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Comparison and Clarification of China and US CCUS Technology Development

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Abstract: The content of the China-US CCUS technology development roadmap is summarized based on the roadmap update in 2019. Qualitative analysis and evaluation were conducted from the perspectives of running CCUS demonstrations or industrial projects, CO_2 pipeline infrastructure, established regulatory frameworks, policy support, research and development capabilities, and geological storage resources. A simple analysis of the development status of carbon capture, storage, and utilization technology through relevant patent data is provided. Future planning by China and the United States in terms of planning volume, investment funds, related industries, transportation methods, geological storage, geological utilization, other utilization methods, and incentive policies is compared. Overall, US CCUS technology development is in the leading position in the world; it has entered the stage of small-scale commercial promotion, while the overall development level of China's CCUS technology is still behind the international advanced level in a small-scale experimental demonstration period, and is still in the catch-up stage. However, as the Chinese government has put forward the strategy of "carbon peaking and carbon neutralization", CCUS has ushered in a golden opportunity for development in China, and some large-scale industrial demonstration projects have been carried out. This study analyzes China's advantages and challenges in developing CCUS and gives some suggestions on the direction that China's CCUS development should take in the future.

Keywords: United States; CCUS; technology development roadmap

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Citation: Li, X.-Y.; Gao, X.; Xie, J.-J. Comparison and Clarification of China and US CCUS Technology Development. *Atmosphere* **2022**, *13*, 2114. https://doi.org/10.3390/atmos13122114

Academic Editor: Kumar Vikrant

Received: 19 November 2022
Accepted: 13 December 2022
Published: 16 December 2022

1. Introduction

Massive emissions of greenhouse gases such as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons (HFCS), perfluorocarbons, and sulfur hexafluoride have exacerbated the greenhouse effect, leading to continued global warming. Among them, man-made carbon dioxide emissions are causing 63% of the overall global temperature rise [1], increasing the possibility of serious, universal, and irreversible impacts on human beings and ecosystems [2]. Therefore, reducing carbon dioxide emissions is considered to be one of the most important means to control global temperature rise.

As a terminal emission reduction technology that can realize large-scale low-carbon development of fossil energy, CCS (carbon capture and storage) has been receiving much attention. In its "Energy Technology Outlook 2020", the International Energy Agency (IEA) claims that according to the sustainable development scenario, a net reduction of zero global CO_2 emissions in the energy industry will have been achieved by 2070. Overall, however, compared to the "prescribed policy scenario" promised by related current national energy and climate policies, CCUS contributed nearly 15 percent of cumulative global CO_2 reductions. The contribution made by CCUS has grown over time as technology has improved, costs have fallen, and other cheaper abatement options have run out [3]. An estimate proposed in the IEA's World Energy Outlook 2019 is that in order to limit global temperature rise within 1.8 °C, CCUS technologies would have to provide about 9% of cumulative emissions reduction by 2050, without relying on large-scale negative emission technologies [4]. A 1.5 °C special report from the United Nations Intergovernmental Panel on Climate Change (IPCC) further points out that to achieve the goal of limiting global temperature rise within 1.5 °C and achieving near-zero carbon emissions by 2050, the application of CCS in various fields is inevitable, and the deployment of a large number of negative-emission technologies is needed [5]. CCS technology also has an obvious effect on reducing emission reduction costs. The IPCC's fifth Comprehensive Report points out that the application of CCS is an indispensable component in achieving climate goals at the lowest cost; if CCS is excluded from the portfolio of emission-reduction technologies, the emission reduction costs will increase by 138% [1]. Therefore, CCS will play an important role in global carbon reduction in the future.

Nonetheless, the entire CCS system is still facing many challenges that limit its development to some extent: high capture costs [6,7], high energy consumption in operation [8], high risk in transport and storage [9–11], and especially the high cost of capture technology and high energy loss through consumption (the impact on the operational efficiency of the original system caused by the installation of capture facilities), which has a significant impact on both developed and developing countries. Based on the above, and combined with specific national conditions, China put forward the concept of carbon utilization—CCUS (carbon capture, utilization, and storage) which, in essence, is the same as CCS. CO_2 is isolated from the atmosphere in the long term by separation, compression, and transportation to a specific location for injection into a reservoir for storage.

Due to the indispensable role of CCUS technology in achieving temperature-control goals, major greenhouse gas emitters attach great importance to the development of CCUS technology. In particular, both China and the United States play a crucial role in controlling global temperature rise. Under the temperature control targets, whether technology can meet the emission reduction requirements in the future largely depends on the deployment of CCUS technology. Therefore, this paper compares and analyzes the current situation and future planning of CCUS technology development in China and the United States, deeply analyzes the advantages and challenges of CCUS development in China and puts forward relevant policy suggestions for CCUS development in China.

