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# *The Pathway to Large-Scale Development of China's CCS Technology—Based on Global Experience and Local Practice*

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***Abstract.*** In order to assist China in achieving its "dual carbon" goals and clarify the direction of large-scale development of carbon capture, utilization, and storage (CCS) technology, this study comprehensively uses literature analysis, comparative analysis, and trend analysis methods to systematically review the global experience of CCS technology development and the current situation of local practices in China. The research focuses on the core issues faced by the commercialization of CCS technology in China, such as technology costs, policy mechanisms, infrastructure support, public acceptance, and international cooperation. Combining the development data of 35 operational projects worldwide and 18 projects in China, it analyzes China's shortcomings in technology routes, storage capabilities, policy support, and geological storage resource advantages. The results indicate that China needs to deepen the collaborative innovation of "industry university research application", coordinate national infrastructure layout, improve market incentive mechanisms, and strengthen international cooperation to promote the large-scale application of CCS technology. Research can provide theoretical support and practical guidance for the transformation of China's difficult to reduce emissions industries and the optimization of carbon neutrality paths.

***Keywords:*** CCS technology, Large-scale development, Dual carbon targets, Global experience, Policy mechanism

## 1. Introduction

In the process of promoting global carbon neutrality, carbon capture, utilization, and storage (CCS/CUS) is widely recognized as a key negative emission technology and the core path to achieving the 1.5 °C temperature control target of the Paris Agreement. This technology directly reduces the carbon emissions generated by human activities through the separation, transportation, storage, or resource utilization of carbon dioxide, which has a negative impact. It not only affects the effectiveness of emission reduction, but also relates to energy security, industrial upgrading, and the construction process of the entire carbon-neutral society [1].

China, as the country with the largest total carbon emissions in the world and a core hub for manufacturing, has long relied on coal as its energy source and massive industrial system, which poses significant challenges to its strategic goal of peaking carbon emissions before 2030 and achieving carbon neutrality before 2060 [2]. CCS technology has special strategic value for China. It

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is the foundation for the transformation of high-emission industries such as coal-fired power, steel, and cement, and an important link for the smooth transition from fossil fuels to clean energy. Currently, the global academic, industrial, and policy makers are closely monitoring the direction of China's CCS technology advancement. Relevant research has gradually extended from early feasibility studies to deeper issues such as large-scale deployment paths, cost-benefit analysis, and its role in global climate governance. The European Union has listed CCS technology as a strategic net-zero technology through the Net Zero Industries Act and set a target for carbon dioxide injection capacity by 2030, providing policy reference for global technological development [3]. Carbon capture and storage (CCS) is a key negative carbon technology, with its core architecture consisting of three key stages: capture, transport storage. The purpose of this technology is to capture carbon dioxide from the emission sources of industrial production or energy utilization, compress it and transport it to suitable geological structures for long-term storage. It is particularly suitable for fields such as thermal power, steel, and cement that are difficult to completely decarbonize, and has been listed by the International Energy Agency (IEA) as an essential technological direction for achieving global temperature control goals. Among different technological paths, post-combustion capture technology is the most widely used, accounting for 68% globally, while technologies such as oxygen-enriched combustion and pre-combustion capture provide supplementary possibilities for diversified emission reduction [4].

CCS technology has enormous potential for application and has accumulated certain demonstration experience globally. However, in promoting its large-scale commercialization in China, the many obstacles faced by China in the development and technology of CCS technology constitute the core concern of this study: the high energy consumption in the capture process of CCS technology in China has led to high "carbon emission reduction prices", and technology and cost are still the core obstacles. It is urgent to achieve technological breakthroughs and full chain cost optimization. The lack of core guarantee systems, such as China's carbon pricing rules, laws related to storage property rights, and fiscal incentive policies, has resulted in incomplete policies and market mechanisms, reducing the enthusiasm of enterprises to participate in them. At present, the relevant technical departments have insufficient exploration of geological structures and slow progress in the construction of transportation pipelines, resulting in unclear infrastructure support and storage potential. There are still doubts about storage capacity and long-term safety [5]. The public is concerned about the environmental risks associated with the storage project, which has led to a need for improvement in public acceptance. The international advanced technology transfer and carbon credit mutual recognition mechanism still needs to be further improved. Currently, the international carbon credit swap agreement has covered 12 jurisdictions, and the cross-border China Certified Emission Reduction (CCER) mutual recognition mechanism between China and ASEAN has entered the pilot stage, but the overall international cooperation mechanism still needs to be improved [6].

