*International Journal of Environmental Protection and Policy*
2024, Vol. 12, No. 3, pp. 64-72
https://doi.org/10.11648/j.ijepp.20241203.12

Research Article

# Research on the Development and Policy Evolution of CCUS Industry at Home and Abroad

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## Abstract

CCUS is internationally recognized as one of the three major pathways to achieve carbon neutrality goals. It is an important choice for realizing zero emissions from large-scale fossil energy utilization and a feasible technological solution to offset carbon emissions in industries such as power, steel, and cement where emissions reductions are challenging. Systematic analysis of the development and policy evolution of the CCUS industry at home and abroad can provide theoretical basis and practical guidance for China's energy transition and development under the background of carbon emission peaking and achieving carbon neutrality. Guided by the strategic goals of national energy security, carbon emission peaking, and achieving carbon neutrality, this study aims to analyze the global development process and stage characteristics of the CCUS industry, investigate the supporting policies in the CCUS field and their evolution patterns, summarize the current status and trends of the CCUS industry at home and abroad, and provide reference for the implementation of national energy green and low-carbon transformation and the construction of a new energy system. In terms of industry, European and American countries emphasize national-level technological guidance and macro-control. The United States has introduced the progressive 45Q tax credit policy, and the European Union has included CCUS in its carbon trading system. The US National Carbon Capture Center provides a testing environment and facilities for CCUS technology research and development, and has established a carbon dioxide industry cluster and transportation hub. In terms of policies, tax credits and carbon trading policies in Europe and America have attracted various types of capital investment, establishing a relatively complete legal framework system. These regions have been leading in CCUS technology research and deployment, holding dominant positions and decision-making power in mainstream international CCUS organizations such as the CSLF, IEA, GCCSI, and OGCI. This study benchmarks the forward-looking and strategic development status of the CCUS industry at home and abroad, elucidates the challenges facing CCUS industry development, and proposes future trends and policy support needs for the CCUS industry. The research reveals that Europe and America emphasize national-level technological guidance and macro-control, focusing on the construction of regional industrial networks and having established a relatively complete legal and regulatory framework system. Compared to other countries, China needs to establish national-level guidance on CCUS development, regional carbon dioxide capture and transportation networks, and enact specific laws, regulations, and technical standards for CCUS.

## Keywords

CCUS, Industry, Development Trend, Challenges, Energy Transformation

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**Received:** 6 May 2024; **Accepted:** 18 June 2024; **Published:** 21 June 2024

# 1. Introduction

The CCUS technology, as an indispensable and important component in achieving carbon neutrality goals, is a primary technological means for large-scale low-carbon utilization of fossil energy at the current stage [1-3]. It can achieve significant reductions in carbon dioxide and other pollutants while meeting the energy demands necessary for social development [4, 5]. This technology provides technical support for China's energy structure to transition smoothly towards a green and low-carbon direction, and it plays a crucial role in supporting the construction of a clean, low-carbon, safe, and efficient energy system [6, 7]. A systematic analysis of the development process and policy evolution characteristics of the domestic and international CCUS industry is essential to understand the development trends and policy demands for the future of the CCUS industry [8-10].

This study conducts research on the development process and stage characteristics of the CCUS industry domestically and internationally, systematically analyzes the current status of the CCUS industry development, summarizes the development trends of the CCUS industry, and dissects the relevant supporting policies and their evolution characteristics. This research aims to provide references for the country's implementation of energy green and low-carbon transformation and the construction of a new energy system.

# 2. The Development Process of the Global CCUS Industry

According to the status of CCUS technology development and application, the development of CCUS has gone through three stages: exploration stage, pilot testing, and demonstration application.

## 2.1. Early Preparation and Exploration Stage (1950s to early 1980s)

The gestation stage of CCUS technology began in the early 1950s, with American scientist Whorton and others obtaining the world's first patent for injecting $CO_2$ to enhance crude oil recovery technology in 1952 [6]. In 1958, Shell was the first to implement a $CO_2$ flooding oil recovery test in the Permian Basin in the United States, demonstrating that injecting $CO_2$ into reservoirs could supplement reservoir energy and increase crude oil production. In 1963, Daqing Oilfield conducted the first carbonated water injection test, showing that the technology could potentially increase recovery rates by 10 percentage points. In 1972, the United States began commercial application of $CO_2$ enhanced oil recovery (EOR) technology and implemented the first CCUS-EOR project in the Kelly-Snyder oilfield, initially increasing individual well production by more than three times [2, 4, 6]. The success of this project marked the maturity of $CO_2$ flooding technology.

