

Review

A Review of CCUS Technology Development: Key Challenges and Strategic Pathways from Demonstration to Commercialization

Zhiyu Wei and Zhili Du *

School of Management, China Institute for Studies in Energy Policy, Xiamen University, Xiamen 361005, China; davewei2001@163.com

* Correspondence: duzhili620@xmu.edu.cn

Abstract

With the intensification of global climate change, Carbon Capture, Utilization and Storage (CCUS) technology has gradually become an important means to address climate change. As the sole technological option for the low-carbon utilization of fossil energy, CCUS technology offers new opportunities for the sustainable development of the energy sector. To systematically assess the current status of technological development and clarify the future development direction, this study conducts a comprehensive evaluation of the technical level, economic efficiency, and scale of CCUS. China has demonstrated considerable advancement in CCUS, particularly in the domains of capture and transportation, but still faces challenges in technology integration and commercialization. By strengthening policy support, reducing technical costs and promoting large-scale deployment, CCUS is expected to play a greater role in the future. This research provides valuable insights for the future development of CCUS and emphasizes the importance of improving its economic viability, with the aim of proving guidance for formulating China's CCUS technology innovation strategy and advancing industrialization.

Keywords: CCUS; carbon neutrality; energy conservation; emission reduction; technological path

1. Introduction

Global climate change has become the most urgent environmental challenge of the 21st century. The World Meteorological Organization (WMO) has determined that the global average surface temperature in 2024 is approximately 1.55 °C higher than the pre-industrial average (1850–1900) based on six international datasets [1]. To mitigate the impacts of climate change, numerous nations have progressively set objectives for achieving carbon peak emissions and carbon neutrality. This initiative is driving a profound decarbonization of the energy sector and fostering an economic transition toward sustainability. However, despite the rapid development of renewable energy and energy efficiency improvement technologies, some high-emission industries, such as power, steel, cement, and chemicals, still face relatively great difficulties and cost barriers in reducing emissions. Effectuating profound decarbonization, while simultaneously guaranteeing energy dependability and fostering economic expansion, has emerged as a pivotal quandary within the global energy technology transition.

Academic Editor: Alberto Pettinau

Received: 19 January 2026

Revised: 22 February 2026

Accepted: 24 February 2026

Published: 26 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

CO₂ is a greenhouse gas closely related to human activities, and reducing its emissions is a core measure to address climate change [2]. Against this backdrop, CCUS emerged. CCUS is widely regarded as one of the key solutions for addressing global climate change and achieving carbon neutrality goals [3]. This method captures CO₂ at the source of emissions. The captured CO₂ is then transported for long-term isolation through geological storage or for resource utilization, thereby significantly reducing greenhouse gas emissions into the atmosphere. According to the International Energy Agency's prediction, CCUS will contribute 14% of CO₂ emission reductions by 2050, and 32% by the end of the 21st century [4].

CCUS covers four main links: capture, transportation, utilization and storage [5,6]. Technologies such as Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with carbon capture and storage (BECCS) reduce atmospheric CO₂ by capturing CO₂ emitted from industrial sources and either storing it or converting it into valuable products [7,8]. Developed countries have carried out extensive research and development in CO₂ capture and conversion, as well as geological utilization and storage of CO₂. Among them, carbon capture technologies primarily focus on technical areas such as absorption and adsorption methods, membrane separation, and front-end engineering design for carbon capture systems. The geological utilization and storage of CO₂ mainly focus on oil displacement, gas displacement, enhanced geothermal energy, as well as CO₂ injection equipment and devices, injection profile evaluation, and monitoring systems, etc. The conversion and utilization of CO₂ mainly include chemical utilization, biological conversion into chemicals and fuels, and mineralization technologies such as steel slag mineralization and concrete curing. China has achieved remarkable results in technological innovation. Over the past decade, the number of CCUS technology patents has grown explosively, while patent applications have remained at the top. It has become a key driver of global CCUS development. Although China is making rapid progress in CCUS with the number of patents ranking first globally in the Orbit patent database, there is still a gap compared with developed countries in commercial integration and in some key technologies.

Against this backdrop, conducting in-depth research into each link in the CCUS chain, optimizing technical processes, and achieving economic breakthroughs are of great significance for promoting the all-round development of the CCUS industry and achieving global climate goals.

This study adopts a narrative review method. Focusing on the current development status of CCUS in China, this study aims to construct a comprehensive analysis framework for the maturity, economic cost and scalability potential of CCUS technology by reviewing and integrating the key literature in this field from 2005 to 2025. The sources of the literature primarily include peer-reviewed studies from databases such as Web of Science and Engineering Village, as well as authoritative institutional sources, to ensure the scientific and cutting-edge nature of the information relied upon. There might be some potential limitations in this study, such as the method being relatively subjective and prone to being influenced by selection bias in the literature. This study enhances rigor by implementing a structured, transparent argumentation process.

2. The Current Situation and Trends

2.1. Commercialization Pathway

The CCUS industry in China has considerable growth potential, with the number of projects and capture capacity increasing rapidly. Figure 1 presents the development of CCUS in China [9].

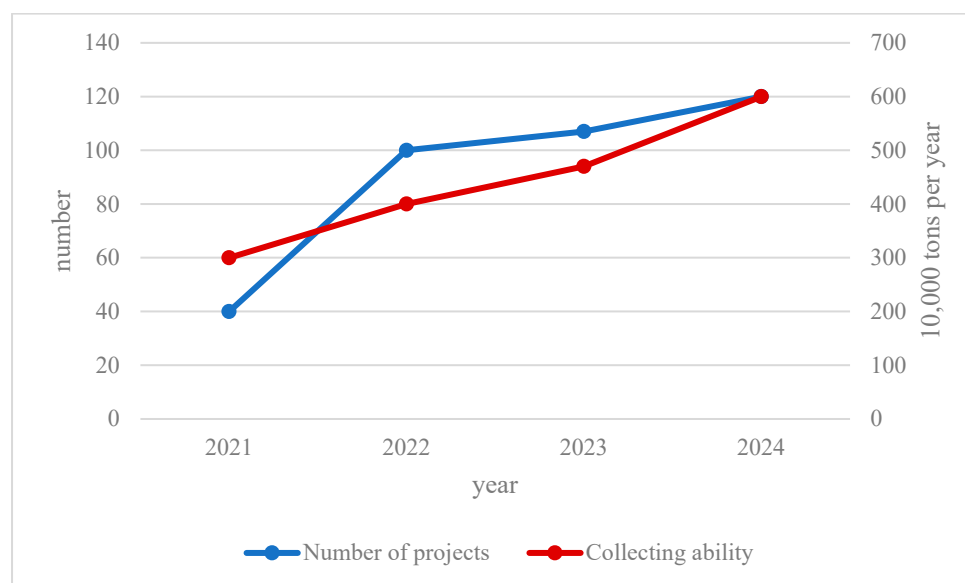


Figure 1. CCUS in China.