2. CCUS Technology Development in China and the United States

2.1. CCUS Technology Development in China and the United States

This section compares and analyzes the status quo of CCUS technology development in China and the United States from six aspects: CCUS projects being operated, pipeline mileage for CO_2 transportation, regulatory frameworks, policies and regulations, research and development capacity, and geological resource storage capacity. In terms of industry standards, both the number and scale of CCUS projects in China have not reached the level of those in the United States, and the industries involved are different, as shown in Figure 1. Compared with the thousands of kilometers of pipeline mileage in the United States, the CO_2 transmission pipeline operation in China still needs development. Despite the increasingly stressed importance of CCUS, there are still deficiencies in supervision, certain policies, and regulations [12]. Three factors leading to fewer projects in the whole process in China are that there is no special regulatory standard similar to that of the United States for carbon transport, storage injection, and environmental protection; the lack of tax credit policies and operational incentives to support and encourage enterprises to carry out low-carbon development; and an unsound carbon pricing mechanism. In the future, we can learn from the relevant legislation in the United States and introduce special CCUS regulations and policies and relevant incentive measures according to the actual situation in China. In terms of research and development, China's CCUS technology research and development started late but developed rapidly. All links in the CCUS technology chain possess certain research and development capabilities, which in general are still in the early pilot demonstration period and have not reached the international advanced level.

In terms of CO_2 geological resource storage, both China and the United States can meet the demand for carbon emission reduction and sequestration in the future. The United States has underground CO_2 sequestration potential in 48 states, and the distribution of source and sink is relatively balanced. While the regions with relatively great potential for CO_2 sequestration are mainly located in the west of China [13], the large emission sites are mainly located in the east, resulting in the possible need for east–west gas transmission. The United States has largely carried out CO_2-enhancing oil recovery rate activities for more than 40 years, bringing significant economic benefits. China is still in the initial stage in this aspect, with only a few experimental demonstration projects. In the near to medium future, CO_2-enhancing oil recovery rate activities will be the main application scenario of CCUS, which can promote the early development of CCUS technology in China.

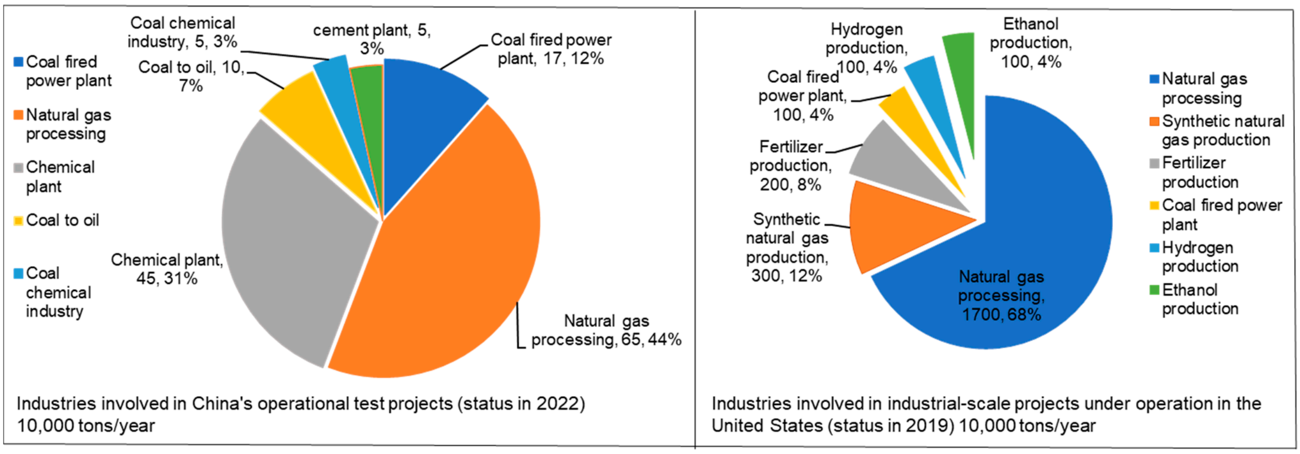

Figure 1. Industries involved in operation trials and industrialized CCUS projects in China and the United States.

To conclude, the United States is in a leading position in the world in terms of CCUS technology research and development, regulatory and policy support, and practical utilization capacity. Small-scale commercial promotion has already been carried out. Nonetheless, China is still in the stage of small-scale experimentation and demonstration, and still needs to catch up with the advanced international level.

2.2. CCUS Patents in China and the United States

To some extent, the number of patents can reflect a country's level of technological development in related industries. According to the WoS (Web of Science) international patent database, 14,507 patents published in the field of CCUS have been found between China and the United States through 2020. Among them, 8787 patents were involved in capture, including 4517 in China and 4270 in the United States, as shown in Figure 2. The number of storage and utilization patents was 5720, among which 3371 were in China and 2349 were in the United States, as shown in Figure 3. The layout of patented technologies in capture both in China and The United States can be seen in Figure 4, and the layout of patented technologies in storage and utilization can be seen in Figure 5. This section discusses in detail the patents for carbon capture, storage, and utilization in both countries.

2.2.1. Annual Trend of CCUS Patents in China and the US

Up to now, the total number of patents in China exceeds that in the United States, but there is a significant difference in time. The earliest published patents for carbon capture in the United States can be traced back to 1970, and the great growth of patent numbers was mainly between 2001 and 2013. This was followed by a decline, indicating that the technology accumulation in terms of carbon capture in the United States has been relatively mature (due to the time lag of patent publication, patent data for 2020 are not included in the scope of this paper, and will not be repeated in the following paper). The main reason for this is that the United States had witnessed an economic recession, affected by the first oil crisis during the 1970s. Therefore, the United States proposed a policy that ensured national energy security and realized energy independence as one of the new means to massively increase oil production. However, the earliest published patents for carbon capture in China can be traced back to 1988, and the increasing trend can be seen from 2007, followed by rapid growth. As of 2019, the number of published patents was still growing, indicating that domestic attention to carbon capture technology was still increasing, and the technology is in a period of rapid development. The main reason for this is that, influenced by the international environment of carbon emission reduction in the new century, coupled with the fact that China became the world's largest carbon emitter in 2006, the country increased its emphasis on carbon capture technology research and development. In the same year, relevant state departments included development and utilization technologies for fossil energy with high efficiency, clean energy, and near-zero CO_2 emissions into the Outline of the National Medium- and Long-Term Scientific and Technological Development Program (2006–2020), which greatly promoted the development of CCUS in China. From then on, the number of published carbon capture patents in China began to climb rapidly, catching up to and finally overtaking the United States. Especially in the past five years, the annual number of published carbon capture patents in China has been significantly ahead of that in the United States.