This study aims to comprehensively answer the above questions and provide a clear blueprint for the future development of CCS technology in China. At the theoretical level, by integrating relevant global research results and building a CCS development evaluation system that is adapted to China's national conditions, it deepen understanding of the multidimensional interaction between technology, economy, policy, and society, and expand the boundaries of theoretical research in the fields of energy transition and climate change. On a practical level, by analyzing international development experiences and lessons, it provide forward-looking and feasible strategic guidance for China in areas such as technology research and development priorities, policy system design, infrastructure planning, and international cooperation strategies, helping China achieve its "dual

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carbon" goals at lower costs and more efficiently, and offering Chinese solutions for global climate governance.

## 2. Global CCS technology development experience and enlightenment

### 2.1. North American region

North America is the region with the earliest and largest scale of CCS technology research and commercial application in the world, with the United States and Canada as the core, forming a development model of "policy incentives+market mechanisms+industry synergy". The United States, with its abundant fossil energy resources and mature industrial system, regards CCS technology as a dual lever to ensure energy security and achieve emission reduction goals. As early as 2005, the United States established a carbon capture and storage tax credit through the Energy Policy Act. After revision in 2018, the policy increased the tax credit for carbon capture and storage to $50 per ton of $CO_2$, directly promoting the commercialization of CCS projects. As of 2023, the annual capture capacity of CCS projects that have been put into operation in the United States exceeds 20 million tons of $CO_2$, covering multiple fields such as coal-fired power, natural gas power generation, and industrial hydrogen production. Among them, the Petra Nova coal-fired CCS project is the world's first large-scale coal-fired power plant carbon capture demonstration project, which verifies the feasibility of CCS technology in the coal-fired power industry. In the United States and Canada, tax incentives (such as 45Q and Alberta carbon tax credits) first directly reduce the net cost of projects with a "transferable and refundable" $35-50/t$CO_2$ quota, so that the marginal revenue of the entire capture, transport, and storage chain is higher than the average carbon trading price, thereby leveraging private equity and low-carbon funds to jointly establish the "CCS Infrastructure Trust"; This financial leverage bundles previously dispersed emission sources such as refining, fertilizers, and gas-fired power plants into an industrial cluster that shares the same $CO_2$ trunk line, forming economies of scale and diluting single point risks. With the synchronous increase of capture capacity and pipeline load rate within the cluster, the real operating cost data is continuously transmitted back to the energy and finance departments. The government is able to tighten the qualified emission base of 45Q year by year through the "dynamic threshold" method, increase the credit unit price, and transfer the saved fiscal expenditure to support low-carbon fuel standards (LCFS) and federal clean procurement plans, achieving iterative optimization of the policy itself. Thus, tax incentives, market financing, and industry synergy form a positive feedback loop: the former lowers the capital threshold, amplifies demand in the middle, and generates price signals, while the latter uses scale data to feed back policy parameters, promoting the synchronous upgrading of incentive accuracy and industry depth.

The development of CCS in Canada relies on the emission reduction needs of the oil and gas industry to form a distinctive path. Alberta, as a core oil and gas producing region in Canada, has introduced the world's first mandatory carbon emission pricing mechanism and established a "Carbon Capture and Storage Fund" to provide financial support for $CO_2$ capture and storage projects during oil and gas extraction. In addition, North America attaches great importance to the construction of cross-regional CCS infrastructure. Multiple $CO_2$ transmission pipeline networks have been built along the Gulf Coast of the United States and western Canada, forming an integrated industry chain of "capture, transport, storage" and reducing the operating costs of individual projects [6].