## 2.2. Reserve Development and Testing Stage (Early 1980s to 2005)

From 1980 to 1992, in response to the oil crisis, the United States enacted laws and regulations to incentivize investment in the energy sector, mobilizing the enthusiasm of oil companies and private capital, and promoting the rapid development of CCUS-EOR technology. During this period, the number of CCUS-EOR projects increased from 17 to 54 [11], and EOR annual production increased from 10,000 tons to 7.83 million tons. In 1988, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) established the IPCC to initiate a research platform and project plan for CCS technology. In 1989, MIT initiated the first carbon capture and storage technology project (CC&ST) [12]. In 1991, the International Energy Agency Greenhouse Gas R&D Programme (IEAGHG) project organization was established, with CCS technology as a key focus [13]. In 1996, Norway completed the world's first commercial project for carbon capture and dedicated storage—Sleipner, with a storage scale of 1 million tons per year [14]. In 1999, Jilin Oilfield conducted $CO_2$ flooding tests for two well groups, resulting in a cumulative oil production increase of 6,540 tons [15]. In 2000, the Weyburn Oilfield in Canada began implementing a $CO_2$ flooding project using coal gasification tail gas [12, 14]. The Carbon Sequestration Leadership Forum (CSLF) was established in 2003, and the UK Carbon Capture and Storage Association was founded in 2005 [4, 14]. During this stage, CCUS technology gained recognition and attention globally, entering a phase of rapid development.

## 2.3. Engineering Demonstration and Application Stage (2006 to Present)

After 2006, countries such as the European Union, the United States, and Australia launched large-scale plans to promote the research and demonstration of CCS technology, including Norway's Mongstad project and the EU's Flagship project. China successively carried out pilot tests and expanded trials of CCUS, represented by $CO_2$ miscible flooding in Jilin Oilfield. In 2009, Australia initiated the establishment of GCCSI. Jilin Oilfield continued to promote industrial applications of CCUS, conducting full life cycle evaluation trials and industrial application trials of $CO_2$ miscible flooding [16, 17]. From 2006 to 2014, international crude oil prices continued to rise and surpassed $100 per barrel, creating substantial profit margins for $CO_2$ flooding projects. During this period, the number of CCUS-EOR projects in the United States increased from 67 to 137 [11], and EOR annual production increased from 9.63 million tons to 13.71 million tons [11]. In 2015, Jilin Oilfield established China's first carbon capture, storage, and enhanced oil recovery (CCUS-EOR) development company and built a national-level CCUS-EOR pilot mining test area [18]. In 2018, the Gates Foundation decided to support air carbon capture technology to address climate change [11, 19]. In the same year, Jilin Oilfield completed the first domestic $CO_2$ cyclic injection station with a daily re-injection capacity of 200,000 cubic meters. Influenced by factors such as the international financial crisis and climate change policies, global CCUS technology research and demonstration projects progressed slowly in the past decade, but overall, they continue to develop and have entered the industrialization stage [20].

# 3. Current Status and Development Trends of CCUS Industry at Home and Abroad

## 3.1. Global CCUS Development Status and Trends

### 3.1.1. Current Status of CCUS Development

According to IEA data, in 2022, more than 140 new CCUS projects were announced globally, increasing the global planned carbon storage capacity by 80% and the planned carbon capture capacity by 30% [21]. By the end of 2022, the global carbon capture capacity reached 45.9 million tons per year [12, 22].

1) Regional Distribution The largest number of projects and capture capacity are in North America, accounting for 37% and 61% respectively [13, 23]. The projects under construction and planning show a dominance of North America and Europe. The project numbers and capture capacity in North America account for 39% and 46% respectively, while in Europe, they are 36% and 34% respectively [4, 22, 24]. The largest CCUS projects in terms of processing capacity are located in the United States, including the Shute Creek gas processing plant and the Century processing plant. Among the top 12 largest CCUS projects globally, five are in the United States and three are in Canada [25]. The largest CCUS project is a natural gas processing facility in Wyoming with a planned annual capture capacity of 7 million tons, operated by ExxonMobil [26]. The second-largest project is a fertilizer plant in Texas operated by Occidental Petroleum, currently capturing over 5 million tons per year.
2) Industry Distribution In terms of industry distribution, the majority of operational projects are focused on natural gas processing, accounting for over 87% [12, 15, 21]. Projects under construction and planning are predominantly in power generation and chemical production, accounting for over 71% [14, 22].
3) Utilization and Storage Types In terms of utilization and storage types, EOR is predominant in operational projects, accounting for over 61%, while geological storage is dominant in projects under construction and planning, accounting for approximately 80% [23-25].

