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Development Trend and Strategic Countermeasures of Clean Coal Technology in China Toward 2035

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Abstract: China's energy structure has long been dominated by coal. To achieve clean, high-efficiency utilization of coal in the country, it is critical to develop clean coal technologies (CCTs). In this paper, after the concept of CCT is defined, the advanced characteristics of CCT are identified, and key cutting-edge technologies are predicted for 2035. By reviewing the development of major cutting-edge technologies in China and abroad, we provide a strategic goal and path for China's CCT development and corresponding policy suggestions. China has achieved a leading role globally in terms of technology research and development, equipment production and demonstration projects for advanced power generation technologies such as 700 °C ultra-supercritical technology, integrated gasification combined cycle/integrated gasification fuel cell combined cycle (IGCC/IGFC), and other technologies in the coal deep processing industry. Moreover, China demonstrates international competitiveness and advantages in research and development. However, there still exist several problems in terms of independent innovation capability, scientific research mechanism and talent cultivation, and balanced development between regions and enterprises. It is necessary to plan for the long-term development of coal energy, to scientifically deploy the development of modern coal chemical industry, actively deploy disruptive technology research and development and its engineering demonstration, and improve CCT research and development and its industrial environment in a comprehensive manner.
Keywords: coal; clean coal technology; energy strategy; 2035

1 Introduction

The development of clean coal technologies and the introduction of clean and efficient coal usage have always been the subject of global attention [1,2]. Coal has been the most important primary energy source in China for a long time [3]. According to data from the National Bureau of Statistics, China's total coal consumption in 2018 reached 2.74×10^9 t of standard coal, accounting for 59% of total energy consumption. Coal-fired power generation plays an essential role in China's power structure. It is estimated that coal-fired power generation will account for approximately 50% of power generation by 2030. However, large-scale and high-intensity coal development and utilization have, on one hand, caused damage to water resources and surface ecology in some important coal-producing regions; on the other hand, they have caused environmental problems such as large-scale coal-burning air pollution in many regions. At the same time, China is the world's largest CO_2 emitter, of which CO_2 emissions caused by coal burning account for about 80% of China's total fossil fuel emissions [4]. The development of clean

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coal technologies has important strategic significance for promoting the sustainable development of China's coal-based energy, safeguarding national energy security, controlling air pollution, and responding to climate change.

Abroad, coal resources are mainly used in coal-fired power generation, and developed countries and regions such as the United States, Europe, Japan, and Australia attach great importance to the development and demonstration of clean coal-fired power generation technologies, especially advanced coal-fired power generation technologies and CO_2 emission reduction technologies that have become a research hotspot [5]. China has built the world's largest clean and efficient coal-fired power system with world-leading emission standards. The clean coal utilization industry has been designated as a "green industry," and the vigorous development of clean coal technologies has become an important way to strengthen the transformation and upgrading of China's coal industry. With the improvement of technological innovation capabilities and the increasing importance of managing energy and environmental problems, clean coal technologies have huge application prospects and market potential in many fields, such as coal-fired power generation, coal chemical industry and comprehensive utilization of resources.

To enhance the development and competitiveness of science and technology, countries all over the world have carried out engineering and technological development strategic research, paying attention to technological foresight, and accordingly formulating medium- and long-term scientific and technological strategic plans [6]. They are laying out basic research, key technology R&D, and project demonstrations in advance, such as the annual major science and technology strategic plan and strategic research report of the United States, the "Lisbon Strategy" and the "EU 2020 Strategy" in Europe, and the technology foresight survey conducted by Japan every five years, all of which cover the energy field. China has also published the *Action Plan for the Innovation of Energy Technology Revolution (2016–2030)*, and research institutes such as the Chinese Academy of Engineering and the Chinese Academy of Sciences have also carried out systematic technical foresight work [7,8].

The next 10–15 years will be a critical period for the development of clean coal technologies in China. Actively developing advanced and disruptive coal conversion and utilization technologies and vigorously speeding up clean coal technology innovation for 2035 are conducive to enhancing the scientific and technological competitiveness of China's coal companies and sectors. The country's coal industry needs to achieve high-quality development and form a world-leading emerging industry of clean and efficient conversion and utilization of coal. This will enable China to build a green, low-carbon, safe, and efficient modern energy system and support the energy revolution.

