Research of present status and development suggestions regarding the carbon capture, utilization and storage

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Abstract. The carbon capture, utilization and storage (hereinafter referred to as "CCUS") technology has already been widely regarded as an available method of great potential for carbon dioxide emission reduction. As predicted, the emission reduction contribution will rise from 3% of the total emission reduction amount in 2020 to 10% in 2030, and to about 20% in 2050, which becomes the individual technology of the greatest contribution to the carbon dioxide emission reduction. This paper illustrates the main links of CCUS technology: the carbon capture process, carbon transport, carbon utilization and carbon storage. This paper introduces the storage methods of carbon dioxide, the geological storage and marine storage. In addition, this paper also analyzes the main storage practices both at home and abroad, the major overseas storage projects and the present status and progress of China's storage. In addition, this paper also discusses the main challenges encountered by China's CCUS development, and proposes the ideas and policy suggestions that promote China's CCUS development.

1. Introduction
The Paris Agreement was reached on the Paris Climate Change Conference held in December, 2015, which mainly aimed to control the rise range of global mean temperature in this century within 2 °C. The Chinese government is committed to reduce the carbon dioxide emission amount per unit of GDP by 60%-65% in 2030, compared with that in 2005. The CCUS technology is an important carbon dioxide emission reduction technology. The CCUS refers to the abbreviation of Carbon Capture, Utilization and Storage. The CCUS is a reasonable use technology of carbon dioxide that separates the carbon dioxide from the power plant, coal chemical industry or other emission sources, and is enriched, compressed and transported to the designated location, injected to the reservoir, and finally stored, so as to realize the long-term separation between the captured carbon dioxide and atmosphere, or injected into the reservoir for flooding purpose [1]. As an emerging technology for the large-scale carbon dioxide emission reduction potential, the CCUS may realize the low carbon utilization of petrochemical energy, and it is considered by the IEA that the global carbon emission amount is expected to be reduced by more than 20% [2]. China's carbon dioxide emission amount ranks second place in the world, and it is very hard to change the present energy consumption method within a short period of time. Therefore, with the rapid economic growth in China, the carbon dioxide emission amount will continuously increase and the tremendous pressure of carbon dioxide emission reduction will be encountered. As a result, the development of CCUS technology is the urgent demand of greenhouse gas emission reduction in China's coal chemical industry, iron and steel, cement and other high emission industries. Meanwhile, as the emerging technology of reducing the greenhouse gas emission amount, CCUS technology is expected to develop rapidly.
emission and retarding the climate change, the CCUS technology is of great significance to respond to the mid-to-long-term climate change in China and promote the low carbon development [3].

Meanwhile, the CCUS technology is also one of the existing emission reduction technologies on which the UK, USA, Japan and other developed countries especially rely to actively cope with the climate change and ensure their leading places in the global clean energy sector. These countries have already invested the tremendous financial and human resources to develop the carbon dioxide capture, storage and utilization and other relevant technologies, so as to push ahead the safety and feasibility study of carbon dioxide storage and utilization. At present, all countries and multinational enterprises in the world closely watch the CCUS development road, and the relevant research and demonstration works have been rapidly developed. The CCUS technical development will bring the great environmental and economic benefits to the world [4].

2. Main links of CCUS technology

The main links of CCUS technology include: carbon capture process, carbon transport, carbon utilization and carbon storage.

2.1. Carbon capture process

The carbon capture process includes: oxy-fuel combustion capture, post-combustion capture, pre-combustion capture, and physical absorption process.

Oxy-fuel combustion capture: the oxy-fuel combustion separation technology adopts the high-purity oxygen (with the molar fraction of 95%~99%) to burn the fuel instead of the air, carry out the flue gas recirculation, and generate the flue gas which is dominated by the dihydrogen monoxide and carbon dioxide. Then, the high purity carbon dioxide will be obtained through the further treatment in the flue gas cooling system. The oxy-fuel features the advantages of easy separation of carbon dioxide, the unnecessary addition of solvent, and the smaller space required by the equipment. However, the source and preparation of large amount of high purity oxygen, belong to the difficult technologies, and the combustion chamber requires better high-temperature resisting materials. Therefore, the further study is required for its combustion mechanism, the emission of flue gas toxic substance, and flue gas recirculation system. In this regard, China is still at the experimental stage, for instance, the 25kW oxy-fuel combustion experimental platform established by Tsinghua University. However, there are more studies in foreign countries, for example, the 30kW oxy-fuel combustion thermal power plant operated in German and Spain [5].