China's CCUS technology still has a significant gap compared to developed countries. As of 2024, only 13% of projects are in the commercial application stage, far lower than the United States' 46% [10]. Regarding technological maturity, China is transitioning from field trials to industrialization, marking a shift from following to keeping pace with international levels [11]. However, European and American countries maintain a clear lead in negative-emission technologies such as direct air capture and bioenergy carbon capture and storage, as well as long-term storage monitoring technologies under complex geological conditions, due to their forward-looking approaches. The comparison of CCUS policies is shown in Table 1. The number of CCUS projects is from GLOBAL STATUS OF CCS 2024 [12]. In terms of economic feasibility, high costs pose a common challenge for both sides. Advanced projects worldwide have effectively reduced unit costs through cluster development [13]. By contrast, China's current CCUS projects still heavily rely on crude oil revenue from enhanced oil recovery for economic viability, lack a stable, diversified value-return mechanism, and have commercial models still under exploration [14]. Regarding Monitoring, Reporting, and Verification (MRV) systems, China has developed integrated monitoring technologies and participated in the formulation of international standards. However, a unified MRV methodology, certified national standards, and internationally recognized monitoring system are still under construction, which to some extent constrains the market recognition and trading of project emission reductions.

Table 1. Comparison of CCUS Policies.

Comparison Dimension	United States	European Union	China
Core Policy Instrument	45Q Tax Credit	EU Emissions Trading System (EU ETS)	National-level strategic planning & technical standards
Key Effective Date	Introduced 2008, revised 2020, enhanced by the Inflation Reduction Act 2022	Launched 2005, "Fit for 55" reform package agreed in 2023	The 14th Five-Year Plan (2021–2025), CCUS Technology Development Implementation Plan
Main Eligibility Conditions	Project must commence construction by specific dates; Captured CO ₂ used for geological storage or utilization; Must meet MRV requirements	Facilities under EU ETS jurisdiction; Use approved monitoring methodologies; CO ₂ must be permanently stored; Must comply	Demonstration projects in key emitting sectors (e.g., power, cement, steel); Must comply with national technical standards and specifications

with the Directive on the Geological Storage of Carbon Dioxide			
Number of Projects	27 projects in operation and 18 commencing construction across the US, Brazil, and Canada in 2024	Across Europe there are five projects in operation, with 10 in construction in 2024	6 of 47 projects in China's first Implementation Plan for Advanced Green and Low-carbon Technology Demonstration are CCUS-related in 2024

In the realm of policy support frameworks, the European Union's 'Industrial Carbon Management Strategy' and the United States' '45Q' tax credit policy have laid a robust foundation with comprehensive legal structures and enduring incentive mechanisms, thereby instilling market confidence. Despite China's integration of CCUS into its overarching national objectives for carbon neutrality and peaking, specific legislative instruments, streamlined authorization pathways, definitive long-term liability frameworks for CO₂ sequestration, and dedicated mechanisms to fully incorporate CCUS-driven emissions reductions into the national emissions trading system are still in development. The stability and predictability of the policy environment require enhancement [15]. In the infrastructure sector, Europe and the United States are actively planning cross-regional carbon dioxide transportation networks and storage hubs to accelerate clustered layouts. While China has conceptualized million-ton-scale cluster initiatives, current projects predominantly exhibit a point-to-point configuration, characterized by underdeveloped shared pipeline infrastructure. This has hindered the optimization of source-sink pairings and the achievement of scaled synergistic benefits [16]. According to the predicted CO₂ capture cost data, The CO₂ capture demand in East China is in Table 2 with cost units in Chinese Renminbi per ton and capacity units in hundreds of millions of tons, based on the 2060 fossil energy continuation scenario [17]. The geography is limited to East China as one of China's seven modeled regions, and the currency uses RMB without inflation or purchasing power parity adjustments. The term capacity refers to the annual CO₂ capture demand for specific industrial sectors, while cumulative capacity represents the sequentially summed total ordered by ascending cost, both pertaining to capture—not storage. All values are modeled predictions.

Table 2. CO₂ Capture Technologies and Corresponding Information.

CO ₂ Capture Classification	Capacity/10 ⁸ t	CO ₂ Capture Cost/(RMB·t ⁻¹)	Cumulative Capacity/10 ⁸ t
Steel industry	2.15	166.51	5.16
Thermal power: post-combustion	1.92	114.65	2.9
Thermal power: pre-combustion	0.11	158.15	3.01
Thermal power: oxygen-enriched combustion	0.11	168.15	5.27
Petrochemical: heating boilers	0.34	96.51	0.98
Petrochemical: exhaust gas capture from chemical plants	0.64	73.15	0.64
Cement industry	0.96	170.94	6.24

2.2. Carbon Capture

Carbon capture technology refers to the process of separating CO₂ from industrial emission sources or the atmosphere. The main technologies include post-combustion capture, pre-combustion capture, oxygen-enriched combustion, Chemical Looping Combustion (CLC), biomass energy capture and direct air capture. Post-combustion capture, which involves separating CO₂ from post-combustion flue gases, is currently one of the

most extensively researched and implemented approaches [18]. For instance, the traditional Monoethanolamine (MEA) capture method and the novel Silica-alkoxylated Polyethylimine (SPEI) adsorbent method have been applied to post-combustion carbon capture in cement plants [19]. The post-combustion capture system based on chemical absorption method has been in the commercial application stage internationally. The current technology is mature, but the energy consumption is relatively high. Other post-combustion capture methods are in the pilot or industrial demonstration stage [20]. The main separation processes of pre-combustion capture include solution absorption, solid adsorption, membrane separation, low-temperature distillation, and combined applications of the above methods. Among them, the physical absorption method is in the commercial operation stage and is mostly applied in industries such as petrochemicals and chemical engineering, while other technologies are in the industrial demonstration stage. Oxygen-enriched combustion, a modification of existing boiler systems, involves substituting air with pure oxygen to facilitate combustion. This process enables precise control over the furnace's combustion and heat transfer dynamics through flue gas recirculation, thereby achieving a high CO₂ concentration in the resultant flue gas. This technology bifurcates into two primary categories: Atmospheric Pressure Oxygen-enriched Combustion (AOC) and Pressurized Oxygen-enriched Combustion (POC). Currently, AOC is undergoing pilot demonstration in China, while POC remains in the laboratory research phase. CLC utilizes solid oxygen carriers to transfer oxygen from the air to the fuel for combustion, avoiding direct contact between the fuel and the air. It can separate CO₂ during the combustion process without the need for air separation to produce oxygen, directly generating high-concentration CO₂ flue gas without N₂. At present, semi-industrial CLC tests have been completed abroad, and the scale of some gas CLC has reached the megawatt level. Concurrently, DAC and BECCS technologies are progressing rapidly.

BECCS and DAC are pivotal negative emission technologies crucial for achieving substantial decarbonization and net-negative emissions objectives [21,22]. BECCS involves the capture, utilization, or storage of CO₂ produced during biomass combustion or conversion, broadly encompassing two primary stages: biomass utilization and CCUS. The technological maturity of each component influences the commercial viability of biomass energy carbon capture [23,24]. Biomass utilization technologies, categorized by processing or product transformation, include combustion, anaerobic digestion, and densification, which are relatively mature and commercially deployed [25]. With the exception of liquid hydrocarbon production, other biomass conversion technologies have also reached commercial application [26]. DAC refers to the process of directly separating and enriching CO₂ from the air. Its significant advantage lies in its independence from proximity to emission sources, offering considerable locational flexibility and making it an optimal solution for mitigating emissions from mobile and diffuse sources [27]. Although DAC is highly flexible, its huge energy consumption and high operating costs are the main obstacles to its large-scale deployment [28]. The development of this technology in the industrial field is still in its infancy, and only small-scale industrial demonstrations have been carried out so far. The existing pilot demonstrations of direct air capture for CO₂ are all located abroad, respectively, from Carbon Engineering of Canada, Climeworks of Switzerland and Global Thermostat of the United States.