2 The concept and scope of clean coal technologies

2.1 Concept and classification of clean coal technologies

Clean coal technology (CCT) refers to advanced technologies such as combustion, conversion synthesis, pollution control, and comprehensive utilization of waste that are designed to reduce pollution emissions and improve utilization efficiency during the clean utilization of coal (excluding mining processes) [9]. Its main technical applications are shown in Table 1. On the basis of coal utilization processes, CCT can be divided into three categories: front-end coal processing and purification technology; mid-end coal combustion, conversion, and pollutant control technology; and back-end waste treatment, carbon emission reduction, and comprehensive utilization technology.

Table 1. CCT classification.

Technology type	Sub-item main technologies
Coal processing and purification	Coal preparation, coal washing, briquette, coal water slurry, and coal blending technologies
Efficient and clean coal combustion	Circulating fluidized bed combustion, pressurized fluidized bed combustion, pulverized coal combustion, supercritical power generation, ultra-supercritical power generation, integrated gasification combined cycle (IGCC), integrated gasification fuel cell combined cycle (IGFC), oxygen-rich combustion
Coal conversion and synthesis	Gasification, liquefaction, hydrogen fuel cell, coal chemical industry, coal to olefin, separate and classified conversion technology
Pollutant control	Industrial boilers and kilns, flue gas purification, desulfurization, denitrification, dust removal, particulate control, mercury emissions
Waste treatment	Fly ash, coal gangue, coal bed methane, mine water, slime
Carbon emission reduction	Carbon capture and storage (CCS) technology, carbon capture, utilization and storage (CCUS) technology
Comprehensive utilization	Polygeneration technology

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2.2 Selection criteria of cutting-edge clean coal technologies

Having a life cycle, technology improves and progresses with time, and even produces breakthrough or subversive updates. Therefore, it is necessary to dynamically evaluate the advanced nature of current clean coal technologies to form a time-effective category for CCT. Table 2 constructs an evaluation index system for the advancement of clean coal technologies. The selection criteria for clean coal technologies are chosen from five dimensions: contribution to cleanliness, maturity, leading degree, application prospect, and breakthrough difficulty.

Table 2. Cutting-edge CCT selection index system.

Evaluation index	Index description	Reference evaluation standard
Contribution to cleanliness	Contribution to clean and efficient utilization of coal	Improve coal utilization efficiency, and reduce pollutant ratio and carbon emission ratio
Technology maturity	Technology Maturity Level	Nine levels of standards for evaluating technology maturity [10,11]
Technology leading degree	Leading degree compared with similar or previous generation technology	Technical performance evaluation parameters, technical advantage gaps
Technology application prospects	Future marketization and industrialization possibilities	Technology industrialization competitiveness, technology market demand analysis
Difficulty of technical breakthrough	Difficulty and possibility of technical realization	Time of technology realization, speed of technology progress

Note: Experts score the indicators quantitatively based on the performance of technological advancement. Large indicators with values ranging from 0 to 10 are used in the evaluation.

3 The research, judgment, and development status of key cutting-edge CCTs

3.1 Key areas and technical directions of CCT development

The development direction of global CCT has long been guided by the clean coal policies and action plans of various countries. In general, the development of global clean technology can be divided into two stages: “pollution reduction” and “carbon emission reduction.” (1) The early stage is a period of clean technology development that mainly focuses on combustion and pollutant control. The main guiding policies include the Clean Coal Technology Demonstration Program (CCTDP, 1984) and the Clean Coal Power Initiative (CCPI, 2002) of the United States; the Fifth Framework Programme for Research, FP5 (1998–2002) and the Sixth Framework Programme for Research, FP6 (2002–2006) of the European Union; and the “21st Century Coal Technology Strategic Plan” proposed by Japan in 2000. (2) In recent years, countries have paid more attention to CO_2 emission reduction and advanced power generation technologies. Among them, CCS/CCUS, integrated coal gasification combined cycle/integrated coal gasification fuel cell combined cycle (IGCC/IGFC) are the most concerned CCTs. Relevant important promotion policies include the *Clean Power Plan* and *Carbon Footprint Standards* of the United States, the European Union’s Seventh Framework Programme for Research (2007–2013) and “Energy 2020”, and the “IGFC Development Plan” formulated by Japan in 2015.