Post-combustion capture: it separates the carbon dioxide from the flue gas emitted from the power plant by adding the chemical reagent, and the separation generally adopts the mono-ethanolamine (MEA) as the absorbent. Generally, the carbon dioxide may not be separated, until the mixture is heated for several hours and kept at the temperature of 150°C. The carbon dioxide is released and the high purity carbon dioxide gas flow is formed, while the absorbent may be reused. However, the post-combustion capture has the following disadvantages: the equipment to be used is too large, the floor area covered is large, and there are a great number of chemical reagents. In addition, upon heating, the toxic gas in the flue gas will be emitted, but the used solvent may be reused after the special treatment. In addition, it has the following advantages: the capture equipment may be concurrently constructed together with the plant, and the start-up and shutdown of the equipment are convenient, while the replacement of equipment will not have any impact upon the power plant. In recent years, it is also proposed to add the thin films or microporous solids into the capture process, which will contribute to the separation between the nitrogen and some gases, and the carbon dioxide [6]. China Huaneng Group has already established the 120,000 t/a and 3,000 t/a capture devices at the Shanghai Shidongkou Thermal Power Plant, and the Beijing Thermal Power Plant respectively, and the recovered carbon dioxide purity is above 99%.

Pre-combustion capture: the pre-combustion capture may be combined with the integrated gasification combined cycle (IGCC) process, which injects the powdered solid fossil fuel, steam, and oxygen into the gasifier through the burner under the high temperature and high pressure conditions,
disintegrate them and generate the gas mixture of hydrogen and carbonic oxide (also known as decarbonization). Then, after cooling, the gas mixture enters into the catalytic converter where the water gas (with the carbon dioxide molar fraction of 15%~60%) dominated by the carbon dioxide and hydrogen is generated in the catalytic reforming process. Finally, it will be separated, purified and compressed, and the carbon dioxide will be separated, while the high purity hydrogen will be used as the hydrogen and sent into the hydrogen gas turbine. In recent years, there are many IGCC technical applications, such as the American Future Gen, and China Huaneng Group's 100,000 t/a capture device established in Tianjin [7]. At present, the pre-combustion capture process still has not had the capture device of million t/a level. Therefore, there is no relevant large-scale technology for reference, and the doubt exists in the reliability of the constructed device or device in construction.

Physical absorption process: the physical absorption process includes the Rectisol method, NHD method, Purisol method, Flour method, and etc. Only the Rectisol method is introduced herein. In 2015, Shanxi Yanchang Petroleum Group entrusted the Xi’an Petroleum University to carry out the feasibility study regarding China's first CCUS liquid carbon dioxide transportation pipeline project, and Shanxi Yanchang Petroleum Group adopted the Rectisol carbon dioxide capture process. The principle of the process is as follows: as the solvent is in low temperature, the Rectisol may remove the carbon dioxide, hydrogen sulfide and other acid impurity gases contained in the virgin gas by utilizing its excellent solubility upon the acid gases (such as carbon dioxide, hydrogen sulfide and etc.). Such carbon dioxide absorption process features the high gas purity, good purity quality, easy operation, and sectionalized and selective conduct of gas desulfurization and decarbonization within a same tower [8]. Therefore, it is the recognized most economic and highest purity gas purification technology both at home and abroad at present. The purity of carbon dioxide captured by using the Shanxi Yanchang Petroleum Group's Rectisol process reaches above 98.8%, and such high purity carbon dioxide is the basis for pipeline transportation and oil flooding purposes.

