

1) BECCS technology

BECCS technology, combining biomass energy technology with CCUS technology, has great potential in emission reduction. In addition to the emission reduction of greenhouse gas CO_2, BECCS technology integrated with the production and utilization of biomass energy is of great significance for China to alleviate energy pressure and ensure energy security. Making the utmost of biomass resources is well situated to rational utilization of abundant waste biomass resources in China, efficient utilization of resources and reducing pollution of agricultural and forestry wastes, which is propitious to resource utilization and environmental protection. BECCS technology has a positive outcome for environmental protection, energy security and food security on the basis of realizing negative CO_2 emission.

Coal-fired power plants equipped with CCUS and co-fired with biomass can achieve substantial CO_2 emission reduction or even negative emissions, which provides a strong technical guarantee for China to achieve carbon neutrality in

2060 [17]. Since the emission reduction potential of BECCS technology is strongly affected by storage location, the emission reduction potentials of coal-fired power plants vary greatly between different region. About 46.8% of coal-fired power plants are able to store CO_2 within a fairly short transportation distance (100 km), and such power plants are mainly located in the central region, the eastern coastal region and some provinces in the northern coastal region, including Jiangsu, Henan, Shanxi, Shandong, Anhui, Hebei and Inner Mongolia. In addition, nearly 60% of CO_2 needs to be stored through interprovincial transportation. Therefore, CCUS hubs shall be established in the region of resource pooling to realize infrastructure sharing and reduce CCUS costs [11].

2) Application of "Hydrogen energy + CCUS"

Hydrogen energy has caused wide public concern over the recent years for its clean, low-carbon, flexible transformation and other features. The cost of hydrogen production from renewable electrolytic water ("green hydrogen", which accounts for only 1% of total hydrogen production) is currently maintained at a high level, while hydrogen production from fossil sources "gray hydrogen", including hydrogen produced from coal, accounts for about 62% of total hydrogen production; Hydrogen produced from natural gas (about 19% of total hydrogen production) is a relatively low-cost solution, the hydrogen production from fossil fuels shall be combined with CCUS technology to reduce carbon emission. The hydrogen produced in this process is called "blue hydrogen", and it will be the main hydrogen production method in the short and medium term in China [18].

The combination of hydrogen production from fossil fuels and CCUS technology is a critical option to get rid of carbon constraints. Hydrogen manufacturer can implement CCUS projects based on CO_2 utilization technology and their location characteristics. Hydrogen manufacturers that are relatively close to oil fields can implement CCUS projects based on oil field storage and enhanced oil recovery. Other hydrogen manufacturer can adopt the CCU technology of CO_2 chemical utilization, mineralization utilization, biological utilization, etc., to achieve low-carbon hydrogen production.

Hydrogen production from fossil fuels can promote the development of CCUS technology in multiple dimensions by providing low capture and storage cost for emission sources in CCUS projects, promoting the construction of low-cost CCUS project clusters, and supporting the development of BECCS technology. Despite the higher CO_2 emissions from the hydrogen production from fossil fuels (especially hydrogen production from coal), the cost of carbon capture and storage is about 50% lower than that of coal-fired power plants, steel plants, cement plants, etc., which provides a higher probability for the low-cost development of CCUS technology [19].

In general, the combination of the CCUS technology and the hydrogen production from coal is able to transform "gray hydrogen" into "blue hydrogen" and expand the application scope of CCUS technology. CCUS technology will play a decisive role in the transformation of China's hydrogen production technology from fossil fuel to multiple energy.

6. Countermeasures and Proposals

Based on the accumulation of engineering experience of CCUS in China, the acceleration of technology research and development, the broad application prospect, the continuous increase of international investment and the extensive research, the conditions are currently in place to scale up CCUS technology, an important measure to deal with the greenhouse effect in the future. Therefore, after the existing problems are solved successively and an easily reproduceable and promotable long-term mechanism is established for the system, a flourishing new situation will emerge and a new normal green development will be formed for CCUS [20].