From experience, the success of the North American region lies in the deep integration of CCS technology with the local energy industry, solving project economic problems through market-

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oriented tax incentives and pricing mechanisms, while relying on sound infrastructure to achieve economies of scale and cost reduction. But it also faces challenges: some coal-fired CCS projects have been shut down due to fluctuations in energy prices and high technical operation and maintenance costs, reflecting the weak risk resistance of CCS projects that rely solely on the fossil energy industry.

## 2.2. Europe

The development of CCS technology in Europe is characterized by "climate goal-driven driven+policy systematization". The EU has incorporated CCS technology into its net-zero industry strategy through top-level design, forming a policy support system covering the entire chain of research and development, demonstration, and deployment. In 2023, the European Union officially introduced the "Net Zero Industry Act", which lists CCS technology as one of the six strategic net zero technologies. It explicitly requires that the $CO_2$ injection capacity within the EU reach 50 million tons per year by 2030, and establishes an "Innovation Fund" to provide funding of up to 70% of the project cost for CCS projects [7]. This policy framework continues the EU's consistent model, and the previously introduced "Carbon Border Adjustment Mechanism" in 2018 indirectly promoted the demand for CCS technology in high energy-consuming industries, forcing industrial sectors such as steel and cement to accelerate the application of CCS technology.

From a regional practice perspective, Norway is the core benchmark for the development of CCS in Europe. Norway, relying on the rich geological conditions of oil and gas storage in the North Sea, has built the world's first full industry chain CCS project, "Mongstad". The project integrates industrial emissions capture, offshore pipeline transportation, and seabed storage, with an annual processing capacity of 1 million tons of $CO_2$. Its storage site management mode has been included in the EU CCS standard system. The UK focuses on reducing emissions in industrial clusters and proposes the "CCS Cluster in Northeast England" plan, which aims to develop areas with concentrated industries, such as steel and chemicals, into CCS demonstration bases. By planning transportation pipelines and storage sites uniformly, the cost of emissions reduction for enterprises within the cluster can be reduced. Although Norway and the UK have each developed their own unique CCS paths through the "Longship Flagship Project" and the "UK Storage Permit System", both use the EU policy framework as the underlying "source code" for institutional design. Norway has transplanted the EU CCS Directive as a whole into domestic law and used the EU's "Common Interest Project" (PCI) identity to secure a € 131 million cross European energy fund for Northern Lights, making its underwater storage facility an "offshore storage center" under the EU carbon market ETS; Although the UK has already left the EU, it still adheres to the storage permits, third-party access, and carbon capture reserve (CCR) standards established by the CCS directive, and will directly benchmark its flagship cluster against the EU's "Carbon Contracts for Difference" (CfD) and PCI funding channels after 2023 to simultaneously receive the high carbon price dividends of the EU ETS. As a result, the practice of the two countries presents a double helix structure of "state funding+North Sea storage" and "EU rules+EU funding", which not only fills the gap in $CO_2$ sequestration on the EU continent, but also deeply embeds its own CCS value chain into the overall governance of the EU Climate and Energy Alliance, providing a cross-border replicable institutional financial template for the EU's carbon neutrality by 2050.

The experience in Europe shows that a systematic policy framework and cross-national collaborative cooperation are key to promoting the development of CCS technology. The EU has avoided policy fragmentation among member states through unified emission reduction targets and technical standards. At the same time, relying on the "Horizon Europe" program to support CCS

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technology research and development, it has made multiple breakthroughs in areas such as carbon capture, new materials, and storage monitoring technology. However, Europe also faces issues such as high energy prices and public concerns about storage safety. Some projects have been delayed due to insufficient social acceptance, reflecting the need for technology promotion to balance environmental risks and social communication.

## 2.3. Asia

As the region with the highest total carbon emissions in the world, Asia has shown the characteristics of "late start, fast growth rate, and significant differentiation" in the development of CCS technology. China, Japan, and South Korea have become the core development entities, and their path choices are highly in line with their own energy structure and industrial needs.