2.2. Carbon transport

The carbon transport refers to the transport of separated and compressed carbon dioxide to the storage location via the pipeline or truck, train, ship and other means of transport, and it is the link connecting the carbon dioxide emission source and storage location. Among the three major links of CCUS, the carbon dioxide transport technology is relatively mature. Generally, the pipeline is the most economic transport method, and the primary approach to transport the carbon dioxide in large amount within a distance of 1,000km away from the carbon dioxide emission source. For the multi-million t/a carbon dioxide transport, or the farther overseas transport, the ship transport is more economically attractive. As the intermediate link of CCUS, the pipeline transport is also the first issue to be solved, so as to realize the large-scale storage and utilization. At present, many countries are trying to carry out a great number of researches upon the CCUS, and planning to adopt the CCUS technology as the significant composition of future energy strategy. However, compared with the high pressure natural gas pipeline, the global experiences of carbon dioxide are relatively less. It is a relatively comprehensive system engineering to transport the carbon dioxide via the pipeline, including the geological conditions, geographical location, public safety and other issues [9, 10]. At present, there are totally about 55 large-scale integrated CCUS projects worldwide, and about 8,000 km carbon dioxide pipeline transport network is established worldwide. Most of them are located in USA. The USA has the relatively perfect key technology of carbon dioxide pipeline transport and has established the relatively complete pipeline selection scheme and pipeline model. Therefore, the USA has obtained the relatively higher performance with regard to the carbon dioxide pipeline transport.

2.3. Carbon utilization

The carbon dioxide-EOR technology and carbon dioxide-ECBM technology are the main carbon dioxide utilization methods in China, which is of great significance to realize the stable and increased production of partial oilfields in China, and enhance the production and utilization of CBM.
The carbon dioxide-EOR is one of the most significant links in CCUS, and the carbon dioxide-EOR principle is as follows: the supercritical/dense phase carbon dioxide will be injected into the oil reservoir under the high pressure, and the carbon dioxide will be used to drive the crude oil to flow into the production well, so as to enhance the recovery ratio of crude oil. The influence factors of carbon dioxide oil flooding include the pressure and temperature, rock property, formation water, crude oil components and other properties of oil reservoir, and the oil flooding methods include the immiscible-phases flooding and miscible-phases flooding.

(1) Immiscible-phases flooding: for the oil reservoir with the lower pressure, higher temperature and heavier components, the surface tension of carbon dioxide and crude oil is comparatively large, and the carbon dioxide may extract the light components of partial crude oil. Meanwhile, partial carbon dioxide will be dissolved into the crude oil, so as to expand the crude oil and reduce the viscosity. However, it fails to form the miscible-phases with the crude oil, and the enhanced oil recovery ratio is within the range of about 5%.

(2) Miscible-phases flooding: for the higher pressure oil reservoir, when the formation pressure is higher than the minimum miscible-phases pressure, the surface tension of carbon dioxide and crude oil will tend to zero, and the carbon dioxide may extract more light components of the crude oil. In addition, more carbon dioxide may be dissolved into the crude oil, and the miscible "single phase" crude oil viscosity will be formed at the macro level, while the surface tension between the crude oil and reservoir rock may be reduced in a more obvious manner. Therefore, the mobility of crude oil will be greatly enhanced and the enhanced oil recovery ratio will be within the range of about 13% [11~12].

Since 1970s, the USA, Canada and other countries have always used the carbon dioxide-EOR technology to enhance the recovery ratio within the oil and gas production fields, and the USA has about 3100km carbon dioxide transport pipeline for oil flooding in the oilfield. In China, there are more and more depleted oilfields, the carbon dioxide-EOR method may not only bring the economic benefits to the oilfields, but also store partial carbon dioxide and realize the environmental benefits. As shown from the overseas flooding examples, generally, when the 2.5~4.1t carbon dioxide is injected into the oilfield, the petroleum output may be increased by 1t. In China, there is the adequate carbon dioxide capture amount, and the rich petroleum geological reserve is also applicable for the carbon dioxide flooding. Therefore, the carbon dioxide-EOR has the bright application prospects in China [13~14].