1) Improve laws, regulations and policy system

The laws and regulations, industrial standards, industrial policies and planning and design of the governmental departments are decisive for the macro guidance of the promotion and development of CCUS. The first proposal is accelerating the establishment of the legal framework for CCUS and formulating the trial polices and regulations for CCUS related industries based on the improvement of existing policies; the second proposal is promulgating the social organization, local and industrial standards based on the experience of the pilot projects, providing proper standards for all sectors of the CCUS whole process technology and promoting the standardized development of the CCUS technology; the third advice is establishing the project approval and licensing system, defining the application requirements for projects, incorporating the contents involved in all sectors of the whole process technology into one supervision platform, implementing the licensing system through the whole project period and thereby ensuring the standardized development of CCUS technology.

2) Enhance cross-department and cross-industry cooperation

The CCUS whole process technology involves multiple technical sectors and industries and departments, so a cross-department and cross-industry cooperation platform should be established for coordination and communication. At the enterprise level, it is proposed to engage the central and local state-owned enterprises in the promotion, accumulate relevant technologies and commercial and management experience through valuable pilot projects and actively explore and establish an exchange platform for experience and achievement sharing, providing a reference for other relevant enterprises and a basis for the formulation of relevant national policies; at the government level, it is proposed to determine the functional roles and scopes of various departments based on the "double-carbon" target, enhance the cross communication on businesses and thereby make joint efforts to improve the supervision efficiency, strengthen the supervision and expand the supervision coverage; at the social level, it is proposed to encourage the social organizations and universities and colleges to join in the cooperation platform and mainly undertake the school-enterprise cooperation and technological research, achieving the comprehensive and deep integration of industries, universities and research.

3) Complete carbon trading system

China's carbon trading system should be completed as soon as possible by referring to the carbon trading system of the European Union, America and South Korea and considering the actual national conditions of China. The first proposal is completing the top design of the carbon trading market. The governmental departments should verify the total carbon emission amount of the energy industry across China through an overall planning, reasonably determine the allocated quotas based on the regional economy, industrial difference, technical measures, production status, etc., by combining the total volume trade and regional trade, introduce the paid quota distribution mechanism in due time and explore the marketized operation and carbon pricing mechanism. The second proposal is enhancing the supervision and motivating the endogenous power. The transfer of carbon emission rights, trade filing, supply and demand information and completion of the annual total indicators should be supervised and managed properly, an accountability mechanism should be established and the carbon trading rules should be standardized. The incentive policies should be promulgated for carbon funds, mortgage loans, green financing, etc. [21].

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

References

[1] Zhang, X., Li, Y., Ma, Q., *et al.* (2021) Research on Development of China's Carbon Capture, Utilization and Storage Technology. *Strategic Study of CAE*, **23**, 70-80. https://doi.org/10.15302/J-SSCAE-2021.06.004

[2] Cai, B.F., Li, Q., Zhang, X., *et al.* (2021) Annual Report of China's CO_2 Capture, Utilization and Storage (CCUS) (2021)—China CCUS Path Study. Chinese Academy of Environmental Planning of the Ministry of Ecology and Environment, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, the Administrative Center for China's Agenda 21, Beijing.

[3] Xing, L.R., Wu, Z.W. and Zhang, R.Y. (2021) Current Development and Prospect Analysis of CCUS Industry. *International Petroleum Economics*, **29**, 99-105.

[4] Cai, B.F., Li, Q., Lin, Q.G., *et al.* (2020) China CO_2 Capture, Utilization and Storage (CCUS) Report (2019). Climate Change and Environmental Policy Research Center of Chinese Academy of Environmental Planning of the Ministry of Ecology and Environment, Beijing.

[5] Sang, S.X., Liu, S.Q., Lu, S.J., *et al.* (2022) Engineering CCUS Whole Process Technology and Progress. *Reservoir Evaluation and Development*, **12**, 711-725.