The *Ninth Five-Year Plan of CCT and the 2010 Development Outline* issued by China in 1997 is the earliest guidance document to accelerate the development of CCT in the country. During the Eleventh Five-Year Plan period, CCT was included in the National High-Tech Research and Development Program (HTRDP 863), becoming one of the themes considered in the field of energy technology. Since entering the Thirteenth Five-Year Plan, China has promulgated a number of policy plans such as the *Thirteenth Five-Year Plan for the Development of the Coal Industry*, *Opinions on Stimulating the Safe and Green Development of Coal and Its Clean and Efficient Use*, *Action Plan for Clean and Efficient Use of Coal (2015–2020)*, and *Notice of the National Energy Administration on Printing and Distributing the Thirteenth Five-Year Plan for Demonstration of the Coal Deep Processing Industry*. In addition, in 2016, the National Development and Reform Commission and the National Energy Administration jointly issued the *Action Plan for the Innovation of Energy Technology Revolution (2016–2030)*, which explicitly sets out a roadmap for the development of relevant technologies for coal mining and clean utilization in 2030. At the same time, the clean and efficient use of coal has now been included in the National Key Research and Development Program of China.

On the basis of research results of the *Development Strategy for Clean Coal Engineering Technology toward 2035* project, this study has determined 10 cutting-edge CCTs for 2035. The technological advancement scores are shown in Table 3. Based on their advanced nature, breakthrough difficulty, and application prospects (Fig. 1), the top three technologies of 700 °C ultra-supercritical coal-fired power generation, advanced IGCC/IGFC, and CCUS are determined as China's key cutting-edge CCTs for 2035.

Table 3. Cutting-edge CCTs for 2035 and their advancement scores.

No.	Cutting-edge CCTs for 2035	Advancement scores
1	700 °C ultra-supercritical power generation technology	43
2	Advanced IGCC/IGFC technology	41
3	CCUS Technology	39
4	Deep control technology of coal-fired power generation pollutants	36
5	Highly flexible smart coal-fired power generation technology	36
6	Coal-based clean fuel and chemical technology	34
7	Advanced circulating fluidized bed power generation technology	33
8	Coal classification and conversion technology	31
9	Coal conversion wastewater treatment and reuse technology	31
10	Symbiotic scarce resources recycling technology	30

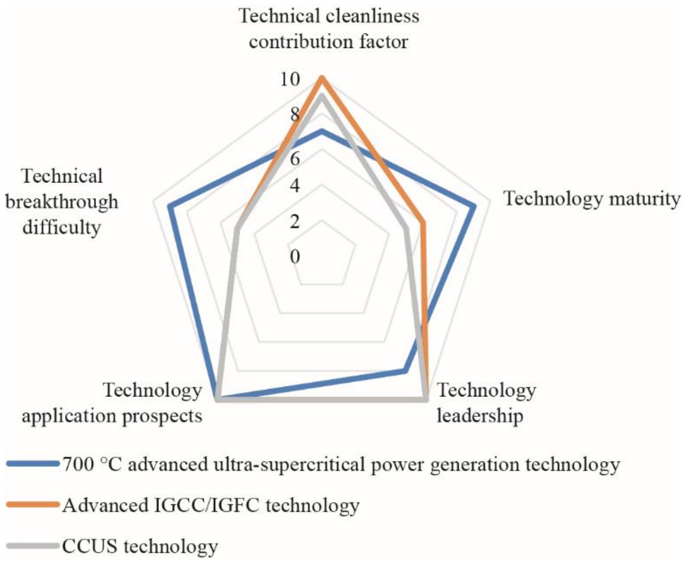

Fig. 1. The specific evaluation results of the key cutting-edge CCTs.

3.2 Development trend of cutting-edge CCTs

3.2.1 700 °C ultra-supercritical power generation technology

Ultra-supercritical power generation technology improves thermal efficiency through high temperature and high pressure. Moreover, 700 °C ultra-supercritical power generation technology refers to a unit power generation technology under the condition of 700 °C/35 MPa or above. Research shows that the efficiency can reach 50% or above if the number of reheating times is increased [12], and the economic benefit of energy-saving and emission reduction is six times that of 600 °C ultra-supercritical technology [13]. The technology can also reduce the cost of CO_2 capture and help improve the application of CCUS technology.

As early as the late 1990s, the United States and the European Union proposed 700 °C advanced ultra-supercritical coal-fired power generation programs based on the existing 600 °C ultra-supercritical power generation technology such as the European Union's "AD700" Advanced Ultra-Supercritical Power Generation Program and the United States' Ultra-Supercritical Coal-fired Generating Unit Boiler Materials and Steam Turbine Program. These programs have made major breakthroughs in the research and development of high-temperature materials for boilers and steam turbines, processing performance testing, and key component testing [14]. However, the progress in the construction of demonstration power plants has not been smooth. So far, no 700 °C ultra-supercritical coal-fired demonstration power plants have been built in the world.