2.4. Carbon storage

The carbon dioxide storage refers to the method of safely injecting the captured carbon dioxide into and storing it in the deep geological structure under the supercritical state (the mixture of gas and liquid), and the types of storage location include the depleted oil and gas reservoir, coalbed and the deep saline aquifer of sedimentary basin. The carbon dioxide safe storage is the final foothold of CCUS technology. To a certain degree, the safety and feasibility at the storage link determines the development potential of CCUS technology. The correct selection of storage location and reserve evaluation is of critical significance to ensure that the stored carbon dioxide will be kept in the geological structure in a long-term and stable manner. The efficient, reliable and scaled storage methods in the CCUS mainly include the depleted oil and gas reservoir storage, deep saline aquifer storage and coalbed storage.

(1) Depleted oil and gas reservoir storage: at present, the researches on the oil and gas reservoirs are relatively complete and thorough, and the data and information are rich, while the geological conditions, such as the temperature, pressure, porous layer and etc., are suitable for storage. In addition, the carbon dioxide storage may be studied via the formation monitoring data and drilling evaluation. With the study regarding the recent 10 more years of carbon dioxide storage technology, such method is the only mature storage technology.

(2) Deep saline aquifer storage: the water at such geological location can neither be used as the drinking water, nor have the production value. The deep saline aquifer has the tremendous storage potential. As estimated, 20%~500% of expected carbon dioxide emission amount prior to 2015
worldwide may be stored [15]. The carbon dioxide may be dissolved into the deep saline aquifer and slowly react with the minerals, so as to form the carbonate and realize the permanent storage of carbon dioxide.

(3) Coalbed storage: the coalbed has the much stronger adhesion which is about twice of methane, namely, the coalbed methane may be displaced to enhance the recovery ratio of CBM. However, the carbon dioxide will have the swelling reaction in the coalbed, which will cause the coalbed spacing to become smaller and make it difficult for the carbon dioxide to be injected into the coalbed. Therefore, its storage prospect is limited.

There are totally 74 carbon capture and storage projects worldwide and about 20 million t/a carbon dioxide may be stored, while most of the carbon dioxide is located at the North America and Europe. The start of China's carbon capture and storage projects is late. As of April, 2017, the successfully operated storage projects include the Changling Storage Location of Jilin Oilfield with the carbon dioxide storage amount of more than 1.1 million tons, and Shenhua Group's 10t/a carbon dioxide storage project constructed in the Ordos Basin, with the storage amount of more than 100,000t.

3. Carbon dioxide storage method
The carbon dioxide storage methods fall into two categories, namely, geological storage and marine storage.

3.1. Geological storage
Generally, the geological storage will inject the carbon dioxide under the supercritical state into the geological structure. The carbon dioxide geological storage mainly includes two fundamental mechanisms, namely, physical storage and chemical storage. Among them, the physical storage refers to the method of capturing the supercritical carbon dioxide into the pore at the top of reservoir under the joint action of bottom structural pressure [8], groundwater dynamics, bad fluid density, capillary pressure of caprock pore, mineral absorption and etc. The partial carbon dioxide captured into the reservoir will be distributed into the groundwater in a dissolved state, and will migrate together with the groundwater at the very low velocity, while the remaining carbon dioxide may be absorbed into the surface of special rock strata. The chemical storage mechanism refers to the mechanism under which the rock minerals and groundwater solution in the reservoir will have the slow chemical reaction with the injected supercritical carbon dioxide fluid under a certain temperature and pressure conditions, and the carbonate minerals or bicarbonate ions will be generated, so as to convert the carbon dioxide into the new substances and make them become stable [16]. Among them, the physical storage is prone to be restricted by the geological structure, ground stress status, groundwater dynamic features, engineering activity disturbance and other factors, and the physical capture will temporarily store the carbon dioxide in the underground rock formation. The chemical method is applicable for the long-term storage of carbon dioxide. If the physical storage and chemical storage are used together, the better effect may be achieved [17].