The CO₂ capture in China is undergoing extensive diversification. Pre-combustion capture is in the industrial demonstration stage, in line with international standards. The post-combustion chemical absorption method is still in the demonstration stage and lags behind the international commercialization level. Oxygen-enriched combustion is in the pilot stage. CLC and other technologies are still in the basic research stage. The technology as a whole is moving towards low-cost and large-scale development, but it faces challenges such as high energy consumption, difficulties in the degradation and recovery of

amine solutions, and the integration and optimization of million-ton systems. The large-scale preparation of materials and the long-term operational stability of the system are also key bottlenecks.

2.3. Conveying

The transportation modalities for CO₂ exhibit variations in terms of technological maturity and deployment scale. Globally, tank truck, marine vessel, and pipeline conveyance methods have achieved commercial viability. However, the operational range, performance and safety of different modes of transportation vary [29]. Tank truck transportation is typically suitable for short-distance, small-batch or flexible CO₂ transportation requirements [30]. Maritime shipping provides enhanced logistical adaptability and reduced operational hazards, occasionally presenting a more cost-effective solution than pipeline conveyance [31]. For example, shipping's inherent flexibility renders it a compelling option when CO₂ sourcing is dispersed or market expansion projections are equivocal [32,33]. Pipeline transportation is the main infrastructure for onshore oil and natural gas transportation, which also plays an important role in CO₂ transportation. CO₂ pipeline transportation has the advantages of economy and convenience, and is of vital importance in CCUS systems [34]. This mode is particularly well-suited for high-volume, extensive, and continuous CO₂ movement, offering comparatively low operational expenditures post-construction [35]. Studies indicate that the transport costs of onshore and offshore pipelines diminish with increased CO₂ mass flow rates, reflecting economies of scale [36].

In recent years, China has made significant progress in large-scale CO₂ transportation technology for multiple application scenarios. The transportation capacity, pipe diameter, and transportation distance have gradually been scaled up. The pipeline transportation capacity has exceeded one million tons, and the pressure has reached the supercritical range [37]. In terms of pipeline transportation, China has established an economic evaluation system for CO₂ supercritical transportation and broken through limitations such as phase control, leakage early warning, and safe venting. Compared with onshore CO₂ transportation pipelines, long-distance dense-phase CO₂ transportation pipelines at sea face formidable challenges including intricate oceanic environments, elevated corrosivity, and inherent limitations in mitigating operational hazards across their infrastructure.

2.4. Chemical Engineering and Bioutilization

CO₂ chemical and biological utilization technology refers to industrial technology that takes chemical or biological conversion as its core feature and uses CO₂ as a carbon and oxygen resource, transforming it into value-added products while offering potential greenhouse gas abatement benefits. The development level of this type of technology is basically in line with China and abroad, and it is generally in the industrial demonstration stage. In the past decade, various biological and chemical utilization technologies have all developed. The most advanced technology is the synthesis of chemical materials using CO₂, such as the synthesis of organic carbonates, degradable polymers and cyanates/polyurethanes, the preparation of polycarbonate/polyester materials and hydrogenation to methanol, etc. [38–41].

2.5. Geological Utilization and Storage

A significant application entails injecting CO₂ into depleted hydrocarbon reservoirs. This process concurrently enables the subsurface sequestration of CO₂ and augments hydrocarbon recovery efficiencies. Subsea geological storage involves the injection of captured CO₂ into subterranean geological strata, thereby achieving durable atmospheric carbon dioxide abatement.

CO₂ geological sequestration and utilization encompass technologies for the purposeful deployment of captured CO₂ within subterranean geological formations, either for direct utilization or for injection into deep geological reservoirs. These methods employ engineering and technical strategies to ensure the long-term containment of CO₂ and its effective isolation from the atmosphere [42]. Reservoir characterization and numerical modeling are critical components in assessing the efficacy and security of carbon storage operations. Storage methodologies are broadly categorized into terrestrial and subsea geological approaches. At present, geological storage is recognized as the most technologically advanced and scalable solution for carbon sequestration. A notable application involves injecting CO₂ into exhausted hydrocarbon reservoirs, a process that not only facilitates the subsurface storage of CO₂ but also enhances hydrocarbon recovery rates [37,43,44]. Subsea geological storage entails the injection of captured CO₂ into geological formations beneath the seafloor, thereby achieving permanent atmospheric removal [16,45]. Projects such as Sleipner, Gorgon and Northern Lights are successful cases of off-shore CCS implementation worldwide.

The development of CCUS in China shows a multi-path parallel trend. The site selection for sequestration needs to take into account geological conditions and safety. Long-term monitoring technology is a key focus of research and development [46].

2.6. CCUS Integrated Optimization

In the industrial sector, China has pioneered the commercial deployment of integrated optimization technologies. Across critical industries including coal-fired power generation, petrochemicals, cement, and steel manufacturing, comprehensive, end-to-end demonstrations of CCUS have been extensively implemented. Concurrently, robust frameworks for safety assessments, monitoring protocols, and full life-cycle evaluations of storage sites have been established. Projections indicate that to reach a capture capacity of 1.74 gigatons per annum by 2050, an estimated 19,000 km of primary trunk pipelines will require construction. Notably, approximately half of these CO₂ transportation routes exhibit significant overlap, leveraging existing oil and gas pipeline corridors, thus highlighting considerable synergistic opportunities [47]. Furthermore, research utilizing the SPATIAL model suggests that the integrated approach of industrial clusters coupled with CCUS can yield substantial scale economies [48].

2.7. Oxyfuel Combustion

Oxyfuel combustion represents a pioneering carbon capture methodology that facilitates the combustion of fossil fuels within an environment of pure oxygen, diverging from conventional air-based combustion. This process yields an exhaust gas stream predominantly composed of highly concentrated CO₂ and water vapor [49]. The facile condensation of water vapor subsequently isolates a near-pure CO₂ stream, rendering it amenable to compression, subterranean sequestration, or industrial valorization.

Leading Chinese energy conglomerates, bolstered by state-sponsored research initiatives, are vigorously prosecuting pilot and demonstration ventures. The strategic imperative involves the seamless integration of oxyfuel systems into extant power generation infrastructure and industrial installations, thereby enhancing operational efficiency and mitigating the considerable energetic penalties and economic burdens historically linked with carbon capture technologies [50]. Although the extensive implementation of this technology confronts impediments related to scalability and further cost optimization, it is widely regarded as an indispensable strategy for facilitating China's transition toward a sustainable energy paradigm.

3. Economic Feasibility Analysis

CCUS currently contends with substantial capital and operational expenditures globally; however, significant cost reductions are projected [51]. In recent years, the energy consumption and cost of CCUS capture in various industries in China have continued to decline significantly. The decline in the thermal power and petrochemical industries has reached 30% to 50% [52–54]. The primary cost driver within CCS value chains is the capture equipment, accounting for 60–80% of total outlays [55]. Strategic deployment can reduce the First-of-a-Kind cost of DAC [56]. However, it is still at a relatively high level compared to stationary emission sources. Key cost factors such as capture cost, transportation cost, pricing mechanism of CO₂-EOR benefits, and future oil price decline rate significantly influence the deployment pattern of CCUS [57]. CCUS presents nascent cost-effective opportunities, particularly when integrated with utilization pathways [51]. Anticipated large-scale deployment and ongoing technological innovation will further bolster CCUS's economic viability.