China is the country with the largest number of 600℃ ultra-supercritical units in operation worldwide, and it also pays attention to the innovative development of 700 °C ultra-supercritical coal-fired power generation technology. To this end, China established an innovation alliance in 2010, and set up a key equipment R&D and

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application demonstration project in 2011. The first test platform for 700 °C key components was successfully put into operation in December 2015.

3.2.2 Advanced IGCC/IGFC technology

IGCC/IGFC power generation technology is regarded as a disruptive clean coal utilization technology to realize the clean utilization of coal-fired power generation with near-zero emissions. With the power supply efficiency expected to reach more than 60%, the technology greatly reduces coal consumption. Once a breakthrough is made, it will become a CCT of revolutionary significance.

With a process of producing electricity through gas-steam combined cycle power generation after coal gasification to syngas, IGCC is considered to be one of the promising clean coal power generation technologies. The United States, Japan, the Netherlands, and Spain have successively built IGCC demonstration power plants. In November 2012, China Huaneng Tianjin 250 MW IGCC demonstration unit was put into commercial operation. The demonstration power plant is China's first self-developed, designed, constructed, and operated IGCC demonstration project. It has achieved a dust and SO_2 emission concentration of less than 1 mg/Nm^3 and NO_x emission concentration of less than 50 mg/Nm^3. The emissions have reached the level of natural gas power generation, and the power generation efficiency is 4% to 6% higher than the conventional power generation technology with the same capacity [5].

IGFC is a high-temperature fuel cell power generation system using gasified gas as fuel, including solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). It has the advantages of IGCC technology, and its efficiency can reach more than 60%. Different from IGCC's physical combustion power generation method, IGFC uses fuel cells to directly generate electricity, and conducts the technical leap of coal-based power generation from pure thermal power generation to combined electrochemical and thermal power generation. Its coal power efficiency can theoretically be doubled, and it also has the advantage of reducing CO_2 capture costs and achieving near-zero emissions of CO_2 and pollutants.

Currently, the high-temperature fuel cell technology represented by SOFC is developing rapidly, and the commercial application of the fuel cell industry in the United States and Japan is at the forefront of the world. In 2010, Bloom Energy in the United States manufactured the world's first commercial SOFC product (ES-5000 Bloom Energy Server) with a power of 100 kW. In 2017, Mitsubishi Heavy Industries of Japan launched a commercial product of a hybrid system codenamed Hybrid-FC combining 250 kW SOFC and micro gas turbines with an overall system efficiency of 65%. China also attaches great importance to the development of high-temperature fuel cell technology. With the support of the National Key Research and Development Program, China has carried out research on stacks of high-temperature fuel cell, power generation systems and related basic scientific issues. In 2017, China launched the national key R&D project of "Coal Gasification Power Generation Technology with Near-Zero Emission of CO_2," which led China to deploy IGFC related technology R&D and conduct the world's earliest IGFC power generation system platform demonstration.

3.2.3 CCUS technology

CCUS technology purifies CO_2 emitted during the production process, and then incorporates it into the new production process for recycling. An upgrade of CCS technology, CCUS technology reuses CO_2. Cutting-edge technologies include advanced CO_2 capture technology; geological, chemical, biological, and mineralization technologies for CO_2 utilization; and key technologies for CO_2 geological sequestration [15].

In recent years, countries around the world are actively accelerating the development and application of CCUS technology. In 2018, Petra Nova's carbon capture and sequestration power plant (installed capacity of 240 MW, annual reduction of 1×10^6 t CO_2) was officially put into operation in the United States, becoming the first commercial power plant to achieve carbon reduction. In the same year, the United States proposed a preferential policy of a tax credit of USD 50/t for CO_2 capture and sequestration and USD 35/t for CO_2 oil displacement and sequestration to stimulate the development of CCUS technology. Regarding the clean and efficient conversion and utilization of CO_2, Germany has made certain progress in the technical direction of solid oxide electrolysis cells (SOEC). Its technical solution is to use renewable energy power to electrolyze water and CO_2 to produce syngas, natural gas, and liquid fuel. China also attaches great importance to low-carbon technology and continuously accelerates the CCUS demonstration project. For example, Shaanxi Yanchang Petroleum (Group) Co., Ltd. launched an integrated demonstration of Yanchang Petroleum 3.6×10^5 t/a CO_2 capture, pipeline transportation, oil displacement, and sequestration in 2017; China Resources Power (Haifeng) Co., Ltd. started the construction of a carbon capture test platform in 2018, and the Shenhua Guohua Jinjie Power Plant set up a 1.5×10^5 t/a CO_2 capture facility [5]. In summary, though countries around the world have made progress in CO_2 capture, oil displacement, sequestration, and utilization, commercialization remains difficult.