As for carbon sequestration and utilization patents, China and the United States also have significant differences in patent research and development time. The United States can be traced back to 1973. After 2000, the number of patents published in this field increased significantly, reaching two peaks in 2002 and 2014. After 2014, the overall trend of decline shows that the United States has accumulated more mature carbon storage and utilization technologies. The reasons are the same as above. China's patents for carbon storage and utilization can be traced back to 1996 at the earliest. After 2007, the number of patents published began to grow rapidly. In 2018, the number of patents published reached a peak, and in 2019, it decreased slightly. This shows that China has paid great attention to carbon storage and utilization technology, and the technology is still in a high-speed development period. The reasons are the same as above, so they will not be repeated. As of 2020, China has surpassed the United States in the total number of patents for carbon storage and utilization that are able to be checked. Especially in the past five years, the number of carbon sequestration and utilization patents disclosed by China each year has been significantly higher than that of the United States.

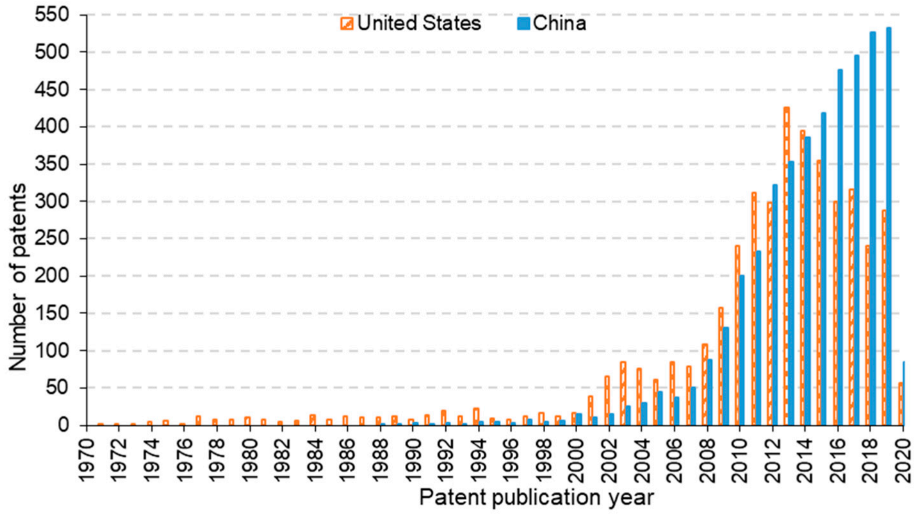

Figure 2. Annual trend of carbon capture patents in China and the US.

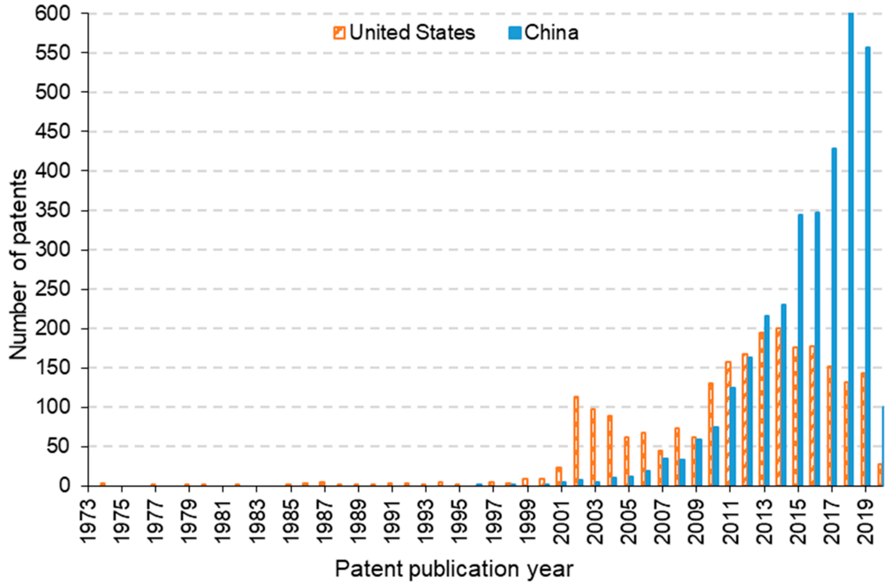

Figure 3. Annual trend of carbon storage and utilization patents in China and the US.

