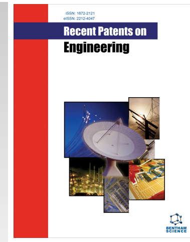
RESEARCH ARTICLE

Development Frontier and Trend Prediction on Carbon Capture Technology



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Abstract: ***Introduction*:** Carbon capture is a crucial component of CCUS, significantly contributes to emission reduction in high carbon-emitting industries, and serves as a vital technical pathway to attain carbon neutrality.

***Method*:** This study systematically analyzes the development of carbon capture technology through an extensive literature review and patent analysis. High-quality academic papers and patent data from major databases were collected and examined to assess technological trends, status, challenges, and policy influences.

***Results*:** Frontier Trends: Carbon capture technology is advancing from conventional amine methods to innovative approaches like composite solvents, direct air capture (DAC), and electrochemistry. China is at the forefront in patent acquisition and is actively engaged in research and development. Status and Challenges: Despite advancements in second-generation technologies, China faces deficiencies in third-generation technologies, demonstrative applications, and market procedures, with promotion hindered by technological constraints and financial obstacles.

***Discussion*:** In response to the prominent challenges faced by China's carbon capture technology, the following measures can be taken: Enhance strategic planning, achieve advancements in fundamental technologies, establish demonstration clusters, refine investment and financing mechanisms, improve standardization systems, and foster international collaboration and patent strategies.

***Conclusion*:** China possesses a solid basis; nevertheless, it must synchronize policy, technology, and industrial resources to expedite the large-scale implementation of carbon capture and achieve the “double carbon” objective. Development trend: The technology will advance towards “integration + intelligence,” including new materials and artificial intelligence, supported by policies and international collaboration, to facilitate cost-effective commercialization.

Keywords: Carbon neutrality, carbon capture, CCUS, trend prediction.

1. INTRODUCTION

In 2024, the 29th Conference of the Parties (COP29) to the United Nations Framework Convention on Climate Change (UNFCCC) adopted the authorization mechanism of the Paris Agreement on carbon removal emission reductions, which clarified the key role of carbon capture, utilization, and storage (CCUS) technology in achieving the global net-zero emission target [1, 2]. For China, CCUS technology is an important technical support for realizing the carbon neutrality goal. Based on the goal of carbon neutrality in China and the international development trend, this paper investigates the development needs, frontier trends, and key challenges of carbon capture technology, and proposes future research [3].

2. METHOD

This study aims to systematically analyze the current status, technological developments, and challenges of carbon capture technology by using a combination of literature review and patent analysis, consequently proposing future development directions and response tactics. Initially, high--quality academic literature and industrial papers about car-

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bon capture from 2015 to 2024 were retrieved from reliable databases, including Web of Science, Scopus, and Google Scholar. The keywords include 'carbon capture', 'CCUS', 'Direct Air Capture', 'Electrochemical Capture', and 'Carbon Capture'. 'Electrochemical Capture', among others. Subsequent to the initial screening, the literature was further curated according to its relevance, impact factor, and citation count to guarantee comprehensive coverage and dependable quality. Secondly, the gathered technical data were classified and analyzed comparatively depending on the Technological Readiness Level (TRL) and technology generations. We analyze the disparities in consumption of energy, cost, capture efficiency, and application scope among various generations of carbon capture devices, elucidating the technological progress and identifying critical obstacles. In addition, an analysis of the patent landscape for carbon capture technologies has been done utilizing the patent databases of WIPO and the State Intellectual Property Office (SIPO), focusing on the trends in patent applications and technological focuses of China, the U.S., and Europe in critical technology sectors, thereby illustrating the dynamics of global technological innovations and competitive situations. This study systematically identifies the primary challenges of carbon capture technology—engineering demonstration, core technological breakthroughs, industry chain synergy, and market mechanisms—based on a comprehensive analysis of literature and patents, and offers a theoretical foundation for suggesting practical development strategies. This study examines the policy support system and financing mechanisms for carbon capture technology, in conjunction with government policy documents and industry development plans. It assesses the technology's facilitative impact on its promotion and marketing, and forecasts future development trends based on this analysis.