4 Strategic objectives and main tasks of China's 2035 CCT development

4.1 Development strategy and goal of CCT in China

Coal is China's primary energy source and an important industrial raw material. Driving clean and efficient use of coal, based on CCT innovation, will be an essential measure to ensure China's energy security and sustainable development of the energy industry. The development of CCT relies on technological innovation to achieve breakthrough developments in improving coal power generation efficiency, enhancing upgrading demonstration of modern coal chemical industry, ultra-low emissions of coal-fired pollutants, CO_2 reduction, and comprehensive utilization of coal resources. To achieve the goals of high efficiency, energy conservation, and low pollution, the development of clean, low-carbon, and efficient power generation technology is the core of coal utilization. The research and development of modern coal chemical technology is the focus of coal conversion.

By 2035, a technical system for clean and efficient use of coal will be fully established. The proportion of concentrated and efficient coal utilization will increase to more than 90%; coal-fired power generation and ultra-low emission technologies will reach the international leading level. The demonstration of a 900 MW-level IGCC power generation system and a 100 MW-level IGFC power generation system will be completed, and the power generation efficiency will reach 60% with near-zero emissions of pollutants and a CO_2 capture rate of more than 95%. See Fig. 2 for the details about China's CCT development strategy goal and technology roadmap for 2035. In this technology roadmap, advanced power generation focuses on the development of 700 °C ultra-supercritical power generation, IGCC/IGFC, and CCUS technology; coal conversion focuses on the development of advanced coal deep processing technology.

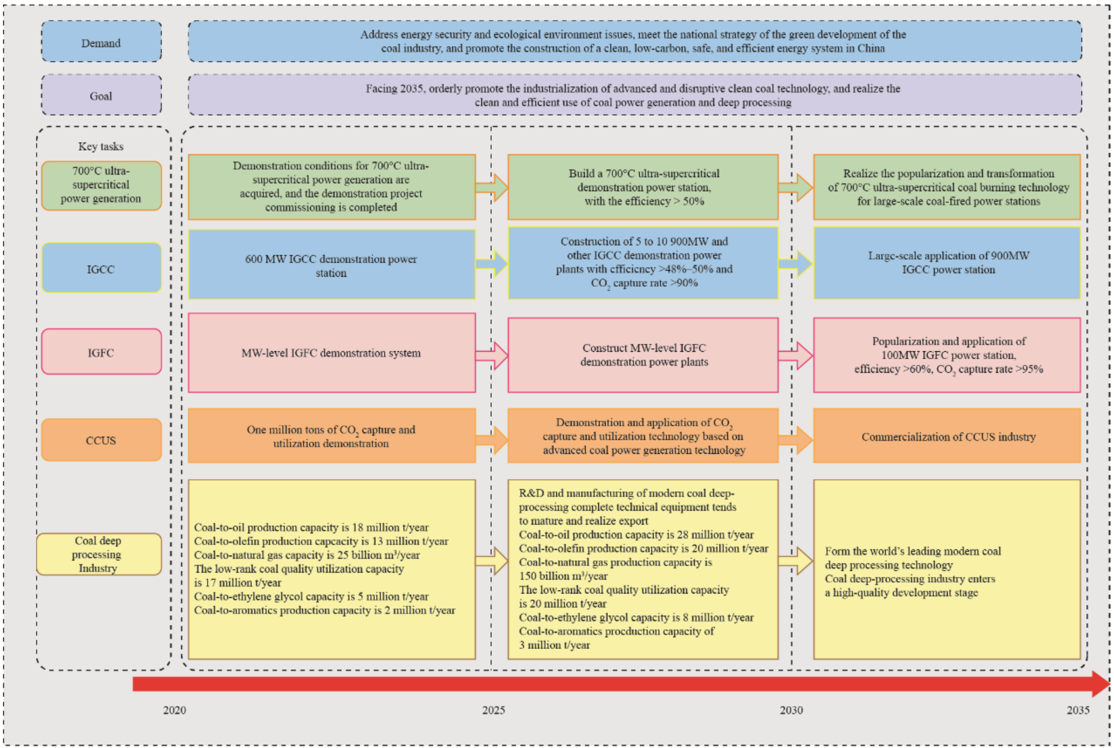

Fig. 2. Development goal and technology road map of CCTs toward 2035.