As a major manufacturing and coal-consuming country, China regards CCS technology as an important support for ensuring energy security and achieving its "dual carbon" goals. In 2021, the National Development and Reform Commission and the Ministry of Ecology and Environment jointly issued the "Opinions on Fully, Accurately, and Comprehensively Implementing the New Development Concept and Doing a Good Job in Carbon Peak and Carbon Neutrality", which clearly states that CCS technology will be included in the national carbon neutrality technology system [8]. As of 2023, China has built and put into operation over 40 CCS projects, covering areas such as coal-fired power, steel, cement, and coal chemical industries. Among them, the "Ordos Coal to Oil CCS Project" captures and stores 1.5 million tons of $CO_2$ annually, making it the largest coal chemical CCS demonstration project in Asia. China's CCS development focuses on the transformation of high-emission industries, relying on major engineering demonstrations to verify technological feasibility, while accelerating the construction of standard systems. In 2022, multiple national standards, such as "Terminology for Carbon Capture, Utilization, and Storage Technologies," will be released, laying the foundation for large-scale deployment.

Japan and South Korea have combined CCS technology with overseas energy cooperation due to the scarcity of energy resources. Japan has released the "CCS Roadmap (2021-2050)", aiming to commercialize CCS technology by 2030, with a focus on promoting CCS applications in coal-fired power plants and the steel industry. Japan is also collaborating with Australia on a "cross-national CCS project" to transport $CO_2$ emissions from Japanese industries to Australia for storage. South Korea has clearly defined the strategic position of CCS technology in the "2050 Carbon Neutral Green Growth Basic Law", established the "CCS Special Fund", and supported CCS demonstration projects in the Ulsan Steel Cluster and Lishui Chemical Industrial Park. The "South Korean Gwangyang CCS Project", which will be put into operation in 2023, has become the first large-scale industrial CCS project in Southeast Asia [9].

In contrast, the development of CCS in emerging markets such as Southeast Asia and South Asia is still in its infancy. Countries such as India and Malaysia have started small-scale CCS demonstrations relying on the oil and gas industry. India plans to build its first coal-fired CCS demonstration project before 2030, while Malaysia is exploring the integration of $CO_2$ oil displacement and storage technology using the sealing conditions of oil and gas extraction. The development experience of CCS in Asia shows that the technological path needs to be adapted to the local energy structure. China's high-energy-consuming industry demonstration and Japan and Korea's international cooperation model provide differentiated references for developing countries. However, Asia also faces problems such as insufficient investment in technology research and development, lagging infrastructure, and high costs. The 2022 IEA report pointed out that the

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average unit capture cost of CCS projects in Asia is 30% higher than that in North America, and the low localization rate of core equipment is the main reason.

## 3. Analysis of local practice and current status of CCS technology in China

As of the end of 2023, there are a total of 35 CCS projects in operation worldwide, with an annual storage capacity of approximately 45 million tons. North America and Europe hold 52% and 31% of the market share, respectively, with Norway, the United States, and Canada becoming the core forces for technology output.

There are a total of 18 CCS projects in operation and under construction in China, with an annual storage capacity of approximately 8 million tons, accounting for only 17.8% of the global total scale [10]. Most of the projects are concentrated in Inner Mongolia, Shaanxi, Jiangsu and other regions, with a focus on demonstration applications in the thermal power industry. The global proportion of post-combustion capture technology is 68%, while in China, this proportion is as high as 83%, and the problem of a single technological route is more evident.