3. RESULTS

3.1. Frontier Trends of Global Carbon Capture Technology Development

Driven by the dual goals of global carbon neutrality and high-quality economic development, the demand for CCUS technology has become urgent [4]. To achieve carbon neutrality in China, the world needs to reduce between 500 and 1,500 million tons of CO_2 per year using the CCUS technology [5]. However, the high cost of current carbon capture technologies, which are the chief technique for CO2 reduction, puts significant pressure on the industry's low-carbon transformation. Carbon capture technologies are evolving toward greater stability, efficiency, lower energy consumption, and cost reductions, with distinct generational advancements [6].

The first-generation technologies primarily rely on basic amine solvents for chemical absorption, offering mature but energy-intensive and costly solutions. The second generation has significantly improved energy efficiency by optimizing compound amine solvents, with the United States and the United Kingdom reducing energy consumption to 2.6 GJ/ton CO_2 and 2.4 GJ/ton CO_2, respectively, while lowering capture costs to $70/ton and $60/ton [7, 8]. The third--generation technologies, leveraging new materials and process innovations such as phase-change solvent technologies in Europe, have further reduced energy consumption to 2.2 GJ/ton CO_2 and lowered capture costs to $39/ton, offering more competitive emission reduction solutions for high-carbon-emitting industries [9].

Novel carbon capture technologies, including electrochemical capture, solid-state adsorption, catalytic desorption, interfacial capture, and CO_2 immobilization using microorganisms or algae, are emerging rapidly [2, 10-12]. Direct Air Capture (DAC) technology has also begun to be deployed on a large scale in the US, Norway, Iceland, and other countries [10, 13]. Global R&D in carbon capture technology has garnered attention, with a large and rapidly growing number of patent applications [14]. Since 2005, the average annual growth rate of global carbon capture technology patents has reached 18.7%, and the number of CCUS patents from China, the United States, and the World Intellectual Property Organization (WIPO) ranks among the top three in the world with China surpassing the United States in 2013, and the total number of applications steadily ranked first in the world [14].

From the perspective of patent layout, the current patents are mainly focused on areas with low technology maturity (low TRL), and the number of patents in key technology directions such as solid adsorbents, membrane separation and capture, and catalytic conversion is still limited [15-17]. For example, although China has made significant progress in amine capture technology, in recent years, U.S. patents have focused more on modular direct air capture (DAC) systems and integrated electrochemical capture devices [18, 19]. In addition, European patents, on the other hand, emphasize CO2 capture processes through electrolytic regeneration [20, 21].

3.2. China's Carbon Capture Technology Development Status and Challenges

China has developed carbon capture technologies applicable to various emission sources of different concentrations and sizes. By the conclusion of November 2024, over 120 CCUS demonstration projects are operational, in development, or under construction, boasting an annual capture capacity of 6 million tons. The overall cost of China's carbon capture technology is low to medium international level and has certain development advantages. For example, the capture cost of integrated oil recovery demonstration projects in the coal chemical and petrochemical sectors is 105-250 RMB/ton CO_2, and the overall cost of the power and cement industries is still lower than the international level, although the cost is higher [19, 22, 23].

China's carbon capture technology is at the stage of “running parallel” and “leading” [2]. The chemical absorption method has made important breakthroughs in energy consumption and cost control, and is on par with the international advanced level. For example, the second generation of composite solvent technology has been adopted in the National Energy Taizhou Power Plant project, reducing energy consumption to 2.2-2.4 GJ/ton CO_2, and the cost of capture is lower than 250 RMB/ton, which has reached the global leading level [5]. However, in terms of third-generation technology, China is still in the stage of industrialization and exploration, and a breakthrough is still needed before commercial application [24].

Despite the positive progress, China's carbon capture technology still faces systemic challenges in engineering demonstration, core technology, industry chain synergy, and market mechanism. On the one hand, there is a lack of large-scale integrated demonstration projects covering the whole process of capture, transportation, utilization, and storage, across industries and regions, which makes it difficult to effectively realize technology validation and commercialization path exploration. Most of the projects are still limited to a single link or small-scale test, and lack of engineering closed loop [25, 26].