4.2 Strategic tasks and implementation paths of China's CCT

4.2.1 Constantly improve the efficiency of coal-fired power generation and gradually achieve near-zero emissions of coal-fired pollutants

Accelerate the optimization of the coal consumption structure by increasing the proportion of coal consumption for power generation and substantially reducing the usage of industrial coal and civil bulk coal to make coal-fired power generation the main coal-consuming field. The full implementation of ultra-low emissions from coal-fired power plants is an important measure to increase the clean utilization of coal and improve the quality of the

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atmospheric environment and is a key factor for the sustainable development of coal power. It is also important to comprehensively implement the energy-saving and ultra-low-emission upgrading and transformation of coal-fired power plants, and resolutely eliminate and shut down coal-fired units with backward production capacity failing to meet the requirements of relevant mandatory standards. By 2035, the proportion of coal used for power generation (combustion + fuel cell) and the efficiency of coal power generation will be further improved. The power generation of coal power units with ultra-low pollutant emissions and of IGFC fuel cells with near-zero emissions will account for more than 90% of the country's coal power generation (coal power units with ultra-low pollutant emissions will account for 80% of coal-fired power generation), eliminating the use of bulk coal and small boilers.

4.2.2 Increase the upgrading demonstration of the coal deep processing industry

Specifically, China should further improve modern coal deep processing technologies for high-efficiency, low-consumption, and low-cost coal-based fuels and chemicals and realize their industrial application. It should develop technologies for integrated process equipment for coal-fired pollutant purification with independent intellectual property rights to achieve safe and efficient treatment of chemical coal wastewater; develop the coupling integration technologies of coal chemical industry and oil refining, petrochemical, power generation, renewable energy, and fuel cells and complete industrial demonstrations; and accelerate the formation of markets for energy and chemical products, such as natural gas, ethylene glycol, ultra-clean oil products, special oil products in aerospace and military, basic chemicals, and specialty and fine chemicals.

The R&D and upgrading demonstration of technical equipment should be accelerated in the coal deep processing industry. The main contents include: (1) raise the coal indirect liquefaction capacity, implement energy cascade utilization, and continue to develop special oil products for aerospace and military use; (2) establish the demonstration project of coal indirect liquefaction in million tons, and develop new processes, catalysts, and high-temperature Fischer-Tropsch process to accelerate the commercial promotion of lubricants, liquid waxes, and olefins; (3) develop coal-based chemicals such as coal-based olefins, coal-based glycols, and coal-based aromatics, and achieve high-end as well as differentiated development of products with new process technologies, equipment, and catalysts; (4) optimize the established coal-to-natural gas demonstration project, increase the development of complete methanation process technology, equipment, and catalysts with independent intellectual property rights, and improve the capability of continuous, stable, and clean production in high-load conditions; (5) strengthen the low-rank coal classification and utilization and water treatment technology R&D and demonstration, further optimize the pyrolysis technology processes and equipment of low-rank coal, overcome the difficulty in gas–solid–liquid separation, and improve tar quality, reasonable and efficient use of semi-coke, and technologies such as tar processing extension; and (6) improve R&D and demonstration of common technologies of coal deep processing in terms of large-scale air separation, gasification, advanced water saving, environmental protection, and recycling.

4.2.3 Actively increase the development of CO_2 capture, utilization, and sequestration industries

To promote the commercialization and application of CCUS, several frontier technologies should be developed including a new generation of CO_2 absorbents and capture materials with high efficiency and low energy consumption, large-scale transportation and CCS technologies of CO_2, pressurized oxygen-enriched combustion, and oil/gas/water/heat production using CO_2. Research on applied technologies should be strengthened such as deep integration of power plants and capture end, development of high-parameter and high-throughput equipment, and long-term monitoring of geological sequestration. The collaborative R&D of CCUS technologies with advanced power generation technologies such as coal gasification power generation technologies with a near-zero emission of CO_2 (mainly IGCC and IGFC) should be improved. CO_2 capture and sequestration should be considered as the key content of the demonstration construction of clean coal power generation. Cutting-edge technologies for CO_2 utilization should be further developed such as CO_2 crude oil displacement technology, SOEC synthesis gas production, and CO_2 reforming coal (semi-coke) CO production technology to accelerate the industrialization of CO_2 utilization.