3.2. Marine storage
The marine storage refers to the method of transporting the carbon dioxide into the deep seabed for storage. The seabed geological structure is the extension of terrestrial geological structure. Therefore, except for the coal field, the other geological storage methods of carbon dioxide, such as the oil and gas fields, deep saline aquifer and other geological structural storage methods of carbon dioxide, are also applicable to the seabed storage. The technology used for the carbon dioxide storage in the deep saline aquifer, terrestrial or coastal geological structure is almost the same. The carbon dioxide storage in the seabed geological structure includes the process in which the carbon dioxide will be separated from the carbon dioxide emission source in the industrial, energy and other relevant fields, transported to the offshore storage location and finally complete the seabed injection and storage. The seabed storage is far away from the aquifer. Except for the caprock, there is the seawater pressure and resistance on the surface. Therefore, some scholars believe that the local risk for the seabed storage of
carbon dioxide is very low. At present, the carbon dioxide seabed storage researches and practices are mainly carried out by the USA, Canada, EU and other developed countries that undertake the quantified emission reduction commitments of greenhouse gas worldwide. As shown from the results, the carbon dioxide seabed storage has the technical reliability and economic feasibility [18~20].

Although the marine storage is a sort of carbon dioxide geological storage method which attracts more attention from the public, it is still controversial due to the existence of a certain environmental risk. Some scholars point out that the carbon dioxide seabed storage needs to focus on the change to the sedimentary environment that may be caused by the leakage, and the impact of local marine acidification (the carbon dioxide seabed storage does not include the marine storage that directly releases the carbon dioxide into the marine waters or the seabed). The carbon dioxide emission will cause the ocean acidification. Due to the significant impact of seawater pH value change upon the marine organism, the carbon dioxide emission will affect the marine biological diversity. As shown from the researches, under the condition of carbon dioxide leakage simulation in the laboratory, the seawater pH value will be declined to below 6 within a shorter period, and both the growth and physiological function of marine sensitive organisms will be obviously restrained. In addition, the long-term leakage may cause the death of experimental organisms.

4. Main storage practices both at home and abroad

4.1. Main overseas storage projects
At present, many international CCUS projects are ongoing. Among them, there are 3 representative projects, namely, the Statoil ASA's Sleipner project in North Sea, the Algerian InSalah project and Canadian Weyburn project. Among them, some projects will inject the carbon dioxide into the seabed or underground, and some projects will inject the carbon dioxide into the oilfield, so as to enhance the recovery ratio of oilfield. In addition, the EU is expected to construct 12 large-scale carbon capture and storage demonstration projects in 2018, and totally € 5 billion will be invested.

The first commercial-scale CCUS work worldwide is the Statoil ASA's Sleipner carbon dioxide storage project in North Sea in 1996. This project will store 1 million t/a carbon dioxide in the underground saline aquifer. The Canadian Weyburn project is the EOR work conducted for the purpose of carbon dioxide storage. This project has stored about 1~2 million t/a carbon dioxide in the oilfield, since 2000. Meanwhile, the oil output in the oilfield is also increased by 50%.

As per the statistics of Australian Global CCS Institute, there are 270 CCUS projects worldwide. Among them, the annual carbon dioxide storage of 70 projects reaches the 1 million t/a commercial scale. However, most projects are still under the planning and research stage at present, and there are no more than 10 actually operated commercial projects, while most projects are concentrated within the oil and gas production fields.

4.2. China's current storage status and progress
Although China has a later start time with regard to the CCUS technical development and research, its CCUS is developed very fast and China is the world leader in light of carbon dioxide capture. China's first whole-process CCUS industrial demonstration project is the Shenhua Group's carbon dioxide saline aquifer storage project conducted in Ordos in June, 2010. This project has an investment of ¥ 210 million, and the design scale is 100,000t/a carbon dioxide storage amount. It is expected that the carbon dioxide stored in Ordos Basin may reach tens of billions tons of carbon dioxide. As the strategic technical reserve of carbon dioxide emission reduction, China also attaches the great importance to the CCUS technical research and development. In June, 2007, China's Ministry of Science and Technology united with 14 departments to jointly issue the China's Science and Technical Special Actions for Addressing Climate Change, defining "research and develop the carbon dioxide capture, utilization and storage key technologies and measures, formulate the carbon dioxide capture, utilization and storage technology roadmap, and carry out the carbon dioxide capture, utilization and storage capacity building and engineering technology demonstration" as one of the key tasks of the
Special Action. Especially in recent years, China's governments, universities and research institutes, enterprises and some international cooperation projects have conducted the CCS preliminary studies and engineering demonstration.