The economic viability of carbon capture is contingent upon the employed methodology, as well as the volumetric CO₂ concentration and the emission source's operational scale [58]. Specifically, facilities generating high-concentration CO₂ streams, including but not limited to coal-fired power stations, cement production facilities, steel manufacturing plants, and chemical processing operations, exhibit comparatively lower capture expenditures [3,59,60]. For coal-fired power plants, the application of CCUS is crucial for achieving economic decarbonization [61].

Pipelines are recognized as the most economical and effective method to transport large amounts of CO₂ [62]. The economics of long-haul, large-scale pipeline transport are primarily dictated by capital expenditures for construction, operational expenditures, and maintenance outlays. In infrastructure construction, the synergistic collaboration and established cost-sharing frameworks among prospective user consortia critically influence overall project expenditures. The formation of strategic alliances and joint infrastructure development initiatives among diverse user segments can yield optimized cost-sharing efficiencies [63]. Furthermore, offshore CCUS endeavors necessitate a thorough assessment of CO₂-induced corrosion effects on pipeline integrity, thereby escalating safety-related expenditures and ongoing maintenance liabilities during the transport phase [6,62]. The valorization of CO₂ into marketable commodities presents a viable pathway to mitigate a portion of the capture and transportation costs, thereby bolstering the overall economic viability of CCUS projects [64].

The storage costs mainly include expenses for geological exploration, drilling, injection, monitoring, and potential leakage risk management, etc. [65,66]. Submarine reservoirs offer superior volumetric capacity and a more secure containment milieu relative to terrestrial repositories [53,67]. However, offshore CCUS projects face technical and economic constraints during the planning stage and require detailed source-sink matching and cost analysis [68]. China has carried out a series of explorations in the field of offshore CCUS, including assessing the potential for CO₂ storage in the Pearl River Estuary Basin and launching the first offshore CO₂ storage project [53].

Despite decades of advancement, numerous CCUS technologies remain in the pilot phase, exhibiting nascent technological readiness. This immaturity translates into substantial investment uncertainties and elevated expenditures [5,69,70]. With technological progress and large-scale deployment, the learning curve effect is expected to reduce future costs [71]. Furthermore, strategic optimization of the CCUS supply chain network architecture has the potential to significantly curtail annualized capital and operational expenditures [59,72,73].

The high initial investment and technological uncertainties make CCUS projects require effective policy incentives, such as carbon tax incentives and carbon emissions

trading [70,73,74]. The Chinese government acknowledges the pivotal role of CCUS in attaining carbon neutrality. Consequently, CCUS has been integrated into the nation's medium and long-term developmental strategies, with a focus on advancing its deployment in critical sectors such as energy and industry [75]. China has promoted a series of CCUS demonstration projects in high-emission industries such as power, coal chemical engineering, steel, and cement, aiming to verify technical feasibility, accumulate operational experience, explore business models, and gradually reduce costs [76]. In essence, China's national policy framework for CCUS is progressively evolving, establishing a robust foundation for the widespread adoption of this technology.

4. The Process of CCUS Scaling up

4.1. Global

The global landscape of CCUS initiatives is exhibiting a trend towards both a broader range of applications and increased capacity. In recent years, a discernible rise in the quantity and magnitude of CCUS industrial demonstration ventures has been observed worldwide. Within the operational large-scale CCUS industrial demonstration projects, the predominant carbon capture methodologies are rooted in industrial separation techniques. These projects are predominantly situated within sectors such as natural gas processing, fertilizer production, chemical production, hydrogen production, oil refining, and coal chemical engineering [77].

Some CCUS projects in Europe and America have entered the commercial operation stage. The United States remains the global leader in CCUS facilities, which is to some extent attributed to the strategies and sustained policy support it has formulated. The EU adopts CCFD (Carbon Contracts for Difference) to assist enterprises subject to the EU Emissions Trading System (ETS) in achieving decarbonization of their production processes. The policies of the Canadian government are also supporting the deployment of CCUS projects. The Canadian Parliament approved the federal investment tax credit for CCUS in June 2024.

The Weyburn-Midale project, a collaboration between the United States and Canada, is currently recognized as the most successful and landmark commercial CCUS project internationally [78]. The Boundary Dam CCUS project is the world's first commercial-scale CO₂ capture project for coal-fired power plants, with an annual capture capacity of 1 million tons. ExxonMobil's Shute Creek CCUS project is currently the world's largest carbon capture project. Since its launch in the 1980s, the project has been in operation until now, and the captured CO₂ is used for oil displacement and geological storage. Ethanol, natural gas processing and hydrogen/ammonia/fertilizer production are the key industries for the current commercial operation of CCUS [79,80]. Commercial-scale CCUS projects targeting low-concentration emission sources, including coal-fired power plants, natural gas combustion facilities, waste-to-energy plants, and cement manufacturing operations, are currently in various phases of construction and development. These facilities are projected to commence operations sequentially by the year 2025.

4.2. China

CCUS development in China has progressed over a decade, evolving from initial pilot phases to a current trajectory of scaled, localized deployment. While certain technologies show promise for commercial viability, significant advancements are still required in the critical domains of capture, transportation, and storage, as well as in their integrated commercial application [81]. The advent of China's dual carbon objectives has catalyzed a rapid expansion phase for CCUS initiatives. Both the quantity and magnitude of CCUS projects have experienced substantial growth. Advancing CCUS projects within China is

projected to yield an aggregate carbon reduction of 8%, with sustained demand for carbon sequestration anticipated up to 2060 [82]. These projects are predominantly situated in carbon-intensive geographical areas, including Eastern and Northern China, and exhibit a discernible trajectory toward large-scale deployment.

In China, the primary source of carbon for industrial utilization is the low-concentration flue gas emanating from coal-fired power facilities. Despite the inherent challenges and substantial financial investment associated with its capture, there has been a notable and accelerated proliferation of carbon capture demonstration initiatives [79]. The trajectory of CO₂ capture is transitioning from preliminary pilot-scale trials to expansive, million-ton-scale deployments. The technological spectrum encompasses a broad array of applications, ranging from the dilute flue gas streams characteristic of power plants to the more concentrated gas effluents found in various industrial processes. Consequently, the burgeoning CCUS industry in China exhibits a strong dependency on sectors characterized by high carbon emissions.

The concentrated deployment of CCUS is broadly acknowledged as a pivotal strategy for mitigating expenses, enhancing operational efficacy, and achieving substantial decarbonization objectives [71]. This integrated cluster paradigm, characterized by centralized capture methodologies, synchronized transportation logistics, and streamlined storage and utilization protocols, will establish the bedrock for the establishment of a comprehensive CCUS value chain.

5. Conclusions

This study presents a systematic evaluation of the current state of CCUS development in China. It acknowledges advancements in critical components while clearly delineating discrepancies between China's progress and international leading standards, particularly in overall commercialization scale, integrated innovation, policy mechanism refinement, and infrastructure synergy. Current literature primarily focuses on the emission reduction benefits and cost-effectiveness of CCUS, but lacks a systematic assessment of the negative environmental externalities that may arise throughout the technology's lifecycle, coupled with an insufficient understanding of systemic risks. To facilitate the transition of CCUS from demonstration to large-scale commercialization, future scientific directions should focus on overcoming existing technological bottlenecks and exploring emerging development pathways.

The technical challenges mainly lie in the energy consumption, reliability and monitoring capabilities throughout the entire process. The mainstream technologies in the capture phase consume excessive energy, significantly reducing the operational efficiency of power plants and other facilities. The core materials and key equipment have a high degree of dependence on external sources, which restricts the independent development of the technology and the reduction in costs. In the utilization phase, the technical route of converting CO₂ into high-value products is still not mature, and the efficiency and stability of catalysts need to be improved. In the storage phase, there has been long-term uncertainty due to the complexity of geological structures, and there is a lack of efficient, precise and low-cost long-term monitoring and leakage warning technologies, which affects environmental safety and public acceptance.