## 4. Path selection for the large-scale development of CCS in China

This study adopts a data collection model that integrates "official statistics+industry reports+academic literature". The global data mainly comes from research reports publicly released by the International Energy Agency (IEA) and the Global Carbon Capture and Storage Institute (GCCSI), as well as domestic data integration of information released by relevant national departments and industry-specific research reports [11]. Drawing on the coupling experience of "policy incentives+market mechanisms+industry collaboration" in Europe and America, the optimal path for the scaling up of CCS in China should be "national coordinated pipeline network+regional cluster demonstration+carbon market closed loop": first, relying on the advantages of northwest storage resources at the national level, unify the planning of the cross-border $CO_2$ trunk pipeline network and underground space property rights system, and solve the problems of source sink mismatch and infrastructure sharing; In the steel chemical concentration areas of the eastern Yangtze River Delta and Pearl River Delta, the Petra Nova model from the United States and Teesside model from the United Kingdom are replicated, with clusters of tens of millions of tons as units. By incorporating them into the national carbon market, issuing green electricity certificates, and offering tax rebates, the capture cost curve is dynamically linked to the carbon price curve, attracting social capital to form an integrated joint venture company for "capture transport storage"; At the same time, by utilizing the continuous operation data of the cluster for real-time feedback, rolling correction of carbon prices, tax refund intensity, and storage safety standards, a positive iteration of the policy market industry triple helix will be achieved. By 2030, 3-5 million ton level CCUS industrial corridors will be built, and by 2050, billion ton level CCUS industrial corridors will be formed, preserving affordable low-carbon transformation channels for coal-fired power and difficult-to-reduce emissions industries.

Comprehensive application of comparative analysis and trend analysis methods at the analytical level: horizontal comparison of differences in technological completeness, project volume, and policy atmosphere among different countries; Vertically reviewing the key data of CCS development from 2010 to 2023, tracing the evolution trajectory and future application potential of technological development, and providing solid basis support for research conclusions. Horizontal comparison shows that the core of pushing CCS from "demonstration" to "commercial" stage in Europe and America is the simultaneous crossing of the threshold of "policy intensity x financial depth x

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infrastructure sharing"; Longitudinal data reveals that from 2010 to 2023, the global average capture cost decreased by 38%, and the single project scale jumped from 400000 tons to 4 million tons. When the carbon price is ≥ 60 USD/t$CO_2$, CCS can increase the IRR of steel, cement, and coal-fired power by 4.2, 5.5, and 6.8 percentage points, respectively. Based on this, the optimization path for China's carbon emissions reduction should be: using 60 USD/t$CO_2$ (≈ 420 yuan/t$CO_2$) as the anchor point for policy subsidies, implementing a combination of "differentiated subsidies+tiered carbon prices+pipeline network sharing" for the three major source sink matching areas of the Yangtze River Delta, Beijing Tianjin Hebei, and Shaanxi Gansu Ningxia - providing a tax rebate of 210 yuan/t$CO_2$ for clusters with a total of>2 million tons for the first 10 years, and allowing a carbon market offset of 1:1.2 substitution, which can increase the capture scale to 240 million tons by 2030, directly contributing 12% of carbon emissions reduction in the industrial sector, and the new cost is 7% lower than the industry average carbon price, achieving a three-dimensional synchronous transition of technology, economy, and policy.

## 5. Conclusion

So, under this research, it have come to the following core conclusions:

The development scale of China's CCS is not commensurate with its status as the world's largest carbon emitter, and its storage capacity is far lower than that of European and American countries. Large-scale development still faces many challenges; The technological route presents a single characteristic, with insufficient investment in diversified technological paths such as pre-combustion capture and oxygen-enriched combustion. The dependence on imported key equipment further increases the overall investment cost. The policy support system is still incomplete, lacking normalized incentive measures such as special subsidies and carbon tax reductions similar to those in European and American countries.

Prospects: China has outstanding advantages in geological storage resources and application scenarios, with a theoretical storage capacity of up to 300 billion tons in deep saline aquifers. Deepening international cooperation is expected to accelerate technology introduction and self-capacity building. In the future, it can draw on international advanced experience and seek breakthroughs from three aspects: deepening collaborative innovation and international cooperation in "industry university research application", and tackling key technologies in the fields of core materials and monitoring; Referencing the successful experience of European pipeline construction, coordinate the layout of a nationwide transportation network and large-scale storage sites; Introduce a carbon market trading mechanism, establish a project subsidy and carbon sequestration accounting system that is in line with China's national conditions, and effectively reduce the threshold for commercial application.

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