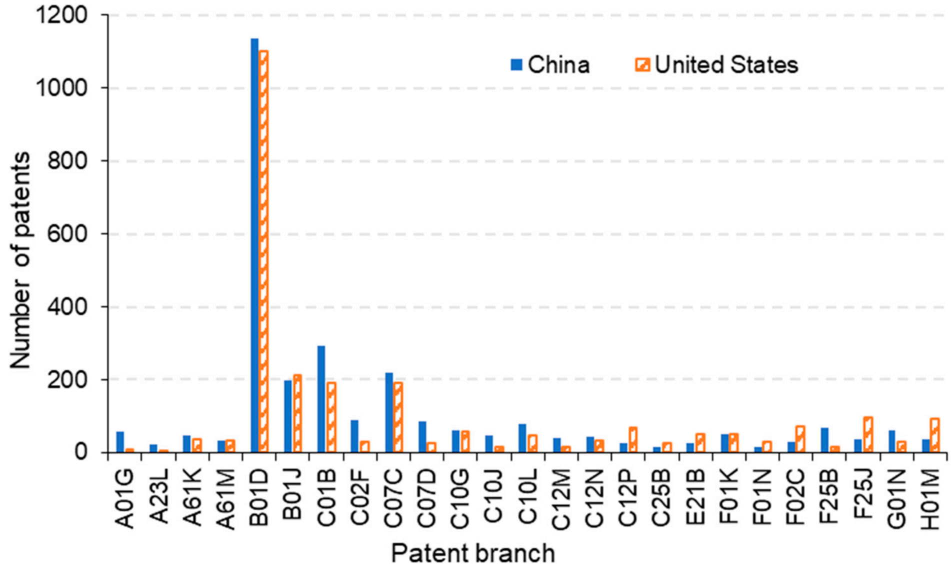

Figure 4. Patent layout of capture technology.

In general, the United States conducted research and development on carbon capture, storage, and utilization more than ten to twenty years earlier than China. From the perspective of the number of patents alone, the United States maintained a great advantage in the early stage of technology development. After entering the new century, with China's emphasis on research and development of related technologies, the number of patents published in China began to increase rapidly. Especially in recent years, the annual increment of patents has been significantly ahead of the United States. By 2020, the total number of patents disclosed (with data available) in terms of capture, storage, and utilization has surpassed that of the United States. It can be seen that thanks to its domestic energy policy, the United States had obvious early R&D advantages in CCUS-related fields, and its overall technology developed and matured early. In China's early economic development, due to various reasons, the energy consumption capacity was insufficient. However, with reform and opening up, due to the dual impact of international emission reduction pressure and strong domestic oil demand (especially after entering the new century), the country has increased its attention to relevant technology research and development, and various technical aspects have developed rapidly. In the future, China should continue to strengthen its technology research and development in CCUS-related fields, especially the research and development and application of high-quality patent technology.

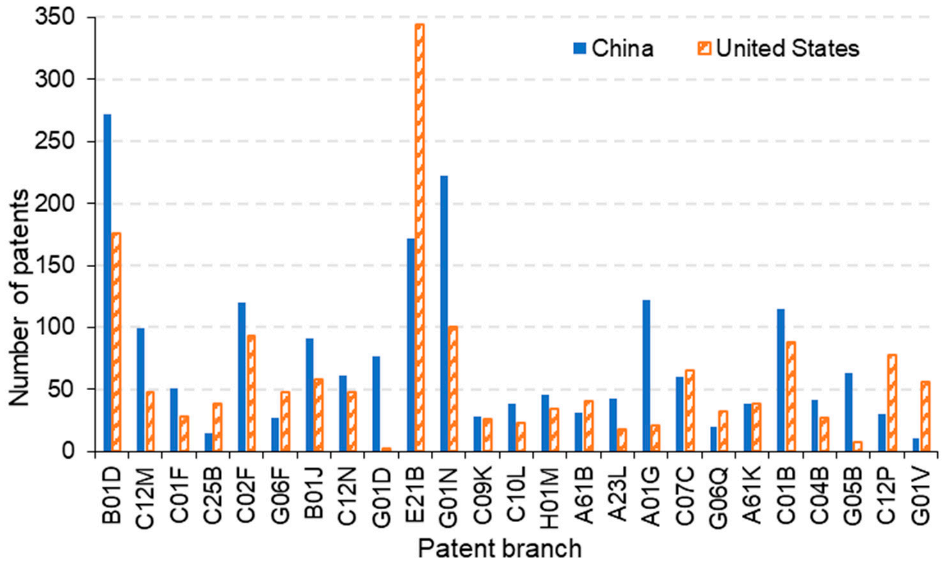

Figure 5. Layout of technology patents for storage and utilization.

2.2.2. CCUS Patent Layout in China and the US

As for carbon capture technology, both China and the United States focus on B01D (CO_2 separated by general physical or chemical methods or devices in operation and transportation), which includes the improvement of traditional carbon dioxide separation methods: chemical separation, physical adsorption devices and processes, solid (liquid) bulk adsorbent, pressure swing adsorption, catalytic reaction, and so on. At the same time, both in China and the United States, the distribution of capture technology research and development in various fields is dispersive and uniform, covering many advanced carbon capture methods such as the use of microbial CO_2 separation (C12N) and advanced condensation and distillation processes and equipment (F25J).