Since the 11th Five-Year Plan, Chinese government has supported many CCUS technical links and relevant science theory, key technology, development strategy and other researches, through the National Program on Key Basic Research Project ("973 Program"), National High-tech R&D Program ("863 Program") and National Science and Technology Support Program. In addition, with regard to the carbon capture, a series of researches regarding the low energy consumption absorbent, variable technical route carbon capture process and other key technical links are carried out and the commercially applied Amines absorbent is developed. In light of the carbon utilization, the theory and key technical researches regarding the carbon dioxide oil flooding, CBM flooding, carbon dioxide biotransformation, chemical synthesis and other different utilization methods are conducted, and the pilot scale production of biodiesel from microalgae and the small-scale carbon dioxide-based biodegradable plastic production lines are established. With regard to the carbon storage, the national carbon dioxide geological reserve potential evaluation has already been started, and the industrial-level saline aquifer storage demonstration project has been implemented.

In 2006, China started the 973 Program "Greenhouse Gas Underground Storage and Resources Utilization through Enhanced Oil Recovery". In 2007, China started the scientific and technical special project "Jilin Oilfield Carbon Dioxide-Bearing Natural Gas Development and Carbon Dioxide and Resources Comprehensive Utilization Research". In 2007, China started the project "Cooperation Action within CCS China-EU (COACH)". In 2008, the Ministry of Science and Technology started the 863 key project "Carbon Dioxide Capture and Storage Technology", which carried out the terrestrial or seabed geological saline aquifer carbon dioxide storage technical research, and developed the low cost and practical carbon dioxide storage technology that is suitable to China's geological conditions.

Meanwhile, China carried out the CCUS international cooperation research with the EU, Australia, Asian Development Bank and other countries and international organizations worldwide, which promoted the positive achievements made in China's CCUS technical development. In 2010, China and Australia signed the "China-Australia Geological Storage of CO2 Project (CAGS)" Contract, which carried out the substantial cooperation regarding the topics of common interests within the CCS field, and jointly promote the research and development of carbon dioxide geological storage, intellectual property sharing and the development of relevant disciplines. In 2010, China started the China-UK cooperation project "Feasibility Study of Carbon Capture and Storage Readiness in Guangdong Province (GDCCSR)", which explored the necessity, possibility, cost benefit and other issues for Guangdong Province to carry out the CCS. Meanwhile, the PetroChina, China Huaneng Group, Shenhua Group and China's other large-sized energy enterprises also set their sights on the CCUS technical research and development, and make the bold exploration and attempt with regard to the CCUS engineering construction.

Although China's CCUS technical development achieves the positive results, the technical level of China's CCUS partial links is still required to be enhanced. Most of the existing CCUS experimental demonstration projects are concentrated on the demonstration of carbon capture technology and EOR technology. However, there are still very few technical demonstration examples with regard to the saline aquifer storage, carbon dioxide storage monitoring and pre-alarm, the large-scale carbon dioxide transport, and etc. Compared with the international advanced level, there is still a big gap.

5. Major challenges encountered by China's CCUS development

The cost of CCUS demonstration project is relatively high, which is the main cause to hinder the development of CCUS. At present, the investment amount of CCUS demonstration works will be at the scale of hundreds of millions RMB. In addition, under the existing technical conditions, the introduction of carbon dioxide will increase the additional ¥140–600/t carbon dioxide operation cost. For instance, the power generation cost of China Huaneng Group's Shanghai Shidongkou Carbon
Capture Project is improved from about ¥0.26/ kWh~¥0.5/ kWh. The significant contribution of CCUS project is the carbon emission reduction. However, under the condition that the external cost of the carbon emission is not internalized, the enterprise's emission reduction benefits cannot be fully reflected. It is almost the enterprise's spontaneous investment behavior to carry out the CCUS, and it is impossible for many projects to be started or it is hard for them to be continued due to the lack of cashes. Under the macroscopic situation of coal industry recession and drop in oil prices, the enterprise's benefits are further reduced, which affects the enterprise's willingness to carry out the CCUS demonstration.