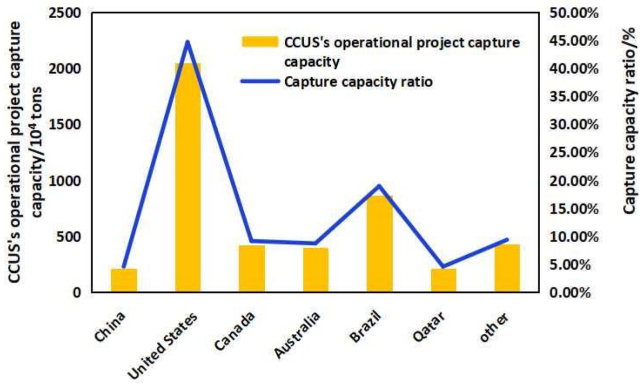


***Figure 1.*** *The carbon capture capabilities of major CCUS operating projects worldwide [20, 22, 26].*

### 3.1.2. CCUS Development Trends

1) CCUS is a Key Pathway to Achieve Global Near-Zero Emissions Goals. In various global pathways analyzed by international organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) to address climate change, CCUS is identified as a key pathway to achieving temperature control this century and realizing near-zero emissions goals, with its irreplaceable status. CCUS is an important technological choice for large-scale decarbonization of fossil energy currently [18, 22, 24]. Industries such as steel and cement, which are difficult to decarbonize, rely on CCUS technology for achieving net-zero emissions.
2) Integrated Development of CCUS Networks is the Future Trend. According to ExxonMobil's projections, the potential market size of CCUS is expected to reach $2 trillion per year by 2040, with an average annual growth rate of 35% [20-23]. To achieve such a large market size, complementary infrastructure needs to be accelerated. The formation of long-distance, shared $CO_2$ transport networks can significantly reduce project costs.
3) Role of Negative Emission Technologies such as Direct Air Capture and Bioenergy with Carbon Capture and Storage will be Highlighted in the Future. Direct Air Capture (DAC) technology captures $CO_2$ directly from the air, offering greater flexibility compared to traditional industrial centralized carbon capture and can be flexibly matched with $CO_2$ utilization processes. The

key to future development lies in the research and development of efficient and low-cost absorption/adsorption materials and equipment. Bioenergy with Carbon Capture and Storage (BECCS) technology has a wide range of applications, with power plants, biomass refineries, or biomass gasification plants utilizing BECCS to achieve $CO_2$ negative emissions. The future focus will be on integrating biomass utilization and CCUS technology to achieve negative emissions [19, 22, 27].

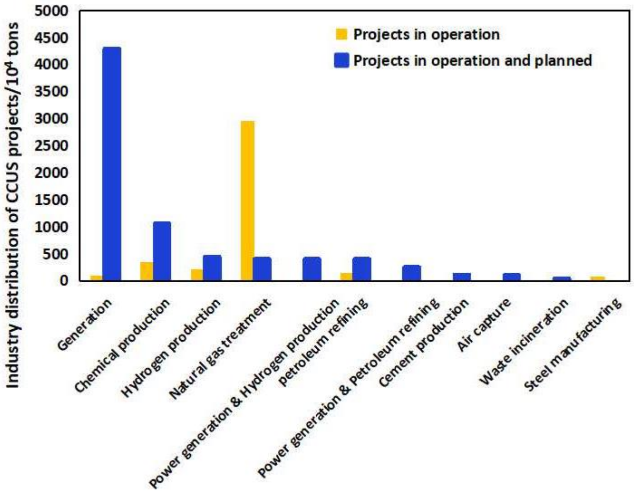


***Figure 2.*** *Industry distribution of CCUS projects [22, 23, 27].*

## 3.2. Current Status and Trends of CCUS Development in China

### 3.2.1. Current Status of CCUS Development

The "Annual Report on Carbon Capture, Utilization, and Storage (CCUS) in China (2023)" indicates that by the end of 2022, China had nearly a hundred operational and planned CCUS demonstration projects. Over half of these projects were operational, with a $CO_2$ capture capacity of approximately 4 million tons per year and an injection capacity of about 2 million tons per year, representing an increase of around 33% and 65% respectively compared to 2021 [13, 15, 22].