In terms of core technology, problems such as high absorber energy consumption, low equipment integration, and lack of operational stability are still prominent. For example, the regeneration heat consumption of the mainstream chemical absorption method is 2.3-3.5 GJ/ton CO_2, the absorbent loss of some devices is high, and the adaptability to different gas sources is also limited [27, 28]. Emerging technologies such as mineralization utilization and dry reforming hydrogen production have made initial breakthroughs, but still lack sufficient data support for industrial applications, and it is difficult to convert laboratory results [29].

In terms of industrial chain synergy, the uneven distribution of carbon sources and sinks, lagging in the construction of transport pipeline networks, the regional coordination mechanism is not yet sound, and the efficiency of matching sources and sinks is low, which affects the optimization of the overall layout. Especially in high carbon emission industries (iron and steel, cement, electric power), due to the lack of uniform standards and mandatory constraints, the initiative of enterprises to implement carbon capture is not strong [30, 31].

In terms of policies and market mechanisms, the degree of patent internationalization is not high, the layout of international patents is insufficient, the carbon pricing mechanism is immature, and there is a lack of stable return paths for emission reduction benefits. Financial incentives are not sustainable enough, financial and fiscal support is limited, and CCUS projects are difficult to finance and have a long return cycle. Most of the demonstration projects rely on special government funds, and the market-driven force still needs to be strengthened [32, 33].

In addition, the standards related to carbon capture are not unified, and there is a lack of a quantitative assessment system for capture efficiency; the mechanism of connecting technology and the carbon market is not clear, and it is difficult for carbon revenue to drive the development of technology. To break the above bottlenecks, it is suggested to strengthen the core technology research and equipment local substitution, promote the regional integrated demonstration construction, establish multiple incentives and a stable carbon pricing system, and realize the scale and industrial development of CCUS [34, 35].

4. DISCUSSION

Aiming at the outstanding challenges faced by China's carbon capture technology in terms of demonstration projects, core technology, industrial synergy, and policy mechanism, the following optimization suggestions are put forward:

[1] Formulate a national CCUS development strategy and technology roadmap: Strengthen top-level design, formulate a national CCUS development strategy and technology roadmap covering the whole process of “capture-transportation-utilization/sequestration”, clarify the development stages and key directions, set up a stable financial support mechanism, and promote the establishment of a systematic innovation ecosystem covering R&D, demonstration, and commercialization. Establish a stable financial support mechanism, and promote the establishment of a systematic innovation ecology covering R&D, demonstration, and commercialization [7, 13, 21, 36].

[2] Breakthrough key core technology bottlenecks: Focus on high-efficiency and low-energy absorbers, new catalytic conversion materials, modularized process equipment, adjustable integrated systems adapted to different gas sources, and improve the efficiency and economy of carbon capture. Promote the rapid transformation of the results from laboratory to engineering applications, and shorten the cycle from proof of concept to industrialization [10, 37].

[3] Accelerating the construction of regional integrated demonstration projects and industrial clusters: Relying on high-carbon industries such as iron and steel, cement, and electric power, selecting regions with a high degree of matching of sources and sinks to carry out a synergistic and integrated demonstration of multi-technologies and multi-paths to create a closed-loop system of “capture-transportation-utilization/sequestration”. To promote the integration and development of CCUS with renewable energy, hydrogen energy, and other low-carbon industries [38].

[4] Establish multiple incentives and investment and financing mechanisms: improve the carbon market price mechanism, build a financial subsidy and carbon credit mechanism based on emission reduction performance, encourage green finance, industrial funds, PPP, and other ways to participate in the investment and financing of CCUS projects, and enhance the project's market-oriented operation capability and return expectations [39, 40].

[5] Improve the standardization and monitoring system: formulate unified standards for carbon capture project design, operational safety, energy efficiency, and emission reduction evaluation. Construct a national

technical efficiency and environmental impact database, promote cross-industry mutual recognition, establish a whole-process dynamic monitoring system, and improve the basis of regulation and public trust [41].

[6] Strengthen technology forecasting, intellectual property layout, and quality improvement: build a platform to analyze the dynamics of the frontier of carbon capture technology, and issue roadmaps and technology warnings regularly. Support the layout of high-value patents, enhance the conversion rate of patented technologies and international competitiveness, and crack the structural problem of "many patents but weak" [42].