The CCUS technical level is still to be improved, which is another obstacle to restrict the CCUS development. At present, China's CCUS experimental demonstration is still at the initial stage, and the CCUS technology is still at the R&D and experimental demonstration stage, while the large-scale and whole-process CCUS project demonstration experiences are very scarce. Therefore, many problems still need to be solved at the technical level, and there are few cases that are actually reproducible, economic and efficient, and commonly accepted. In addition, under the existing CCUS technical conditions, due to the arrangement of CCUS, the primary energy consumption will be increased by 10%~20%, and the efficiency loss is very huge, which is also one of the major obstacles that hinders the extensive application of CCUS technology.

Due to the incomplete policy and legal systems, it is hard to provide the good support to the CCUS development. Firstly, Chinese government has already definitely pointed out the carbon emission control target as of 2020 and 2030 separately, but it has not proposed the specific quantified constraint indices with regard to the industries and enterprises. Therefore, most enterprises take a wait-and-see attitude towards the CCUS, and still don't adopt the CCUS as an important choice for the low carbon transformation of enterprises. Secondly, China has not established the CCUS development strategy at the national level, and most of the existing policies are dominated by the flexible guidance and encouragement, instead of the definite policy incentives with regard to CCUS. In addition, the CCUS generally is related to the major long-term development strategies of the enterprises. If there is no stable policy expectation, it is hard for the enterprise to make the investment decision. Thirdly, China still has not established the specifications and rules, and standard system in light of the whole-process CCUS demonstration project. Both the governments and enterprises worry about the potential environmental risks and safety risks of CCUS project implementation, which will further affect the enterprise's initiative upon the development of CCUS.

The trans-departmental and trans-regional coordination mechanism still has not been established, which affects the actual promotion of CCUS project. On one hand, the CCUS project generally has the trans-departmental and trans-regional features. During the process of project application, approval and execution, many regions and departments may be involved. Under the condition that the existing specification is not especially clear and lack of the efficient communication and coordination, it will increase many trading costs, which will make it hard to promote the CCUS project. On the other hand, the whole-process CCUS demonstration project involves the variable enterprises on the multiple industrial chains, and all interested parties of the project will encounter the benefits sharing, responsibility sharing, risk sharing and other difficulties. If it is impossible to establish the efficient coordination mechanism or industrial specification, it is hard to establish the fair and long-term cooperation model, which will further greatly affect the promotion of CCUS project.

6. Ideas and policy recommendations for promoting the development of China's CCUS

After the comprehensive consideration of the present status and future trend of China's CCUS development, it is found that China's CCUS will be still at the experimental demonstration stage within a certain period in future. The general idea of CCUS development is still to gradually realize the whole-process, integrated and scale demonstration of CCUS technology through the multi-field technical demonstration and phased implementation, which not only accumulates the experiences, but also gradually promotes the cost reduction and level enhancement of CCUS technology, so as to properly prepare for the long-term commercial application of CCUS.
The general idea of CCUS development during the period of 2020–2030 is the extensive promotion and arrangement, so as to realize the technical breakthrough. It is suggested to strengthen the promotion effort of large-scale and whole-process CCUS demonstration project, so as to form the upstream and downstream interrelated CCUS demonstration industry system and promote the development of relevant infrastructure and expansion of supporting equipment manufacturing industry. Meanwhile, it is required to promote the key technical links to realize the breakthrough, realize the obvious reduction of CCUS technical application cost and enhance the industrial technical capacity of CCUS whole process design, construction and operation. At this stage, it is suggested to primarily strengthen the following main works:

1. The newly built thermal power plant shall be equipped with the carbon capture readiness, and the siting needs to consider the carbon dioxide storage location;
2. The large-scale and whole-process CCUS demonstration projects shall be carried out in the coal chemical industry and oil and gas field, and the trans-sector coordination mechanism shall be established;
3. The small-scale CCUS demonstration shall be carried out in the iron and steel, cement and other industrial sectors;
4. The engineering demonstration of combined carbon capture and saline aquifer storage shall be carried out;
5. The carbon dioxide transport pipeline and supporting facilities construction shall be actively promoted. Through the above efforts, it intends to establish the commercial example of CCUS scale application in the coal chemical industry and other sectors by 2030, establish several million tons level large-scale and whole-process CCUS demonstration project, and try to make the annual carbon dioxide emission reduction caused by CCUS reach 30~50 million tons.

In order to achieve the above targets, it is required to strengthen the CCUS related strategic planning and system design, enhance the CCUS policy support and economic incentives, and gradually form the policy guarantee system that is in favor of the good development of CCUS, so as to lay a solid foundation for CCUS to take the long-term important emission reduction function. Specifically, it is suggested to strengthen the relevant works from the following four aspects:

1. The strategic planning shall be strengthened. As per the overall requirements of national low-carbon development and energy revolution, it is required to formulate the overall strategy or planning of CCUS development at the national level, define the strategic positioning of China's CCUS development, formulate the overall direction and roadmap of CCUS development, and to form the positive and stable policy anticipation. It is required to strengthen the total amount control of carbon emission, formulate and propose the industry-wise quantified constrained objective at the earliest, and to enhance the enterprise's low-carbon development awareness and the initiative of CCUS development.

2. The regulations and standards shall be perfected. Centering around three stages, namely, CCUS project application, construction and operation, and shutdown, it is required to perfect the CCUS laws and regulations framework system in steps, gradually establish the examination and approval system in light of CCUS project, and establish and perfect the technical specifications involving the CCUS construction and operation. In addition, it is also required to strengthen the specifications and standards formulation with regard to the CCUS underground space ownership approval, environmental management, safety regulation and etc., study and formulate the preferred system and selection criteria of CCUS experimental demonstration project.

3. The planning and coordination shall be strengthened. In combination with the features of CCUS project, it is required to establish the trans-regional and trans-departmental collaborative approval and supervision mechanism, establish and perfect the communication and coordination mechanism between the government departments, between the central and local governments, and between the governments and enterprises, and strengthen the planning and coordination among the variable regions and industries. It is required to study and propose the cooperation specifications between the
enterprises, establish the responsibility and interest sharing mechanism of the interested parties, and construct the reasonable design and operation model with regard to the multi-body CCUS project.

(4) The economic incentives shall be strengthened. It is required to explore the implementation of tax deduction and exemption, differentiated subsidies and other innovative incentive policies that contribute to the CCUS development, strengthen the direct financial support upon the large-scale, whole-process and significant CCUS demonstration projects, and encourage the local government to increase the policy incentives upon the CCUS. It is required to explore the CCUS commercial investment and financing mechanism under which the government and market are organically combined, actively utilize the green finance, climate bonds, low-carbon funds and many other means to support the CCUS project demonstration, and explore the reasonable mechanism under which the CCUS will be incorporated into the carbon emission right trading market [21].

7. Conclusion
The CCUS technology is the effective method to reduce the carbon dioxide emission, and some enterprises in China have already made the rapid progress in light of carbon capture, utilization and storage, such as Petrochina, Shenhua Group, China Huaneng Group, and etc. In the future, the fossil fuel is still the dominant fuel in the world. Therefore, the CCUS technology will still be the main solution to solve the emission of greenhouse gas emission and reduce the carbon emission within a certain period in future. China's energy utilization framework is dominated by the coal. Therefore, the CCUS technology may greatly reduce China's carbon dioxide emission, and feature the large use scope and bright prospect. However, at present, China's CCUS technology is still under the R&D stage, and the development of CCUS technology in China still encounters many obstacles, such as the lack of mature industrial technology, continuous financial support, uniformed supervision and standards, and the long-term development planning, and etc. However, China is the most potential CCUS market in the world. At present, the opportunities and challenges for the development of CCUS technology in China co-exist.

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