1) Industry Distribution In terms of industry distribution, the coverage has expanded, with major industrial sectors conducting relevant demonstrations, primarily in petrochemicals, coal chemicals, and power generation.
2) Utilization and Storage Types Regarding utilization and storage types, geological utilization (mainly $CO_2$-EOR) currently dominates, but chemical and biological utilization projects are increasing annually.

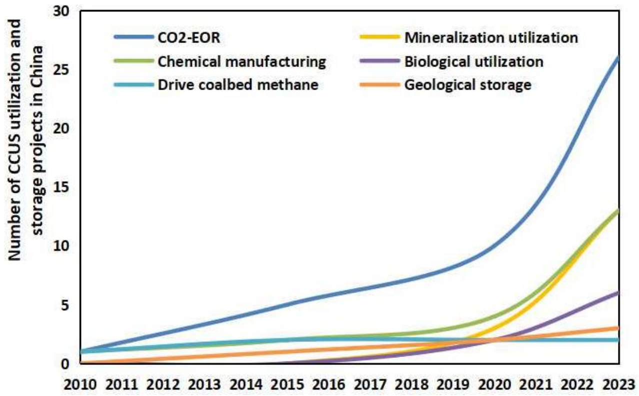


***Figure 3.*** *Number of CCUS utilization and storage projects in China. [6, 13, 28].*

### 3.2.2. Trends in CCUS Development

Based on research findings from both domestic and international sources, there is a significant demand for CCUS emissions reduction in China under the carbon neutrality goals. Currently, China is continuously developing technologies to reduce costs, optimizing the entire CCUS process engineering, accelerating breakthroughs in large-scale integrated demonstration projects, advancing the planning and layout of CCUS pipelines, and constructing industrial cluster infrastructures. With the establishment of a low-cost, low-energy consumption, safe, and reliable CCUS technology system and industrial cluster in the future, the CCUS industry in China is expected to create hundreds of billions in value [12]. Over the past decade, China has seen rapid development in pre-combustion capture, chemical utilization, geological utilization, and storage technologies, which are generally on par with international standards [15, 20]. However, there are still certain gaps in post-combustion capture, pipeline transportation, enhanced oil and gas recovery, deep saline water extraction and storage, among others [20, 22]. China has shown limited attention to DAC and BECCS, with relatively weak research in these areas. Strengthening innovation and reserves in DAC and BECCS-related technologies and accelerating the pace of demonstration projects are key directions for future development.

# 4. CCUS Related Support Policies and Evolution

Support policies for CCUS development cover areas such as climate change policy, energy policy, industrial development policy, and research and innovation policy, which are crucial for the advancement of technology and demonstration projects. These policies play an important role in enhancing the economic benefits of CCUS demonstration projects and boosting investor confidence.

The evolution of CCUS support policies has transitioned from relatively vague to gradually clearer, encompassing four main aspects: policies involving all technological aspects of $CO_2$ capture, utilization, and storage; policies supporting technology research and demonstration project construction; policies aimed at enhancing and improving the commercial and financial ecosystem for CCUS development; and policies promoting international cooperation platforms and strategies for CCUS [15, 18-21].

## 4.1. Support Policies in Major Developed Economies

Major developed economies began researching CCS technology as early as the 1980s. Compared to CCS, CCUS incorporates $CO_2$ utilization, but the fundamental principles of both are similar, primarily aimed at reducing carbon emissions. Currently, although there are differences in the terminology used internationally, the concept of CCUS has been widely accepted worldwide [21]. To standardize and promote industrial development, countries such as the United States, the European Union, and Australia have successively issued a series of policies related to planning, legislation, tax incentives, technical standards, and more [18]. Overall, the CCUS policies of developed economies like the United States, the European Union, and Australia are relatively proactive, with actions focused on increasing financial and tax incentives, boosting investment in technology research and development, strengthening risk management, and promoting the orderly advancement of CCUS optimization and commercialization based on their respective circumstances [2].