In terms of CO_2 sequestration and utilization technologies, both China and the United States mainly focus on CO_2 geological sequestration and utilization technologies (E21B), represented by CO_2-enhancing oil and gas extraction. In addition, CO_2 chemical utilization and bio-utilization technologies are also key areas of layout in the two countries. It is worth noting that the United States has a clear advantage in early research and development in the field of post-injection CO_2 monitoring, risk warning, and control technology. The main reason for this is that in the United States captured CO_2 is mainly used to improve the oil recovery rate and has been successfully used for more than 40 years. Without a doubt, related fields have strong technical strengths. But China is still in its infancy in this field and the layout of it is weak.

In general, in terms of patent category layout, both China and the United States have the same emphasis on capture technology, and the technology is evenly distributed, focusing on the improvement of traditional carbon dioxide separation methods and paying attention to the utilization of carbon dioxide, but the United States has obvious advantages in early research and development in the fields of carbon dioxide post-injection monitoring, risk warning, and control technology, while China is still relatively weak in this field. Considering the practical needs of China's future CCUS technology development, further efforts are needed in the field in the future.

2.3. CCUS Technology Plans in China and The United States

The CCUS roadmap, released by the United States in 2019, has a strong emphasis on ensuring energy security and economic affordability. The roadmap mainly expounds comprehensively and in detail on the status quo of CCUS technology development in the United States, the economy of large-scale deployment in the future, the technical development requirements of each element, and the supporting policies, laws, and regulations, mentioning three important time periods in the following 25 years—"activation" (in the next 5 to 7 years): comprehensive incentive measures of 50 USD/ton of CO_2, the capacity of capturing source-point CO_2 emissions and storage can reach 40 million tons/year, and the cumulative jobs provided can be 10,000/year; "Expansion" (within the next 15 years): the comprehensive incentive measure of 50~90 USD/ton of CO_2, the storage capacity of captured source-point CO_2 can reach 150 million tons/year, and the accumulated jobs provided can be 40,000/year; "Scale" (in the next 25 years): with comprehensive incentives of 90~110 USD/ton of CO_2, the storage capacity of source-point CO_2 emissions can reach 50,000 tons/year and provide 230,000 cumulative jobs/year.

According to the CCUS roadmap, CCUS is a technology that can promote the construction of an ecological civilization and the implementation of a sustainable development strategy, enabling large-scale decarbonization to happen. The roadmap describes the current status and challenges of CCUS technology development, priority actions, early opportunities, and policy recommendations. It also refers to the phased goals of CCUS development and the envision of technology development up to 2050. The economic indexes related to different capture technologies (pre-combustion, post-combustion, oxygen-rich combustion), utilization technologies (geological, chemical, biological), transportation and storage technologies (land pipeline, submarine pipeline, offshore ship, land brackish water layer, depleted oil and gas field, submarine brackish water layer) and the specific technologies needed at each time node on the path to system integration and clustering has been given as well.

This section compares and analyzes CCUS technology development plans between China and the United States from eight aspects—future planning for seal stock, capital investment, industries involved, transportation modes, geological storage, CO_2-EOR and other geological uses, other uses of CO_2, and incentive policies. The plan for future capture utilization and storage can be divided into several stages, which are similar between China and the United States. In the United States, increasing financial incentives and related policy support are provided in the three program periods (activation, expansion, and scaling), helping to reach 50 million tons per year by 2045. To reach 80 million tons of storage per year by 2050, China currently has five planning stages in its roadmap but has not given specific financial incentives or policy support.

In terms of financial input, the United States plans to provide a large amount of financial support for basic research and development and demonstration of capture technology, pipeline infrastructure construction, research and development of geological storage utilization technology, and carbon capture operation participants in the next three stages. China has not yet introduced financial incentives similar to those in the United States. Instead, it provides more policy guidance and encouragement. Some scientific research demonstration projects have been funded by special funds from the state or subsidies from local governments.

Separate characteristics in the industries involved in emission reduction can be seen in China and the US. In the US, emission reduction is mainly applied in natural gas processing, synthetic natural gas production, fertilizer production, coal-fired power generation, hydrogen production, and ethanol production. Meanwhile, in China emission reduction technologies are mainly used in coal-fired power generation, natural gas purification, and traditional chemical and new coal-based chemical industries. The differences are mainly caused by resource endowments, structures of energy supply, and use in both countries.

In terms of CO_2 transportation, a pipeline is recognized as the most economical choice for large-scale long-distance transportation on land. The United States already has

5000 miles of CO_2 transportation pipeline, accounting for 85% of the total mileage of CO_2 transportation pipelines in the world [14]. According to an analysis by the US Department of Energy, the scale of the CO_2 transportation pipeline in the United States is expected to increase by two times by 2030, which meets the needs of the U.S. electric power sector for the transportation of captured CO_2. Currently, China's pipeline transportation is still in its early stages. Only PetroChina Jilin Oilfield, with large-scale pipeline design capability, has a 50 km demonstration transportation pipeline. According to the roadmap, by 2030, China's land pipeline transportation will be commercially applied [8]. As we can see, there is still a huge gap between China and the United States in this aspect. If China wants to CO_2-enhance oil recovery and have large-scale deployment of CO_2 in the future, pipeline construction is an essential link.

In terms of geological sequestration utilization, the United States plans three stages involving practices of tax reform related to carbon sequestration, new laws and regulations to enable more federal land to be used for CO_2 sequestration, strengthening related practitioners and their training, and considering the gradual expansion of sequestration from onshore to offshore strata sequestration. China has completed a demonstration project of onshore brackish reservoir storage technology with an annual scale of 100,000 tons of saltwater sequestration. It plans to achieve a breakthrough in the security guarantee technology for brackish reservoir storage and realize commercial application of the technology by 2035. The gap between China and the United States on the injection technology for geological sequestration is not obvious, but further efforts are needed in the field of post-injection monitoring, risk warning, and control technology.