The core economic challenge lies in the current high overall cycle costs and fragile business model. From capture, transportation to storage or utilization, the costs of each phase are added together, making the unit emission reduction cost of CCUS much higher than the current carbon market price, lacking market competitiveness. The initial investment for projects is huge, while the main emission industries have limited profit margins, and the investment willingness is not strong. The lack of infrastructure, such as dedicated transportation pipelines, further increases the system cost. In addition, the market for the

resource utilization of CO₂ has not yet formed a scale, and the economic performance of the main absorption paths is greatly affected by fluctuations in commodity prices, lacking stable, high-value commercial exports, and it is difficult to form a sustainable profit loop.

The legislative challenge is reflected in the insufficient enforceability and clarity of the policy framework. The existing policies are mainly in the form of planning guidance and technical regulations, lacking mandatory emission reduction constraints or installation requirements to create a stable market demand. At the incentive level, substantive economic incentives such as fiscal subsidies, tax incentives, and special financial tools for CCUS projects are still weak. In terms of the standard system, key institutional mechanisms such as cross-industry and cross-regional project approval processes, division of responsibilities, long-term storage environmental liability attribution, and carbon measurement and verification methods have not been fully established, increasing the legal and policy risks of project development and hindering the large-scale entry of social capital.

6. Recommendations

The Chinese government ought to augment its financial commitment to the research and development of foundational CCUS technologies to secure a vanguard position in the global technological arena. It is imperative for the administration to refine the carbon pricing framework and integrate externalities by implementing carbon levies or establishing emissions trading platforms. To alleviate the initial capital expenditure burden on entities adopting CCUS, the government could institute fiscal incentives, grants, and other forms of enticement.

Furthermore, the Chinese administration should bolster international collaborations within the CCUS sector, proactively assimilate cutting-edge technological advancements, furnish fiscal and tax-related assistance, and motivate corporations and academic bodies to elevate the caliber of their patents and enhance global market standing. Corporations must strategically optimize their patent portfolios in the international marketplace, with particular emphasis on key European and North American territories, to safeguard their intellectual property rights.

Augmenting capture efficacy represents a significant avenue for cost reduction. The refinement of extant capture methodologies can diminish energy utilization, thereby curtailing operational expenditures. The optimization of CO₂ transport infrastructure, the expansion of storage capacities at existing locales, and the mitigation of storage expenses are crucial for improving efficiency and reducing energy consumption across all phases of CCUS deployment.

Author Contributions: Conceptualization, Z.W. and Z.D.; methodology, Z.W.; validation, Z.D.; formal analysis, Z.D.; investigation, Z.W.; writing—original draft preparation, Z.W.; writing—review and editing, Z.D.; visualization, Z.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study.

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

References

1. World Meteorological Organization. *State of the Global Climate 2024*; World Meteorological Organization (WMO): Geneva, Switzerland, 2025; p. 42.

2. Thamarai, P.; Deivayanai, V.C.; Saravanan, A.; Vickram, A.S.; Yaashikaa, P.R. Carbon Mitigation in Agriculture: Pioneering Technologies for a Sustainable Food System. *Trends Food Sci. Technol.* **2024**, *147*, 104477. <https://doi.org/10.1016/j.tifs.2024.104477>.
3. Raihan, A. Carbon Capture, Utilization, and Storage (CCUS) in the Context of Earth Energy Systems: A Multidisciplinary Review. *Geosci. Front.* **2025**, *16*, 102177. <https://doi.org/10.1016/j.gsf.2025.102177>.
4. IEA. Energy Technology Perspectives 2020. 10 September 2020. Available online: <https://www.iea.org/reports/energy-technology-perspectives-2020> (accessed on 23 February 2026).
5. Gupta, N.C.; Tanwar, R.; Dipesh; Kaushik, A.; Singh, R.; Patra, A.K.; Sar, P.; Khakharia, P. Perspectives on CCUS Deployment on Large Scale in India: Insights for Low Carbon Pathways. *Carbon Capture Sci. Technol.* **2024**, *12*, 100195. <https://doi.org/10.1016/j.ccst.2024.100195>.
6. Yan, T.; Xu, L.-C.; Zeng, Z.-X.; Pan, W.-G. Mechanism and Anti-Corrosion Measures of Carbon Dioxide Corrosion in CCUS: A Review. *iScience* **2024**, *27*, 108594. <https://doi.org/10.1016/j.isci.2023.108594>.
7. Dongpeng, S.; Yuan, Z.; Dong, C. Applications of Microfluidics in Carbon Capture, Utilization and Storage (CCUS). *Energy Environ. Prot.* **2023**, *37*, 117–124. <https://doi.org/10.20078/j.eep.20230103>.
8. Pal, M.; Karaliūtė, V.; Malik, S. Exploring the Potential of Carbon Capture, Utilization, and Storage in Baltic Sea Region Countries: A Review of CCUS Patents from 2000 to 2022. *Processes* **2023**, *11*, 605. <https://doi.org/10.3390/pr11020605>.
9. China Environmental Science Society CCUS Special Committee. *Series Report on China's Carbon Capture Utilization and Storage Progress 2025: New Developments, New Stages, New Trends*; Asian Development Bank: Metro Manila, Philippines, 2025.
10. Shi, M.; Gao, S.; Lyu, H.; Ma, Q.; Zhang, X.; Li, J. Comparison on the Development and Policy Frameworks of CCUS Technology in China and the United States. *Clean Coal Technol.* **2024**, *30*, 19–31. <https://doi.org/10.13226/j.issn.1006-6772.CCUS24041602>.
11. Dou, L.; Sun, L.; Lyu, W.; Wang, M.; Gao, F.; Gao, M.; Jiang, H. Trend of Global Carbon Dioxide Capture, Utilization and Storage Industry and Challenges and Countermeasures in China. *Pet. Explor. Dev.* **2023**, *50*, 1246–1260.
12. Global Status of CCS 2024. 16 October 2024. Available online: <https://www.globalccsinstitute.com/publications/global-status-of-ccs-2024/> (accessed on 23 February 2026).
13. Zhang, J.; Wang, Z.; Kang, J.-N.; Song, X.; Xu, D. Several Key Issues for CCUS Development in China Targeting Carbon Neutrality. *Carbon Neutrality* **2022**, *1*, 17. <https://doi.org/10.1007/s43979-022-00019-3>.
14. Jiang, K.; Ashworth, P.; Zhang, S.; Liang, X.; Sun, Y.; Angus, D. China's Carbon Capture, Utilization and Storage (CCUS) Policy: A Critical Review. *Renew. Sustain. Energy Rev.* **2020**, *119*, 109601. <https://doi.org/10.1016/j.rser.2019.109601>.
15. Ren, Q.; Wei, S.; Du, J.; Wu, P. Research Progress and Perspectives on Carbon Capture, Utilization, and Storage (CCUS) Technologies in China and the USA: A Bibliometric Analysis. *Environ. Sci. Pollut. Res.* **2023**, *30*, 76437–76454.
16. Bui, T.V.; Dao, H.H.; Nguyen, H.T.; Ta, Q.D.; Le, H.N.N.; Kieu, P.; Mai, C.L.; Tran, T.D.; Nguyen, H.S.; Nguyen, H.D.; et al. A Critical Review on the Opportunities and Challenges of Offshore Carbon Capture, Utilization, and Storage. *Sustainability* **2025**, *17*, 9250. <https://doi.org/10.3390/su17209250>.
17. Zhao, X.; Xiao, J.; Hou, J.; Wu, J.; Lyu, X.; Zhang, J.; Liu, Y. Economic and Scale Prediction of CO₂ Capture, Utilization and Storage Technologies in China. *Pet. Explor. Dev.* **2023**, *50*, 751–764. [https://doi.org/10.1016/S1876-3804\(23\)60425-2](https://doi.org/10.1016/S1876-3804(23)60425-2).
18. Memon, S.U.R.; Manzoor, R.; Fatima, A.; Javed, F.; Zainab, A.; Ali, L.; Ullah, U.; Saleem, A.; Ullah, Q. A Comprehensive Review of Carbon Capture, Utilization, and Storage (CCUS): Technological Advances, Environmental Impact, and Economic Feasibility. *Sch. Acad. J. Biosci.* **2024**, *12*, 184–204. <https://doi.org/10.36347/sajb.2024.v12i07.003>.
19. Jaffar, M.M.; Rolfe, A.; Brandoni, C.; Martinez, J.; Snape, C.; Kaldis, S.; Santos, A.; Lysiak, B.; Lappas, A.; Hewitt, N.; et al. A Technical and Environmental Comparison of Novel Silica PEI Adsorbent-Based and Conventional MEA-Based CO₂ Capture Technologies in the Selected Cement Plant. *Carbon Capture Sci. Technol.* **2024**, *10*, 100179. <https://doi.org/10.1016/j.ccst.2023.100179>.
20. Lu, G.; Wang, Z.; Bhatti, U.H.; Fan, X. Recent Progress in Carbon Dioxide Capture Technologies: A Review. *Clean Energy Sci. Technol.* **2023**, *1*. <https://doi.org/10.18686/cest.v1i1.32>.
21. Desport, L.; Gurgel, A.; Morris, J.; Herzog, H.; Chen, Y.-H.H.; Selosse, S.; Paltsev, S. Deploying Direct Air Capture at Scale: How Close to Reality? *Energy Econ.* **2024**, *129*, 107244. <https://doi.org/10.1016/j.eneco.2023.107244>.
22. Mishra, A.; Kumar, M.; Medhi, K.; Thakur, I.S. Biomass Energy with Carbon Capture and Storage (BECCS). In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 399–427. <https://doi.org/10.1016/b978-0-444-64309-4.00017-9>.
23. Herman, K.S.; Sovacool, B.K. Applying the Multi-Level Perspective to Climate Geoengineering: Sociotechnical Bottlenecks for Negative Emissions and Cloud Seeding Technologies. *Energy Res. Soc. Sci.* **2024**, *115*, 103637. <https://doi.org/10.1016/j.erss.2024.103637>.