[7] Deepen international cooperation and open synergy: Strengthen joint research and development with global leading organizations and enterprises in key areas such as absorber R&D, DAC system, and carbon dioxide conversion, and promote the introduction, digestion, absorption, and re-innovation of advanced technologies. At the same time, we will expand overseas demonstration projects and patent layouts to enhance China's voice in the global carbon management technology system [43, 44].

CONCLUSION

Global Carbon Capture, Utilization, and Storage (C-CUS) technology is rapidly evolving from early exploration to systematic deployment, and its development trend is characterized by higher energy efficiency, lower unit operating cost, wider industrial applicability, and deep coupling with clean energy, hydrogen energy, carbon-negative technology, *etc*. CCUS is a crucial pathway for achieving carbon peaking and carbon neutrality, and it is also emerging as a strategic focal point in the latest phase of green industrial competition. It is increasingly emerging as a strategic focal point in the latest phase of green industrial competition.

China has made remarkable progress in second-generation solvent capture technology, and some of the technical indicators have reached or even led the international level, especially in the control of energy consumption and system integration of chemical absorption methods, which has accumulated valuable experience. However, compared with international leading countries, China still faces many challenges, including weak international patent layout, slow technology commercialization, lack of cross-industry integrated solutions, and third-generation cutting-edge technologies (*e.g.*, electrochemical capture, direct air capture (DAC), solid adsorbents, *etc*.) are still in the early stage of exploration, and breakthroughs are urgently needed in core theories, engineering demonstrations, and commercial mechanisms [45].

To accelerate the comprehensive development of CCUS technology, China should form a synergy in scientific research, policy guidance, industrial synergy, and international cooperation. First, it should continue strengthening the basic research and technology attack, focusing on low-energy and high-efficiency capture technology, multi-source carbon gas treatment capacity, and high-value-added CO_2 conversion pathway. Second, a policy and institutional support system oriented from demonstration to dissemination should be constructed, including financial subsidies, carbon price guidance, green financial incentives, tax concessions, and other diversified tools [36, 46].

In terms of industry, it is recommended to speed up the promotion of regionalized synergistic development of high carbon emission industries (*e.g.*, electric power, iron and steel, cement, and petrochemicals), and to explore a new mode of integration of "industry + carbon management". At the international level, China needs to strengthen joint research and development with leading institutions in Europe and the United States, enhance the original innovation capacity of key technologies and the degree of internationalization of patents, and take the initiative to participate in the formulation of global carbon emission reduction rules and technical standards [47].

Finally, the widespread deployment of CCUS needs to be based on a sound standards system and monitoring and evaluation mechanism to enhance technical safety, public acceptance, and long-term economic viability. Only through the systematic synergy of scientific research, policy, market, and industry can China continue to enhance its voice and competitiveness in the global CCUS industry, and make a more significant contribution to the global response to climate change and the realization of a green and low-carbon transition.

CURRENT & FUTURE DEVELOPMENT

Notwithstanding advancements in liquid absorption technology, elevated energy consumption and expenses remain the primary constraints hindering its widespread use. Therefore, the research focus is gradually shifting to the development of new materials and processes to improve absorption efficiency and reduce energy consumption. Functionalized ionic liquids, chemical looping combustion (CLC), electrochemical capture, direct air capture (DAC) technology, and other emerging technologies have begun to receive more and more attention from researchers, and some preliminary results have been achieved. These emerging technologies show better prospects in theoretical research, and some of them have already entered the demonstration stage. For example, electrochemical capture technology and DAC technology have been preliminarily applied in the United States, Norway, and other countries.

From the perspective of future development trends, the integration and intelligence of technology will be an important direction for the development of the CCUS field. Through the combination of multiple capture technologies to further optimize the energy efficiency of the capture process, and combined with big data and artificial intelligence technology, real-time monitoring and optimization of the carbon capture process can effectively improve the economy and applicability of the technology. In addition, the cost of CCUS technology will continue to decrease in the future, especially in the capture segment, through the adoption of new absorbents, improvement of thermodynamic conditions in the capture process, and optimization of the process flow, which is expected to significantly reduce the overall capture cost [48, 49].