The United States has been the world leader in CO_2-enhanced oil recovery and it has more than 40 years of experience, having developed a comprehensive tax credit policy. In the next 5 to 10 years, research on issues related to enhanced offshore oil recovery will be considered, and with increased incentives at different planning stages, The proportion of CO_2-EOR in the U.S. oil industry will increase from 10% in the "activation" phase to 75% in the "scale" phase. Although CO_2-enhanced oil recovery (EOR) research in China has been applied in many oil displacement and storage demonstration projects, the technology is still in the early stages and the project is in the industrial demonstration stage, which is a large gap between the two countries.

China and the United States also have their characteristics in terms of other CO_2 utilization methods. The United States proposed four important CO_2 utilization directions in the future: thermochemistry, electrochemistry and photochemistry, carbonization and cement carbonation, and biological utilization, and believed that carbonization and cement carbonation have the greatest potential for immediate use and long-term isolation of CO_2. China mainly focuses on CO_2 chemical utilization technology and CO_2 bio-utilization. The bio-utilization technology of CO_2 conversion into food and feed has been commercialized on a large scale.

In terms of incentive policies, the United States currently has a tax credit policy specifically for carbon emissions in the Internal Revenue Code and proposes to further revise Part 45Q, raise the CO_2-EOR tax credit in Article 43, and expand Article 48 of the tax law to include more emission source scenarios and technologies. In recent decades, the policies issued by China are mainly macro-policies such as national or local strategic planning and development planning with only one technical guideline, but no measures related to emission reduction compensation and investment. The existing policies and regulations related to CCUS mainly focus on regulating storage site selection and encouraging technology development and lack incentives, which inhibits the development of the project to a certain extent.

Based on the above comparison, the United States promotes the development of CCUS through a large amount of long-term capital investment in research and development, supporting relevant policies, laws, and regulations, and drastic financial measures, and has introduced specific policies, laws, and regulations, financial and investment incentives, production or operation incentives, and financial support. At present, the development of

CCUS in the United States has entered the stage of small-scale commercial promotion and has reached an international advanced level.

From a macro and overall perspective, China has put forward technical guidance, pointed out the development direction, and tried to give the vision and target planning and initiative for future technology development. This is more of a guiding role for the development of CCUS in China, and it lacks specific policies, laws and regulations, financial and investment incentives, production or operation incentives, and financial support. At present, there is still a gap between the development of CCUS in China and the international advanced level. China is in the stage of small-scale experimentation and demonstration; technology research and application are not perfect, and policy research, formulation, and application are insufficient. Therefore, we should increase the layout and focus on research in these aspects.

2.4. Application Status of CCUS Projects in China and the United States

The United States is a leader in the deployment of global CCS, with 12 of the world's 26 operating facilities. The oldest CCS project is the Terrell Natural Gas Plant in Texas, which was built in 1972. It still permanently captures and stores carbon dioxide at the rate of 0.4 Mtpa and uses it to improve oil recovery. The largest CCS project in the world is Shute Creek Gas Processing Plant, located in Wyoming, which is affiliated with ExxonMobil. This project can capture 7 million tons of CO_2 every year.

In terms of the legal system, the U.S. government and private sector have invested heavily in the R&D and application of CCS, but less attention has been paid to the legal liability of geological storage of carbon dioxide. Legislators also tend to promote the development of CCS by limiting corporate liability. At present, China's political support for CCS is still fragmented, lacking the overall leadership of the government, the industry is still hesitant, and some scientists still hold different opinions [15].

According to statistics, as of July 2021, in terms of the number of projects (Figure 6), the United States had surpassed China in both completed projects and projects planned to be built in the future.

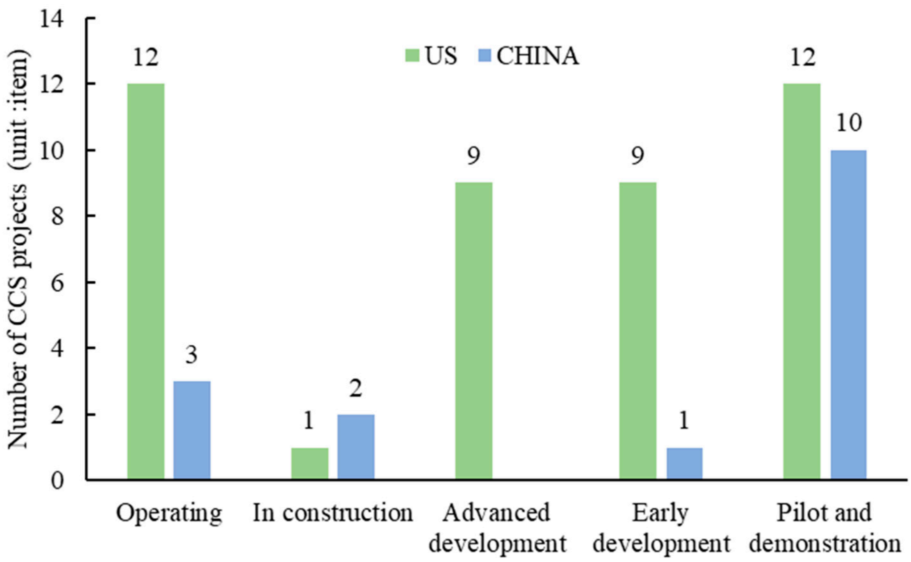

Figure 6. Number of CCS facilities in China and the US [16].