24. Ogle, R.A.; Dee, S.J.; Mastalski, I. Process Safety in Bioenergy with Carbon Capture and Storage Systems (BECCS). *Process Saf. Prog.* **2024**, *44*, 31–38. <https://doi.org/10.1002/prs.12657>.
25. Mersch, M.; Markides, C.N.; Mac Dowell, N. The Impact of the Energy Crisis on the UK's Net-Zero Transition. *iScience* **2023**, *26*, 106491. <https://doi.org/10.1016/j.isci.2023.106491>.
26. Shahbaz, M.; AlNouss, A.; Ghiat, I.; McKay, G.; Mackey, H.; Elkhailifa, S.; Al-Ansari, T. A Comprehensive Review of Biomass Based Thermochemical Conversion Technologies Integrated with CO₂ Capture and Utilisation within BECCS Networks. *Resour. Conserv. Recycl.* **2021**, *173*, 105734. <https://doi.org/10.1016/j.resconrec.2021.105734>.
27. Jiang, H.; Wang, S.; Xing, L.; Pinfield, V.J.; Xuan, J. Machine Learning Based Techno-Economic Process Optimisation for CO₂ Capture via Enhanced Weathering. *Energy AI* **2023**, *12*, 100234. <https://doi.org/10.1016/j.egyai.2023.100234>.
28. Fuhrman, J.; McJeon, H.; Patel, P.; Doney, S.C.; Shobe, W.M.; Clarens, A.F. Food–Energy–Water Implications of Negative Emissions Technologies in a +1.5 °C Future. *Nat. Clim. Change* **2020**, *10*, 920–927. <https://doi.org/10.1038/s41558-020-0876-z>.
29. Han, C.; Zahid, U.; An, J.; Kim, K.; Kim, C. CO₂ Transport: Design Considerations and Project Outlook. *Curr. Opin. Chem. Eng.* **2015**, *10*, 42–48. <https://doi.org/10.1016/j.coche.2015.08.001>.
30. Luo, Z.; Wu, P.; Wen, H.; Wang, Y.; Liu, C.; Du, X.; Liu, L. Effect of Source Strength on the Simulation of Jet Dispersion and Hazard Distances during Accidental Release of Liquid CO₂. *Process Saf. Environ. Prot.* **2024**, *183*, 1152–1169. <https://doi.org/10.1016/j.psep.2024.01.064>.
31. d'Amore, F.; Natalucci, L.; Romano, M.C. Optimisation of Ship-Based CO₂ Transport Chains from Southern Europe to the North Sea. *Carbon Capture Sci. Technol.* **2024**, *10*, 100172. <https://doi.org/10.1016/j.ccst.2023.100172>.
32. Aspelund, A.; Mølnvik, M.J.; De Koeijer, G. Ship Transport of CO₂. *Chem. Eng. Res. Des.* **2006**, *84*, 847–855. <https://doi.org/10.1205/cherd.5147>.
33. Barrio, M.; Aspelund, A.; Weydahl, T.; Sandvik, T.; Wongraven, L.; Krogstad, H.; Henningsen, R.; Molnvik, M.; Eide, S. Ship-Based Transport of CO₂. In *Greenhouse Gas Control Technologies 7*; Elsevier Science Ltd.: Amsterdam, The Netherlands, 2005; pp. 1655–1660. <https://doi.org/10.1016/b978-008044704-9/50193-2>.
34. Lu, H.; Ma, X.; Huang, K.; Fu, L.; Azimi, M. Carbon Dioxide Transport via Pipelines: A Systematic Review. *J. Clean. Prod.* **2020**, *266*, 121994. <https://doi.org/10.1016/j.jclepro.2020.121994>.
35. Zhang, Z.X.; Wang, G.X.; Massarotto, P.; Rudolph, V. Optimization of Pipeline Transport for CO₂ Sequestration. *Energy Convers. Manag.* **2006**, *47*, 702–715. <https://doi.org/10.1016/j.enconman.2005.06.001>.
36. Luo, J.; Xie, Y.; Hou, M.Z.; Xiong, Y.; Wu, X.; Lüddecke, C.T.; Huang, L. Advances in Subsea Carbon Dioxide Utilization and Storage. *Energy Rev.* **2023**, *2*, 100016. <https://doi.org/10.1016/j.enrev.2023.100016>.
37. Liang, B.; Chen, C.; Jia, C.; Wang, C.; Wang, X.; Zha, Y.; Wang, R.; Meng, Z.; Wang, H. Carbon Capture, Utilization and Storage (CCUS) in Oil and Gas Reservoirs in China: Status, Opportunities and Challenges. *Fuel* **2024**, *375*, 132353. <https://doi.org/10.1016/j.fuel.2024.132353>.
38. Alian Fard, A.; Hosseinfard, F.; Salimi, M.; Amidpour, M. Feasibility Assessment of Low-Carbon Methanol Production through 4E Analysis of Combined Cycle Power Generation and Carbon Capture Integration. *Therm. Sci. Eng. Prog.* **2024**, *56*, 103037. <https://doi.org/10.1016/j.tsep.2024.103037>.
39. Dhanusha, R.; Srinivasappa, P.M.; Alla, S.C.; Hemavathi, M.; Prasad, D.; Chaudhari, N.K.; Jadhav, A.H. Efficient Selective Catalytic Fixation of CO₂ into Epoxide to Form Cyclic Carbonates Using Sodium Aluminate Engineered Gamma Alumina Catalyst. *Appl. Organomet. Chem.* **2024**, *38*, e7429. <https://doi.org/10.1002/aoc.7429>.
40. Draxler, M.; Schenk, J.; Bürgler, T.; Sormann, A. The Steel Industry in the European Union on the Crossroad to Carbon Lean Production—Status, Initiatives and Challenges. *BHM Berg-Und Hüttenmännische Monatshefte* **2020**, *165*, 221–226. <https://doi.org/10.1007/s00501-020-00975-2>.
41. Seong, W.; Hahm, H.; Kim, S.; Park, J.; Abboud, K.A.; Hong, S. Self-Assembled Bimetallic Aluminum–Salen Catalyst for the Cyclic Carbonates Synthesis. *Molecules* **2021**, *26*, 4097. <https://doi.org/10.3390/molecules26134097>.
42. Khalaf, M.; Kim, H.; Sun, A.Y.; Van Essendelft, D.; Shih, C.Y.; Liu, G.; Siriwardane, H. High-Performance Reservoir Simulation with Wafer-Scale Engine for Large-Scale Carbon Storage. *Energies* **2025**, *18*, 5874. <https://doi.org/10.3390/en18225874>.
43. Kang, N.; Sarsenbekuly, B.; Wu, H. Progress of CCUS Technology with Enhanced Oil Recovery. *J. CO₂ Util.* **2025**, *102*, 103233. <https://doi.org/10.1016/j.jcou.2025.103233>.
44. Oladipo, O.T. Carbon Capture, Utilization, and Storage (CCUS) in Offshore and Onshore Oil Platforms. *Int. J. Res. Innov. Soc. Sci.* **2025**, *9*, 1642–1653. <https://doi.org/10.47772/ijriss.2025.9010135>.
45. Zhao, J.; Zheng, J.; Ren, L.; Lin, R.; Zhou, B. A Review on Geological Storage of Marine Carbon Dioxide: Challenges and Prospects. *Mar. Pet. Geol.* **2024**, *163*, 106757. <https://doi.org/10.1016/j.marpetgeo.2024.106757>.