4.2.4 Strengthen basic research and technological breakthroughs in disruptive technologies

China should increase basic research and technological breakthroughs on 700 °C advanced ultra-supercritical power generation technology and IGCC/IGFC coal clean power generation technology, and focus on system design optimization including the overall design of power plants as well as the overall design of boilers and steam turbines; research and development of high-temperature heat-resistant alloy materials, particularly high-temperature materials with independent intellectual property rights and key components of the host machine, to realize large-scale commercial application of ultra-supercritical power generation technologies.

The research focus of IGCC's breakthrough technologies includes: advanced coal gasification technology suitable for different coal types, serialization, and large capacity; F-level and H-level gas turbine technology suitable for IGCC; low-energy-consumption oxygen production technology; and gas-sensible heat recovery and utilization technology. Meanwhile, China can master and improve the IGCC system integration technology through efficient and low-cost IGCC industrial demonstration, thus to reduce cost and accumulate actual experience in operation, maintenance, and management of an IGCC power plant.

To further improve the efficiency of IGCC and the economy of CO_2 capture, it is necessary to focus on the development of large-scale IGFC disruptive coal power generation technologies, namely integrated gasification molten carbonate fuel cells (IG-MCFC) and integrated gasification solid oxide fuel cells (IG-SOFC). IG-MCFC should focus on the design and manufacturing technology of large-area MCFC key components, large-capacity battery stack assembly and sintering operation technology, CO_2 membrane gas separation technology, and IG-MCFC system integration technology; IG-SOFC should focus on gasification fuel SOFC power generation technology, oxygenator membrane oxygen supply technology, SOEC electrolysis technology, and IG-SOFC system integration and optimization technology. By 2035, the MW-level industrialization of IGFC power plants can be realized, and the manufacturing capacity of MW-level fuel cells (SOFC, MCFC) and IGFC power plants of the entire industrial chain can be achieved.

4.2.5 Establish major engineering science and technology projects of IGCC/IGFC

To improve the efficiency of coal power generation, achieve near-zero emissions from coal power generation, and drive the industrialization of coal gasification power generation polygeneration, the major key technologies in the new generation of IGCC and IGFC engineering technologies should be developed to further improve the efficiency of coal power generation. The coal gasification power generation technology with near-zero emissions should be prioritized. The independent R&D capabilities of processes, systems, equipment, materials, and platforms should be comprehensively enhanced in the field of clean and efficient utilization of coal gasification power generation, to make major original achievements in basic theoretical research and realize industrial application demonstration, thereby providing technical support for the polygeneration industrialization of coal gasification power generation.

5 Countermeasures and suggestions for the development of CCTs in China

Over the next 20 years, China will continue to be a major country in the development and utilization of coal resources worldwide, but the proportion of coal in the energy consumption structure will continue to decrease, the total coal consumption will enter a plateau, and coal-fired power generation will become the main coal-consuming field. Restricted by multiple factors, such as uneven development of CCTs among regions and companies, shortcomings in independent innovation capability of core technologies, imperfect management mechanism, and policy environment, and the need to strengthen technology investments and talent training, China has not yet achieved clean and efficient coal utilization. However, it has achieved a world-leading level of R&D, equipment manufacturing, and engineering demonstration of some CCTs. Especially in the industrialization of 700 °C ultra-supercritical power generation technology, advanced IGCC/IGFC technology, CCUS technology, and coal deep processing technology, China has had certain international competitiveness. Therefore, it is critical to focus on the development of cutting-edge clean coal technologies for 2035.

5.1 Accelerate the adjustment of coal consumption structures and industries and plan for long-term development of CCTs and coal industries

Strengthen the top-level design of the national medium- and long-term coal development, maintain the continuity and effectiveness of CCT-related policies, and regulate the periodicity of technological innovation and coordinated management of coal energy policies. Fiscal and taxation policies need to be tilted toward the optimization of coal consumption structures and energy efficiency. Conduct research on supporting laws, regulations, policies, and environmental protection incentive mechanisms for clean and efficient use of coal and establish sound market incentives to guide companies to preferentially develop and use advanced CCTs. Continue to improve the efficiency of coal used in power generation, and gradually control the emission of pollutants from coal-fired power generation from ultra-low emissions into an era of near zero emissions.