[6] Hoover, B., Yaw, S. and Middleton, R. (2020) Cost MAP: An Opensource Software Package for Developing Cost Surfaces Using a Multi-Scale Search Kernel. *International Journal of Geographical Information Science*, **34**, 520-538. https://doi.org/10.1080/13658816.2019.1675885

[7] Brunsvold, A., Jakobsen, J.P., Husebye, J., *et al.* (2011) Case Studies on CO_2 Transport Infrastructure: Optimization of Pipeline Network, Effect of Ownership, and Political Incentives. *Energy Procedia*, **4**, 3024-3031. https://doi.org/10.1016/j.egypro.2011.02.213

[8] Shi, Z.C., Zhao, S.S., Zhang, Y.X., *et al.* (2021) Research on Development of Carbon Capture and Storage Technology during the Industrial Energy Consumption Process. *Natural Gas and Oil*, **39**, 28-37.

[9] Tapia, J., Lee, J.Y., Ooi, R., *et al.* (2018) A Review of Optimization and Decision-Making Models for the Planning of CO_2 Capture, Utilization and Storage (CCUS) Systems. *Sustainable Production & Consumption*, **13**, 1-15. https://doi.org/10.1016/j.spc.2017.10.001

[10] Hasan, M., First, E.L., Boukouvala, F., *et al.* (2015) A Multi-Scale Framework for CO_2 Capture, Utilization, and Sequestration: CCUS and CCUM. *Computers & Chemical Engineering*, **81**, 2-21. https://doi.org/10.1016/j.compchemeng.2015.04.034

[11] Huang, J., Chen, Q.Z., Zhong, P., *et al.* (2022) Evaluation Report of China's Carbon Capture, Utilization and Storage Technology. The Administrative Center for China's Agenda 21, Beijing, pp. 198-224.

[12] China Electricity Council (2022) Analysis and Prediction Report of China's Power Supply and Demand Situation for the First Half of 2022. Beijing.

[13] Annual Report on Climate Change Actions (2021) Carbon Emission Peak and Carbon Neutrality Album. Social Sciences Academic Press, Beijing.

[14] Committee for Energy Conservation of Metallurgical Industry of China Energy Conservation Association, China Metallurgical Industry Planning and Research Institute (2022) China Steel Industry Energy Conservation and Low Carbon Development Report (2021). Beijing.

[15] Wang, Y. (2019) Technological and Economic Evaluation Research of CCUS-EOR Full Process Project Based on Carbon Capture of Iron and Steel Plants. North China Electric Power University, Beijing.

[16] China Cement Association (2022) 2021 Statistics on Current Supply and Demand and Market Scale of China's Cement Industry. Beijing.

[17] Chen, W.H. and Lu, X. (2022) Research on Deployment Optimization of CCUS Clusters in Chinese Coal-Fired Power Plants under the Carbon Neutrality Target. Climate Change Research, , 18(3): 261-271.

[18] Liu, Y.Y. and Chen, L.L. (2022) Research on Coupling of Hydrogen Energy and CCUS Technology under the Carbon Neutrality Target. *Energy and Energy Conservation*, **197**, 15-17.

[19] Zhang, X., Xu, M., Xu, D., *et al.* (2021) Evaluation of Carbon Footprint of China's CCUS Technical Improvement for Coal-Based Hydrogen Production. *China Population, Resources and Environment*, **31**, 1-11.

[20] Zhao, Z.Y., Yao, S., Yang, S.P., *et al.* (2022) Under the "Double-Carbon" Target: Current Development, Existing Problems and Proposals of China's CCUS. Environmental Science. https://doi.org/10.13227/j.hjkx.202203136

[21] Gao, S., Li, M.Y., Duan, M.S., *et al.* (2019) International Carbon Market Mechanism under *Paris Agreement*: Basic Situation and Prospect Forecast. *Climate Change Research*, **15**, 222-231.