3. Technical Advantages and Challenges of CCUS Development in China

As the major contributors to global anthropogenic carbon emissions, China and the US will bear great pressure to reduce carbon emissions in the future. As a technology with large-scale carbon emission reduction potential, CCUS is expected to realize the low-carbon use of fossil energy and is widely regarded as one of the important technologies to deal with global climate change and control greenhouse gas emissions. Both countries have carried out some work in the field of CCUS technology, facing both advantages and challenges.

China's advantages in developing CCUS technology mainly include the following five aspects:

(1) The energy structure dominated by fossil energy will exist for a long time, especially under the influence of resource occurrence. As an energy type with high carbon emissions, coal will still play a dominant role in China's energy supply and consumption structure in the future. According to the data from the National Bureau of Statistics, coal still accounted for 57.7% of China's energy consumption structure in 2019; it is estimated in the existing literature that in 2030, the total production of primary energy will reach 4.3 billion tons of standard coal and CO_2 emissions will peak at 11.2 billion tons [8]. After the peak and de-peaking, China will achieve the goal of carbon neutrality to meet the real need by 2060.

(2) The top-down policy decision-making process of the Chinese government, involved in government guidance, market dominance, enterprise participation, and demonstration mechanisms, as well as relevant research institutes in R&D, is a highly efficient and powerful force for the development of the industry.

(3) Large-scale centralized emission sources are many and widely distributed, mainly concentrated in the economically developed eastern and southern regions; The emission sources are various [17], mainly from power [18], cement, iron and steel, chemical and coal chemical industry, and other large industrial sources, among which the thermal power industry accounts for the largest total carbon emissions, will be the key field for the application of emission reduction technology in the future [19]. As of 2019, there have been 18 capture projects in operation in China, with a total capture capacity of about 1.7 million tons, mainly concentrated in the coal chemical industry, followed by the thermal power, natural gas, methanol, cement, and fertilizer industries [18].

(4) CO_2 storage capacity in China is theoretically huge, estimated to be trillions of tons, due to geological conditions for large-scale CO_2 storage. The saltwater layer (95.6%) is the main one, supplemented by oil and gas reservoirs, coal beds, and other geological reservoirs [8]. From 2011 to 2015, the first and largest whole-process demonstration project for coal-based carbon dioxide capture and deep brackish water geological storage completed the 300,000-ton injection target, which marked great progress in terrestrial brackish water storage of carbon dioxide [20].

(5) There are a variety of promising CO_2 utilization approaches, such as CO_2-EOR [21] and CO_2-ECBM [22]. CO_2-EOR has entered the stage of small-scale industrial demonstration and is about to enter the primary stage of commercial application [8], whose potential benefits can promote the multi-directional development of the entire CCUS technology industry chain.

The challenges mainly come from four aspects. Initially, China's development stage cannot afford the high energy consumption and high cost of the entire CCUS system, which is a common problem in current global CCUS development. At present, the capture cost of low-concentration CO_2 in China is relatively high, 300~900 CNY/ton [8]. It is not economically competitive even if it is applied to drive oil with potential benefits. Secondly, there is a lack of clear legislation and policies to develop CCUS; thirdly, the spatial distribution pattern of dislocation between east and west increases the difficulty of CCUS integration demonstration and promotion [23,24], as shown in Figure 7. Lastly, complex geological conditions and dense population distribution need higher technical requirements for large-scale sequestration.