46. Sonke, J.; Bos, W.M.; Paterson, S.J. Materials Challenges with CO₂ Transport and Injection for Carbon Capture and Storage. *Int. J. Greenh. Gas Control* **2022**, *114*, 103601. <https://doi.org/10.1016/j.ijggc.2022.103601>.
47. Tang, H.; Chen, W.; Zhang, S.; Zhang, Q. China's Multi-Sector-Shared CCUS Networks in a Carbon-Neutral Vision. *iScience* **2023**, *26*, 106347. <https://doi.org/10.1016/j.isci.2023.106347>.
48. Zhang, J.; Zhao, L.; Jin, L.; Zhu, C.; Wang, H.; Wang, L. Optimizing Regional CCUS Clusterization Deployment for Multi-Industrial Sectors: A Carbon Neutrality Pathway for Emission-Intensive Region. *Carbon Capture Sci. Technol.* **2025**, *17*, 100495. <https://doi.org/10.1016/j.ccst.2025.100495>.
49. Raho, B.; Colangelo, G.; Milanese, M.; de Risi, A. A Critical Analysis of the Oxy-Combustion Process: From Mathematical Models to Combustion Product Analysis. *Energies* **2022**, *15*, 6514. <https://doi.org/10.3390/en15186514>.
50. Zheng, C.; Liu, Z.; Xiang, J.; Zhang, L.; Zhang, S.; Luo, C.; Zhao, Y. Fundamental and Technical Challenges for a Compatible Design Scheme of Oxyfuel Combustion Technology. *Engineering* **2015**, *1*, 139–149. <https://doi.org/10.15302/j-eng-2015008>.
51. Taghizadeh-Hesary, F.; Vandercamme, L.; Phoumin, H. Enhancing the Economic Feasibility of Carbon Capture, Utilisation, and Storage (CCUS) Projects. *J. Environ. Assess. Policy Manag.* **2024**, *26*, 2350024. <https://doi.org/10.1142/s1464333223500242>.
52. Boa Morte, I.B.; Ofélia de Queiroz, F.A.; Morgado, C.R.V.; de Medeiros, J.L. Electrification and Decarbonization: A Critical Review of Interconnected Sectors, Policies, and Sustainable Development Goals. *Energy Storage Sav.* **2023**, *2*, 615–630. <https://doi.org/10.1016/j.enss.2023.08.004>.
53. Li, J. Accelerating the Offshore CCUS to Carbon-Neutral China. *Fundam. Res.* **2025**, *5*, 715–726. <https://doi.org/10.1016/j.fmre.2022.10.015>.
54. Ueckerdt, F.; Bauer, C.; Dirnau, A.; Everall, J.; Sacchi, R.; Luderer, G. Potential and Risks of Hydrogen-Based e-Fuels in Climate Change Mitigation. *Nat. Clim. Change* **2021**, *11*, 384–393. <https://doi.org/10.1038/s41558-021-01032-7>.
55. Filippov, S. The Economics of Carbon Dioxide Capture and Storage Technologies. *Therm. Eng.* **2022**, *69*, 738–750.
56. Young, J.; McQueen, N.; Charalambous, C.; Foteinis, S.; Hawrot, O.; Ojeda, M.; Pilorgé, H.; Andresen, J.; Psarras, P.; Renforth, P.; et al. The Cost of Direct Air Capture and Storage Can Be Reduced via Strategic Deployment but Is Unlikely to Fall below Stated Cost Targets. *One Earth* **2023**, *6*, 899–917.
57. Yan, X.; Tong, D.; Davis, S.J.; Liu, Y.; Li, W.; Wang, H.; Zheng, D.; Guo, Y.; Liu, Y.; Xu, R.; et al. Cost-Competitive Plant-by-Plant Strategy for Spatially Resolved CCUS Deployment toward Carbon Neutrality in Global Key Industries. *One Earth* **2025**, *8*, 101378. <https://doi.org/10.1016/j.oneear.2025.101378>.
58. Khurana, S.; Beck, S. Carbon Capture, Utilization, and Sequestration Value Chain. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 2–5 May 2022. <https://doi.org/10.4043/32042-ms>.
59. Aras, C.M.; Ntamo, L.; Hasan, M.M.F. Optimal Design of Carbon Capture, Utilization and Storage (CCUS) Networks under Uncertain Geological Storage Volumes and CO₂ price. *Comput. Chem. Eng.* **2025**, *201*, 109203. <https://doi.org/10.1016/j.compchemeng.2025.109203>.
60. Monteiro, J.; Roussanaly, S. CCUS Scenarios for the Cement Industry: Is CO₂ Utilization Feasible? *J. CO₂ Util.* **2022**, *61*, 102015. <https://doi.org/10.1016/j.jcou.2022.102015>.
61. Fan, J.-L.; Li, Z.; Li, K.; Zhang, X. Modelling Plant-Level Abatement Costs and Effects of Incentive Policies for Coal-Fired Power Generation Retrofitted with CCUS. *Energy Policy* **2022**, *165*, 112959. <https://doi.org/10.1016/j.enpol.2022.112959>.
62. El-Kady, A.H.; Amin, M.T.; Khan, F.; El-Halwagi, M.M. Analysis of CO₂ Pipeline Regulations from a Safety Perspective for Offshore Carbon Capture, Utilization, and Storage (CCUS). *J. Clean. Prod.* **2024**, *439*, 140734. <https://doi.org/10.1016/j.jclepro.2024.140734>.
63. van Beek, A.; Groote Schaarsberg, M.; Borm, P.; Hamers, H.; Veneman, M. Cost Allocation in CO₂ Transport: A Multi-Actor Perspective. *J. Clean. Prod.* **2024**, *435*, 140271. <https://doi.org/10.1016/j.jclepro.2023.140271>.
64. Garcia, J.A.; Villen-Guzman, M.; Rodriguez-Maroto, J.M.; Paz-Garcia, J.M. Comparing CO₂ Storage and Utilization: Enhancing Sustainability through Renewable Energy Integration. *Sustainability* **2024**, *16*, 6639. <https://doi.org/10.3390/su16156639>.
65. Onita, F.B.; Ochulor, O.J. Novel Petrophysical Considerations and Strategies for Carbon Capture, Utilization, and Storage (CCUS). *Eng. Sci. Technol. J.* **2024**, *5*, 2548–2561. <https://doi.org/10.51594/estj.v5i8.1443>.
66. Lin, Z.; Kuang, Y.; Li, W.; Zheng, Y. Research Status and Prospects of CO₂ Geological Sequestration Technology from Onshore to Offshore: A Review. *Earth-Sci. Rev.* **2024**, *258*, 104928. <https://doi.org/10.1016/j.earscirev.2024.104928>.
67. Li, J.; Li, P.; Li, Y.; Tong, F. Technology System of Offshore Carbon Capture, Utilization, and Storage. *Strateg. Study Chin. Acad. Eng.* **2023**, *25*, 173.
68. Sun, L.; Liu, Q.; Chen, H.; Yu, H.; Li, L.; Li, L.; Li, Y.; Adenutsi, C.D. Source-Sink Matching and Cost Analysis of Offshore Carbon Capture, Utilization, and Storage in China. *Energy* **2024**, *291*, 130137. <https://doi.org/10.1016/j.energy.2023.130137>.