The future of CCUS technology will not only require technological breakthroughs but also rely on the support of policy and the market environment. With the gradual development of the global carbon market and the promotion of national policies, the commercialization of CCUS technology will be further accelerated. Strengthening international cooperation and promoting technology sharing and cooperation, especially efforts in technology standardization and policy coordination, is expected to accelerate the popularization and application of CCUS technology worldwide [3].

STUDY LIMITATIONS

This paper summarizes the key trends and strategic directions at the current stage of CCUS technology development and policy planning in China. However, several limitations should be noted. First, the study does not include empirical evaluation or scenario-based modeling of CCUS adoption, which could further substantiate its recommendations. Second, although representative recent patents were reviewed, a comprehensive patent landscape analysis—such as trend evolution, institutional collaboration networks, or international benchmarking—was not conducted. This area of analysis will be systematically explored in future research. Third, the study does not provide detailed techno-economic feasibility assessments for specific industries (*e.g.*, steel and cement), which may affect the generalizability of certain findings. Future studies are encouraged to incorporate quantitative modeling, industry case studies, and deployment data to validate and expand the strategic recommendations presented here.

LIST OF ABBREVIATIONS

CCUS = Carbon Capture, Utilization, and Storage

CO_2 = Carbon Dioxide

DAC = Direct Air Capture

CLC = Chemical Looping Combustion

TRL = Technology Readiness Level

WIPO = World Intellectual Property Organization

R&D = Research and Development

AUTHORS' CONTRIBUTIONS

It is hereby acknowledged that all authors have accepted responsibility for the manuscript's content and consented to its submission. They have meticulously reviewed all results and unanimously approved the final version of the manuscript.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

The data and supportive information are available within the article.

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CONFLICT OF INTEREST

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REFERENCES

[1] X. Zhang, X. Yang, and X. Lu, *China Carbon Capture, Utilization, and Storage (CCUS) Annual Report (2023),* China 21st Century Agenda Management Center, Global Carbon Capture and Storage Institute: Tsinghua University, 2023.

[2] M.U. Sieborg, A.K.H. Nielsen, L.D.M. Ottosen, K. Daasbjerg, and M.V.W. Kofoed, "Bio-integrated carbon capture and utilization: At the interface between capture chemistry and archaeal CO2 reduction", *Nat. Commun.,* vol. 15, no. 1, p. 7492, 2024. http://dx.doi.org/10.1038/s41467-024-51700-3 PMID: 39209831

[3] Z. Jiutian, W. Zhiyong, K. Jia-Ning, S. Xiangjing, and X. Dong, "Several key issues for CCUS development in China targeting carbon neutrality", *Carbon Neutrality,* vol. 1, no. 1, p. 17, 2022. http://dx.doi.org/10.1007/s43979-022-00019-3

[4] A. Bashir, M. Ali, S. Patil, M.S. Aljawad, M. Mahmoud, D. Al-Shehri, H. Hoteit, and M.S. Kamal, "Comprehensive review of CO2 geological storage: Exploring principles, mechanisms, and prospects", *Earth Sci. Rev.,* vol. 249, p. 104672, 2024. http://dx.doi.org/10.1016/j.earscirev.2023.104672

[5] H. Chu, Z. Huang, Z. Zhang, X. Yan, B. Qiu, and N. Xu, "Integration of carbon emission reduction policies and technologies: Research progress on carbon capture, utilization and storage technologies", *Separ. Purif. Tech.,* vol. 343, p. 127153, 2024. http://dx.doi.org/10.1016/j.seppur.2024.127153

[6] D. Baskaran, P. Saravanan, L. Nagarajan, and H-S. Byun, "An overview of technologies for capturing, storing, and utilizing carbon dioxide: Technology readiness, large-scale demonstration, and cost", *Chem. Eng. J.,* vol. 491, p. 151998, 2024. http://dx.doi.org/10.1016/j.cej.2024.151998

[7] F. Nath, M.N. Mahmood, and N. Yousuf, "Recent advances in CCUS: A critical review on technologies, regulatory aspects and economics", In: *Geoen. Sci. Eng.,* 2024, p. 212726.