***Table 1.*** *The CCUS/CCS priority policies of major foreign countries and organizations [2, 15, 16].*

| Country / Organization | Policy /Action | Primary Coverage |
|---|---|---|
| United States of America | Federal Government 45Q Tax Credit | Since 2018, continuous revisions and improvements have been made, and incentives have been strengthened. The maximum tax deduction for carbon oxides in geological storage can reach $50/ton, and the maximum tax deduction for carbon oxides in oil recovery and other uses can reach $35/ton. It is known as the "most advanced CCS special incentive measure in the world" |
| | California government low-carbon fuel standards | Carbon credit trading prices continue to rise, exceeding $200/ton in 2020, effectively promoting the commercialization development of CCUS |
| | Technology R&D investment | In 2020, the US Department of Energy invested $270 million to develop CCUS technology |
| European Union | The European Green Agreement and the European Climate Act | In 2019, the European Green Agreement was implemented, and in 2021, the European Climate Act was passed, transforming the EU's political commitment to carbon neutrality into a legal obligation and giving rise to more policies supporting CCS development |
| | EU Innovation Fund | Established in 2020, with a total amount of 10 billion euros, it is widely regarded as an effective source of funding for the subsequent development of CCS in the European Union |
| | Horizon Europe Plan (2021-2027) | We plan to allocate a budget of 32 million euros and 58 million euros respectively for 2021 and 2022 to fund CCUS technology research and development |
| Australia | Framework for Accelerating the Promotion of Low Emission Technologies | Released in 2020, the deployment path of CCS in ammonia production and other applications was discussed |

## 4.2. Evolution of CCUS Related Support Policies in China

Compared to developed economies, China's work on CCUS started relatively later and placed greater emphasis on the value development of $CO_2$ resource utilization. The concept of CCUS was first proposed in 2006 in China [29], suggesting that recent $CO_2$ emissions reduction must be closely integrated with utilization, primarily through enhanced oil recovery and resource utilization [14]. Based on the development of CCUS in China, the evolution of related policies has gone through three main stages.

***Table 2.*** *Evolutionary characteristics of China's CCUS related policy stages [16, 24, 25].*

| Stage Name | Stage characteristics |
|---|---|
| Initial Exploration Stage (2006-2010) | In 2006, efforts were made to promote the "decarbonization" of fossil energy sources, followed by the release of national plans and special actions for climate change response, officially advocating for the vigorous development and application of CCUS technology at the national level.<br>In 2009, significant attention was given to the deployment of carbon geological storage, adaptive assessment, and pilot projects for saline aquifer storage. |
| Pilot Demonstration Stage (2011-2020) | In 2011, China first outlined the development goals and priorities for different stages of CCUS.<br>In 2013, the establishment of the Carbon Capture, Utilization, and Storage Industry Technology Innovation Strategic Alliance promoted collaboration between industry, academia, and research.<br>In 2019, China further clarified its CCUS technology strategic positioning, proposing the overall vision of building a low-cost, low-energy consumption, safe, and reliable CCUS technology system and industrial cluster. During this stage, China deepened its positioning and layout for CCUS technology and industrial development, conducting practices in environmental risk assessments, technical standard construction, investment and financing support, and further advancing pilot demonstration project construction, effectively promoting the standardized development of CCUS. |
| Industrial Demonstration Stage (2021-Present) | In 2021, CCUS was included in the "Green Bond Support Project Catalog (2021 Edition)" for the first time, effectively broadening investment and financing channels. Since the second half of 2021, a series of directives have been intensively released by the State-owned Assets Supervision and Administration Commission of the State Council, focusing on promoting high-quality development in central enterprises to achieve peak carbon emissions and carbon neutrality. These directives are expected to provide strong support for the industrial development of CCUS under the driving force of the subsequent "Dual Carbon" goals. |

## 5. Insights on the Development of CCUS Industry

### 5.1. Industrial Development Aspects

Since 2006, China has introduced relevant policies to promote the development of CCUS industry, advocating for low-cost CCUS technology innovation and the construction of full-process, integrated, and large-scale CCUS demonstration projects. However, compared to the advanced international status, there still exists a certain gap in the development of CCUS in China.