69. Ye, J.; Yan, L.; Liu, X.; Wei, F. Economic Feasibility and Policy Incentive Analysis of Carbon Capture, Utilization, and Storage (CCUS) in Coal-Fired Power Plants Based on System Dynamics. *Environ. Sci. Pollut. Res.* **2022**, *30*, 37487–37515. <https://doi.org/10.1007/s11356-022-24888-4>.
70. Zhang, W.; Dai, C.; Luo, X.; Ou, X. Policy Incentives in Carbon Capture Utilization and Storage (CCUS) Investment Based on Real Options Analysis. *Clean Technol. Environ. Policy* **2021**, *23*, 1311–1326. <https://doi.org/10.1007/s10098-021-02025-y>.
71. Yang, L.; Wei, N.; Lv, H.; Zhang, X. Optimal Deployment for Carbon Capture Enables More than Half of China's Coal-Fired Power Plant to Achieve Low-Carbon Transformation. *iScience* **2022**, *25*, 105664. <https://doi.org/10.1016/j.isci.2022.105664>.
72. Leonzio, G.; Foscolo, P.U.; Zondervan, E.; Bogle, I.D.L. Scenario Analysis of Carbon Capture, Utilization (Particularly Producing Methane and Methanol), and Storage (CCUS) Systems. *Ind. Eng. Chem. Res.* **2020**, *59*, 6961–6976. <https://doi.org/10.1021/acs.iecr.9b05428>.
73. Liu, S.; Ye, Z.; Zhou, J.; Liu, C.; Li, C.; Liang, G. Optimal Deployment of CCUS Networks Coupled Carbon Capture Technologies with Tax Incentive Policy. *Int. J. Green Energy* **2025**, *22*, 2698–2716. <https://doi.org/10.1080/15435075.2025.2471431>.
74. Zhou, J.; Liu, C.; Liang, G.; Liu, S.; Li, C.; Hong, B. Carbon Allowance Allocation and CO₂ Flows Analysis in CCUS under the Carbon Market. *J. Clean. Prod.* **2024**, *473*, 143566. <https://doi.org/10.1016/j.jclepro.2024.143566>.
75. Xu, B.; Wang, T.; Ma, D.; Song, R.; Zhang, M.; Gao, L.; Li, S.; Zhuang, B.; Li, M.; Xie, M. Impacts of Regional Emission Reduction and Global Climate Change on Air Quality and Temperature to Attain Carbon Neutrality in China. *Atmos. Res.* **2022**, *279*, 106384. <https://doi.org/10.1016/j.atmosres.2022.106384>.
76. Cachola, C.d.S.; Ciotta, M.; Azevedo dos Santos, A.; Peyerl, D. Deploying of the Carbon Capture Technologies for CO₂ Emission Mitigation in the Industrial Sectors. *Carbon Capture Sci. Technol.* **2023**, *7*, 100102. <https://doi.org/10.1016/j.ccst.2023.100102>.
77. Wang, P.; Li, Y.; Sun, N.; Han, S.; Wang, X.; Su, Q.; Li, Y.; He, J.; Yu, X.; Du, S.; et al. Hydrate Technologies for CO₂ Capture and Sequestration: Status and Perspectives. *Chem. Rev.* **2024**, *124*, 10363–10385. <https://doi.org/10.1021/acs.chemrev.2c00777>.
78. Bagheri, M.; Ryan, S.; Byers, D.; Raab, M. Reducing Cost of CCUS Associated with Natural Gas Production by Improving Monitoring Technologies. *APPEA J.* **2020**, *60*, 1–9. <https://doi.org/10.1071/aj19137>.
79. Zhang, Z.; Wang, T.; Blunt, M.J.; Anthony, E.J.; Park, A.-H.A.; Hughes, R.W.; Webley, P.A.; Yan, J. Advances in Carbon Capture, Utilization and Storage. *Appl. Energy* **2020**, *278*, 115627. <https://doi.org/10.1016/j.apenergy.2020.115627>.
80. Shah, S.; Shah, M.; Shah, A.; Shah, M. Evolution in the Membrane-Based Materials and Comprehensive Review on Carbon Capture and Storage in Industries. *Emergent Mater.* **2020**, *3*, 33–44. <https://doi.org/10.1007/s42247-020-00069-2>.
81. Fan, Y. The Current Situation and Future Development Trends of CCUS. *Theor. Nat. Sci.* **2025**, *102*, 9–16. <https://doi.org/10.54254/2753-8818/2025.mur22050>.
82. Liu, Z.; Chen, Y.; Wei, X.; Zhao, C.; Zhang, Y.; Luo, H.; Dong, K.; Rui, Z.; Xu, H.; Yang, L.; et al. Carbon Capture Utilization and Storage Promotes Poverty Alleviation and Sustainable Development in China. *Commun. Earth Environ.* **2025**, *6*, 539.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.