[8] X. Gao, C. Zheng, and C. Liu, *"Method for carbon dioxide capture and concentration by partitioned multistage circulation based on mass transfer-reaction regulation"*, U.S. Patent 11,980,844,

[9] P.J. Foody, *"Process and system for producing low carbon intensity renewable hydrogen"*, U.S. Patent 11,760,630,

[10] P. Popielak, I. Majchrzak-Kucęba, and D. Wawrzyńczak, "Climate change mitigation with CCUS - A case study with benchmarking for selected countries in adapting the European Union's Green Deal", *Int. J. Greenh. Gas Control,* vol. 132, p. 104057, 2024. http://dx.doi.org/10.1016/j.ijggc.2023.104057

[11] R. Sharifian, R.M. Wagterveld, I.A. Digdaya, C. Xiang, and D.A. Vermaas, "Electrochemical carbon dioxide capture to close the carbon cycle", *Energy Environ. Sci.,* vol. 14, no. 2, pp. 781-814, 2021. http://dx.doi.org/10.1039/D0EE03382K

[12] M. Karimi, M. Shirzad, J.A.C. Silva, and A.E. Rodrigues, "Carbon dioxide separation and capture by adsorption: A review", *Environ. Chem. Lett.,* vol. 21, no. 4, pp. 2041-2084, 2023. http://dx.doi.org/10.1007/s10311-023-01589-z PMID: 37362013

[13] F. Bisotti, K.A. Hoff, A. Mathisen, and J. Hovland, "Direct air capture (DAC) deployment: National context cannot be neglected. A case study applied to Norway", *Chem. Eng. Sci.,* vol. 282, p. 119313, 2023. http://dx.doi.org/10.1016/j.ces.2023.119313

[14] C. Wang, H. Jiang, E. Miao, Y. Wang, T. Zhang, Y. Xiao, Z. Liu, J. Ma, Z. Xiong, Y. Zhao, and J. Zhang, "Accelerated CO2 mineralization technology using fly ash as raw material: Recent research advances", *Chem. Eng. J.,* vol. 488, p. 150676, 2024. http://dx.doi.org/10.1016/j.cej.2024.150676

[15] H. Gao, Y. Huang, X. Zhang, Z.A.S. Bairq, Y. Huang, P. Tontiwachwuthikul, and Z. Liang, "Catalytic performance and mechanism of SO42−/ZrO2/SBA-15 catalyst for CO2 desorption in CO2-loaded monoethanolamine solution", *Appl. Energy,* vol. 259, p. 114179, 2020. http://dx.doi.org/10.1016/j.apenergy.2019.114179

[16] I.S. Omodolor, H.O. Otor, J.A. Andonegui, B.J. Allen, and A.C. Alba-Rubio, "Dual-function materials for CO2 capture and conversion: A review", *Ind. Eng. Chem. Res.,* vol. 59, no. 40, pp. 17612-17631, 2020. http://dx.doi.org/10.1021/acs.iecr.0c02218

[17] R S Norhasyima, and T M I Mahlia, "Advances in CO□ utilization technology: A patent landscape review", *J. CO□ Util.,* vol. 26, pp. 323-335, 2018.

[18] S.M. Dudley, and C.W. Spittle, *"Communications security architecture implementing a service negotiation plane channel"*, U.S. Patent No. 12,250,535,

[19] B. Baynes, S. Voskian, and T. Alan Hatton, *"Electrochemical device and methods for carbon dioxide capture and concentration"*, U.S. Patent No. 11,903,144,

[20] J.S. Jakobsen, *"CO2 capture process with electrolytic regeneration"*, U.S. Patent No. 11,903,144,

[21] A. Bang, D. Moreno, H. Lund, and S. Nielsen, "Regional CCUS strategies in the context of a fully decarbonized society", *J. Clean. Prod.,* vol. 477, p. 143882, 2024. http://dx.doi.org/10.1016/j.jclepro.2024.143882

[22] Z. Lu, J. Wang, M. Shahidehpour, L. Bai, Y. Xiao, and H. Li, "Cooperative operation of distributed energy resources and thermal power plant with a carbon-capture-utilization-and-storage system", *IEEE Trans. Power Syst.,* vol. 39, no. 1, pp. 1850-1866, 2024. http://dx.doi.org/10.1109/TPWRS.2023.3253809