Establish industry technology selection standards for clean and efficient use of industry coal, develop alternative coal banks for CCTs, feasibility evaluation specifications and subsidy standards for coal utilization and conversion efficiency, pollutant emissions, and carbon emissions, and realize the sustainable, reliable, standard,

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and economic operation of CCT power generation with standardized technology management. Based on the policy guidance of carbon market transactions and carbon emissions, transfer the cost of CCUS technology to the final consumer to improve the economic feasibility of CCUS technology. Actively guide advanced coal chemical industry, coal quality classification and utilization, and study technologies such as "coal-to-hydrogen" and "coal-based fuel cell power generation" to provide the possibility of full-scale coal utilization in the future.

5.2 Prioritize the development of a coal deep processing technology route adapted to national conditions and scientifically deploy the modern coal chemical industry

Improve the quality of coal used for deep processing and reduce the proportion of coal used for fuel; prioritize the development of coal grading and utilization technologies that suit China's national conditions; conduct in-depth research on the suitability of coal property and gasifiers; and carry out key technology research such as low-rank coal upgrading, coal gasification, and new catalysts.

Establish an evaluation system for the rational layout of the modern coal chemical industry, carry out a comprehensive evaluation of technical schemes for completed demonstration projects of coal-to-oil, coal-to-olefins and coal-to-gas technologies, optimize deep processing technologies and industrial development paths, and eliminate outdated coal chemical projects with high pollution and low efficiency. Coordinate local governments to strengthen supervision and improve modern coal chemical standards and environmental approval processes. Carry out scientific evaluation of coal chemical technology, equipment R&D and demonstration with independent intellectual property rights, conduct the analysis of the export potential of complete sets of technical equipment, drive the coal deep processing industry to "go global," and develop foreign coal resources and markets.

5.3 Actively deploy disruptive technology R&D and project demonstration relying on major scientific research projects

Strengthen policy support for R&D of CCTs, such as clean and efficient coal-fired power generation, low pollutant emissions, and carbon emission reduction, and clarify key development directions for clean and efficient coal conversion and utilization technologies, and encourage companies and research institutions to jointly develop clean and efficient coal power generation technologies and engineering demonstration. Accelerate the development and demonstration of advanced technologies, such as ultra-low emissions of coal-fired power plants, IGCC/IGFC, 700 °C ultra-supercritical, and CCUS, and provide support in industrial policies.

Set up a special fund for the development of CCTs to focus on a number of fundamental issues that restrict the clean utilization of coal and low-carbon conversion. Develop a national CCT R&D list, formulate reasonable R&D goals and phased implementation R&D plans, guide companies to strengthen CCT R&D, and formulate support and incentive policies for CCT R&D based on technology development and equipment R&D laws.

5.4 Improve the clean and efficient utilization of coal throughout the industry chain, and strengthen the talent system to guarantee for technical innovation

Develop a model for the precise development and utilization of coal resources based on green coal resources and formulate industry technical standards for evaluation of green coal resources. By increasing the base of coal resources and the proportion of production in green mining areas, improve the quality of coal used in the entire industrial chain and the level of clean and efficient utilization of coal in China starting from the input side. Ensure the clean use of the back-end through the safe and efficient development of the front-end green coal resources and the washing and processing [16]. Explore an optimized route for the development of the coal industry that relies on the advantages of coal resources, reduces the clean coal utilization costs, and lowers the environmental impact of coal development, utilization, or conversion.

Strengthen the self-cultivation of CCT innovation talents and set up a training channel for clean coal engineering talents with a continuous undergraduate–master–doctorate education background and inter-disciplinary knowledge through industry, enterprise, and college cooperation. To adapt to the development needs of coal emerging industries led by technological innovation, colleges and universities with coal background are encouraged to set up professional directions related to basic engineering R&D of clean and efficient coal use and scientific research management and adopt preferential admission and tuition reduction policies. Give full play to the main role and advantages of resource concentration of large companies in the development, application, and promotion of CCTs, and encourage them to cooperate with colleges and universities to jointly train professional and technical personnel in the field of clean coal for relevant companies.

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