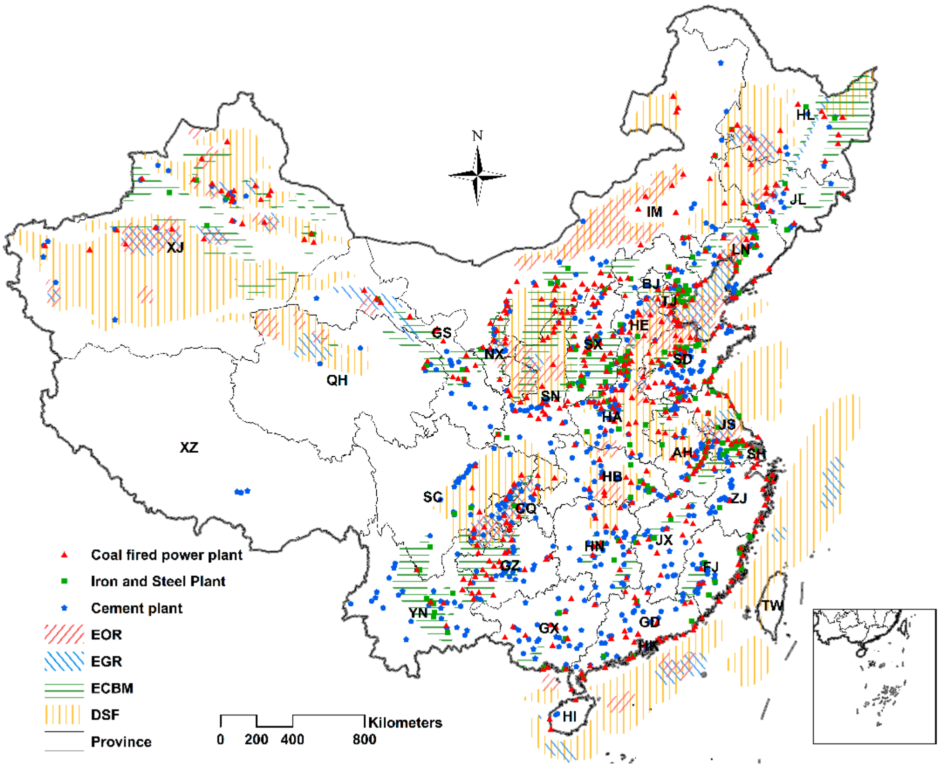

Figure 7. Large carbon emission source points and storage locations in China.

4. Conclusions

China has made obvious progress in the basic research and development of CCUS, and some of the technologies are relatively mature, especially in the field of CO_2-EOR, which is about to enter the early stages of commercial application and will soon be the main application scenario in the short term. However, there is still a gap between the whole system and process and the international advanced level. It is also urgent to improve support policies and regulatory frameworks, which contribute to the healthy development of related fields upstream and downstream. The spatial distribution of sources and sinks in China creates the possibility of east–west gas transmission, which brings great challenges to China's large-scale deployment. In a business environment lacking market motivation and most projects being guided by the government, an innovative business environment should be cultivated and established with the participation of research institutes and the implementation of enterprises to encourage and support the development of advanced scientific research capabilities.

5. Inspiration

Based on these comparisons, here are three inspirations:

Technical level: China participated late but made rapid progress in the basic research and development of capture, transportation, utilization, and storage. In the future, capture should focus on the research and development of post-combustion capture technology and both oxygen-rich combustion and pre-combustion capture technology. In terms of transportation, more investment should be made in the research and development of land pipeline transportation technology, while considering the need for subsea pipeline transportation. In terms of utilization, in the short term, we should increase investment in the research and development of CO_2-enhanced oil recovery and CBM flooding, while in the long term, we should consider chemical utilization and bio-utilization technology. In terms of geological sequestration, considering that the major types of Chinese sequestration sites are brackish layers, the research and development of deep brackish layer sequestration technology should be focused on, especially in the field of post-CO_2 injection monitoring, risk warning and control technology, and environmental protection.

Economic level: In the whole process of capture, transportation, and storage, the cost of capture is the highest; in low-concentration emission sources, the cost of capture can account for about 75% of the total cost of the whole process, and the level of capture cost directly determines the economy of the overall technology application. In the future, it is necessary to strengthen research and development investment in the second generation of capture technology, which can greatly reduce energy consumption and cost, for example new pre- and post-combustion membrane separation methods and chemical chain combustion technology in oxygen-rich combustion. The proposal of China's "carbon peak" and "carbon neutral" goals provides a rare opportunity for the development of China's CCUS. The country should introduce more economic support for low-carbon development in major industries and encourage enterprises to actively participate in, develop, and apply low-carbon technologies.

Policy level: The current regulatory policies and laws and regulations in all aspects of the CCUS industry are not perfect, so it is necessary to accelerate the research and promulgation of pipeline infrastructure construction and transportation standards, as well as injection site environmental protection (drinking water safety, etc.) and other related policies and regulations; in the absence of economic incentives (tax credits, direct financial subsidies, and special fund support) and financial support to encourage low-carbon development, it is necessary to study and introduce tax credit financial policies and other investment incentives to encourage low-carbon development and explore effective financing support mechanisms.

6. Suggestions

Based on the above conclusions and revelations, here are five policy recommendations:

(1) Increase investment in basic research and development and establish a dedicated fund: strengthen weak technology research and development, especially post-combustion capture technology closely related to our future carbon emission reduction, focus on reducing the energy consumption and cost of capture, encourage and support the research and development of new capture technology. Promotion of CO_2-EOR can increase oil production, reduce oil dependence, and ensure national energy security. At the same time, it can lower the entry threshold for the implementation of CCUS and promote the development of technology.

(2) Research and introduce incentive policies and measures to promote the commercialized usage of CCUS: formulate CCUS industry norms and standards systems, especially carbon dioxide pipeline transportation standards, environmental protection of injection sites, post-injection risk monitoring and safety management, etc.

(3) Strengthen the research on industrial chain cooperation, build a platform for government–industry–university–research cooperation, efficiently integrate the resources of relevant departments, enterprises, and institutions; promote effective collaboration among them and achieve joint coordination.

(4) Promote early integrated demonstrations actively and systematically: promote a screening and evaluation mechanism for early demonstration projects, select new coal and traditional chemical industries and use the Bohai Bay Basin and Ordos Basin to carry out early demonstration projects.

(5) Establish supervision regulations and industry norms for CCUS demonstration projects; financial and policy support along with incentives from the government for demonstration projects; integrated demonstration projects are especially necessary.

Author Contributions: Conceptualization, X.-Y.L. and J.-J.X.; methodology, X.-Y.L.; software, X.-Y.L.; validation, X.-Y.L. and J.-J.X.; formal analysis, X.-Y.L.; writing—original draft preparation, X.-Y.L.; writing—review and editing, J.-J.X.; visualization, X.G.; super-vision, X.-Y.L.; project administration, X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

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

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