[23] Y. Yang, W. Xu, Y. Wang, J. Shen, Y. Wang, Z. Geng, Q. Wang, and T. Zhu, "Progress of CCUS technology in the iron and steel industry and the suggestion of the integrated application schemes for China", *Chem. Eng. J.,* vol. 450, p. 138438, 2022. http://dx.doi.org/10.1016/j.cej.2022.138438

[24] X. Liu, X. Liu, and Z. Zhang, "Application of red mud in carbon capture, utilization and storage (CCUS) technology", *Renew. Sustain. Energy Rev.,* vol. 202, p. 114683, 2024. http://dx.doi.org/10.1016/j.rser.2024.114683

[25] A. Yagmur Goren, D. Erdemir, and I. Dincer, "Comprehensive review and assessment of carbon capturing methods and technologies: An environmental research", *Environ. Res.,* vol. 240, no. Pt 1, p. 117503, 2024. http://dx.doi.org/10.1016/j.envres.2023.117503 PMID: 37907166

[26] C. Charalambous, E. Moubarak, J. Schilling, E. Sanchez Fernandez, J.Y. Wang, L. Herraiz, F. Mcilwaine, S.B. Peh, M. Garvin, K.M. Jablonka, S.M. Moosavi, J. Van Herck, A.Y. Ozturk, A. Pourghaderi, A.Y. Song, G. Mouchaham, C. Serre, J.A. Reimer, A. Bardow, B. Smit, and S. Garcia, "A holistic platform for accelerating sorbent-based carbon capture", *Nature,* vol. 632, no. 8023, pp. 89-94, 2024. http://dx.doi.org/10.1038/s41586-024-07683-8 PMID: 39020168

[27] T.M. Thiedemann, and M. Wark, "A compact review of current technologies for carbon capture as well as storing and utilizing the captured CO2", *Processes,* vol. 13, no. 1, p. 283, 2025. http://dx.doi.org/10.3390/pr13010283

[28] G. Lu, Z. Wang, U.H. Bhatti, and X. Fan, "Recent progress in carbon dioxide capture technologies: A review", *Clean Ener. Sci. Tech.,* vol. 1, no. 1, p. 32, 2023. http://dx.doi.org/10.18686/cest.v1i1.32

[29] B. Agún, and A. Abánades, "Comprehensive review on dry reforming of methane: Challenges and potential for greenhouse gas mitigation", *Int. J. Hydrogen Energy,* vol. 103, pp. 395-414, 2025. http://dx.doi.org/10.1016/j.ijhydene.2025.01.160

[30] K. Li, Y. Mao, J.L. Fan, J. Li, X. Li, J. Li, X. Xiang, C. Gu, and X. Zhang, "A national-scale high-resolution CCUS-shared pipeline layout for retrofitting multisectoral plants via onshore-offshore geological storage", *iScience,* vol. 27, no. 10, p. 110978, 2024. http://dx.doi.org/10.1016/j.isci.2024.110978 PMID: 39391718

[31] T.A. Gunawan, L. Gittoes, C. Isaac, C. Greig, and E. Larson, "Design insights for industrial CO 2 capture, transport, and storage systems", *Environ. Sci. Technol.,* vol. 58, no. 33, pp. 14608-14617, 2024. http://dx.doi.org/10.1021/acs.est.4c05484 PMID: 39105763

[32] B. Sun, B. Fan, C. Wu, and J. Xie, "Exploring incentive mechanisms for the CCUS project in China's coal-fired power plants: An option-game approach", *Energy,* vol. 288, p. 129694, 2024. http://dx.doi.org/10.1016/j.energy.2023.129694

[33] W. Zhang, C. Dai, X. Luo, and X. Ou, "Policy incentives in carbon capture utilization and storage (CCUS) investment based on real options analysis", *Clean Technol. Environ. Policy,* vol. 23, no. 4, pp. 1311-1326, 2021. http://dx.doi.org/10.1007/s10098-021-02025-y

[34] Q. Ma, S. Wang, Y. Fu, W. Zhou, M. Shi, X. Peng, H. Lv, W. Zhao, and X. Zhang, "China's policy framework for carbon capture, utilization and storage: Review, analysis, and outlook", *Front. Energy,* vol. 17, no. 3, pp. 400-411, 2023. http://dx.doi.org/10.1007/s11708-023-0862-z