#### 5.1.1. Lack of Top-Level Strategic Planning

Countries and regions such as the United States, the United Kingdom, Australia, and the European Union have issued CCUS technology development roadmaps and strategic plans, clearly defining short-term, medium-term, and long-term demonstration project support policies, technological directions, and research and development priorities, strengthening national-level technical guidance and macro-control. China has not yet established a national-level CCUS development strategy, only mentioning the development of CCUS in some policy documents, primarily focusing on guidance and encouragement, lacking specific implementation plans.

#### 5.1.2. Lack of Cost Mitigation Mechanisms

The United States provides a progressive subsidy through the 45Q tax credit policy, significantly increasing the enthusiasm of high-emission enterprises to construct CCUS projects. The European Union has integrated CCUS into the carbon trading system, relying on relatively high carbon trading prices to reflect the emission reduction value of CCUS. It has been estimated that the full-process cost of CCUS capturing $CO_2$ after coal combustion is 400-500 yuan per ton, with carbon capture equipment adding 0.26-0.4 yuan per kilowatt-hour to electricity generation costs [25, 28]. However, China has not established specific financial and tax support and incentive mechanisms for CCUS. The average carbon trading price in China is only about one-tenth of that in the European Union, making it difficult to effectively incentivize the implementation of CCUS projects.

### 5.2. Policy Support Aspects

Over the past decade, national and local governments have issued a series of CCUS-related policies, promoting the advancement of technical capabilities in carbon capture, transportation, utilization, and storage in China. China has operationalized over 20 CCUS pilot demonstration projects [24, 35], with an annual carbon capture capacity exceeding 2 million tons [25, 28]. Under the model of policy guidance and active corporate participation, China's CCUS industry has gained a certain scale of practical experience. Compared to major developed economies abroad, China still lags behind in terms of both technological advancement and scale levels in CCUS.

### 5.2.1. Lack of Financial Incentives or Subsidy Policies, Insufficient Industrial Investment and Financing Capabilities

Foreign CCUS projects have seen a trend of investment shifting from self-funded by enterprises to government assistance, joint investments by enterprises, or the establishment of joint venture companies. China has yet to introduce specific financial incentives or subsidy policies for CCUS, with investment in pilot demonstration projects mainly coming from key state-owned enterprises, and very low participation from private capital.

### 5.2.2. Slow Progress in Legal Regulations and Standard System

Construction, Challenges in Ensuring Standardized Development Countries such as the United States, the European Union, and Australia have established relatively comprehensive legal and regulatory frameworks for the CCUS industry, with related standards being progressively developed, while China has not yet issued specific laws and regulations for CCUS, with a limited number of technical standards released, and related work still in its nascent stages.

## 6. Conclusions

This study analyzes the development process and stage characteristics of the global CCUS industry, summarizes the development trend of the CCUS industry, analyzes the relevant support policies and evolutionary characteristics of CCUS, and provides reference for the implementation of green and low-carbon energy transformation and the construction of new energy systems in the country. Research has found that Europe and America emphasize national level technical guidance and macroeconomic regulation, pay attention to the construction of regional industrial networks, and have formed a relatively complete legal and regulatory framework system. Compared to other countries, China needs to establish a national level CCUS development strategy guidance and a regional $CO_2$ capture and transportation network, and issue CCUS specific laws, regulations, and technical standards.

## Abbreviations

| | |
|---|---|
| CCUS | Carbon Capture, Utilization and Storage |
| DAC | Direct Air Capture |
| BECCS | Bioenergy with Carbon Capture and Storage |


## Acknowledgments

This research was one of the projects financially endorsed by China National Petroleum Corporation's Soft Science Research Project "Research on Strategic Measures for Accelerating China's Shale Oil and Gas Revolution through Engineering Technology Business" (CNPC Research 20240111-5), as well as Strategic Research and Consulting of the Science and Technology Committee of China National Petroleum Corporation Limited "Research on Iterative Upgrading and Development of Engineering Technology and Equipment" (2023DQ0715).


## Author Contributions

**Jing Yu:** Conceptualization, Investigation, Writing – original draft

**Bo Zhou:** Methodology, Project administration

**Pingliang Fang:** Conceptualization, Project administration

**Bing Li:** Investigation, Formal Analysis

**Wenchao Sun:** Data curation, Formal Analysis

**Long Chang:** Methodology, Writing – review & editing

## Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

## Conflicts of Interest

The authors declare no conflicts of interest.

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