[35] K. Jiang, P. Ashworth, S. Zhang, X. Liang, Y. Sun, and D. Angus, "China's carbon capture, utilization and storage (CCUS) policy: A critical review", *Renew. Sustain. Energy Rev.,* vol. 119, p. 109601, 2020. http://dx.doi.org/10.1016/j.rser.2019.109601

[36] L. Feng, Q. Ren, G. Ioppolo, and W. Liao, "Integrating China's carbon capture, utilization, and storage policy for sustainable development: Insights from content analysis", *Sustain. Dev.,* vol. 32, no. 5, pp. 5104-5119, 2024. http://dx.doi.org/10.1002/sd.2959

[37] S. Rezaei, A. Liu, and P. Hovington, "Emerging technologies in post-combustion carbon dioxide capture & removal", *Catal. Today,* vol. 423, p. 114286, 2023. http://dx.doi.org/10.1016/j.cattod.2023.114286

[38] H. Tang, W. Chen, S. Zhang, and Q. Zhang, "China's multi-sector-shared CCUS networks in a carbon-neutral vision", *iScience,* vol. 26, no. 4, p. 106347, 2023. http://dx.doi.org/10.1016/j.isci.2023.106347 PMID: 36994081

[39] B Fattouh, H Muslemani, and R Jewad, "Capture carbon, capture value: An overview of CCS business models", *OIES Paper: CM,* pp. 1-5, 2024.

[40] S.J. Friedmann, E.R. Ochu, and J.D. Brown, "Capturing investment: Policy design to finance ccus projects in the US power sector", *NY. Columb. SIPA Cent. Glob.,* pp. 1-5, 2020.

[41] E Hanson, C Nwakile, and V O Hammed, "Carbon capture, utilization, and storage (CCUS) technologies: Evaluating the effectiveness of advanced ccus solutions for reducing CO2 emissions", *Results Surf. Interfaces,* p. 100381, 2024.

[42] M. Hao, R. Bi, and Y. Liu, "A review of CO2 capture utilization and storage in china: Development status, cost limits, and strategic planning", *Processes,* vol. 13, no. 3, p. 905, 2025. http://dx.doi.org/10.3390/pr13030905

[43] M. Nooraiepour, P. Gladysz, and E. Melaaen, "The Norwegian-Polish CCS Network: A Case Study in Bilateral Collaboration for European Climate Action", *arXiv:2501.05539,* pp. 1-7, 2025.

[44] M M Ramirez-Corredores, "Sustainable production of CO2-derived materials", *Mater. Sustain.,* vol. 2, no. 1, p. 35, 2024.

[45] H. Bouaboula, J. Chaouki, Y. Belmabkhout, and A. Zaabout, "Comparative review of Direct air capture technologies: From technical, commercial, economic, and environmental aspects",

Chem. Eng. J., vol. 484, p. 149411, 2024.
http://dx.doi.org/10.1016/j.cej.2024.149411

[46] S. Xu, and S. Dai, "CCUS As a second-best choice for China's carbon neutrality: An institutional analysis", *Clim. Policy,* vol. 21, no. 7, pp. 927-938, 2021.
http://dx.doi.org/10.1080/14693062.2021.1947766

[47] D. Helm, "The European framework for energy and climate policies", *Energy Policy,* vol. 64, pp. 29-35, 2014.
http://dx.doi.org/10.1016/j.enpol.2013.05.063

[48] T.M. Alabi, N.P. Lawrence, L. Lu, Z. Yang, and R. Bhushan Gopaluni, "Automated deep reinforcement learning for real-time scheduling strategy of multi-energy system integrated with post-carbon and direct-air carbon captured system", *Appl. Energy,* vol. 333, p. 120633, 2023.
http://dx.doi.org/10.1016/j.apenergy.2022.120633

[49] G. Wen, Z. Li, Q. Long, K. Azizzadenesheli, A. Anandkumar, and S.M. Benson, "Real-time high-resolution CO 2 geological storage prediction using nested Fourier neural operators", *Energy Environ. Sci.,* vol. 16, no. 4, pp. 1732-1741, 2023.
http://dx.doi.org/10.1039/D2EE04204E