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Preliminary Discussion on the Technology Roadmap of Clean Coal Combustion in China

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Abstract: Owing to the urgent need to prevent and control pollution, China needs to accelerate the development of clean coal combustion technologies. However, research relating to technology roadmaps of clean coal combustion in China is lacking. This paper briefly introduces the main features of the coal utilization structure in China, and the significance of developing clean coal combustion technologies. Focusing on six types of clean coal combustion technologies, strategic ideologies and targets are discussed, together with the current status in China and abroad, future technical directions, major fields, and key technologies. A technology roadmap for clean coal combustion in China before 2050 is then provided together with relevant policy recommendations. Results indicate that to reduce dispersed coal-burning pollution in the near future, China must accelerate the application of new circulating fluidized bed technologies in small and medium-sized coal-fired industrial boilers and popularize a batch of high-quality briquettes and advanced stoves in the field of residential coal combustion, whereas in the long term, the government must strengthen planning and guidance to increase the proportion of coal used in clean and efficient centralized power generation, and continue to research and develop green coal power generation technologies and associated systems for future use.

Keywords: clean coal combustion; technology roadmap; ultra-supercritical unit; circulating fluidized bed; pollution control

1 Introduction

1.1 Features of coal usage in China

According to coal equivalent calculations, coal accounted for 62% of China's total primary energy consumption and 69.8% of China's total primary energy production in 2016. In developed nations such as the U.S. and in Europe, centralized large-scale power generation is the dominant mode of coal usage (dominant meaning 75% or more), whereas coal usage is much more diverse in China. Fig. 1 illustrates the structure of coal use in China in 2016 [1]: 57.4% was used to generate centralized power/heat (52% for power generation and 6.4% for heat generation), 33% was employed in industry and construction to fire industrial boilers and furnaces (approximately 17%) and as coking coal in steel production (approximately 16%), and the remaining 8.6% was used as fuels in household applications, mainly by rural households. In general, coal in China is used dominantly in

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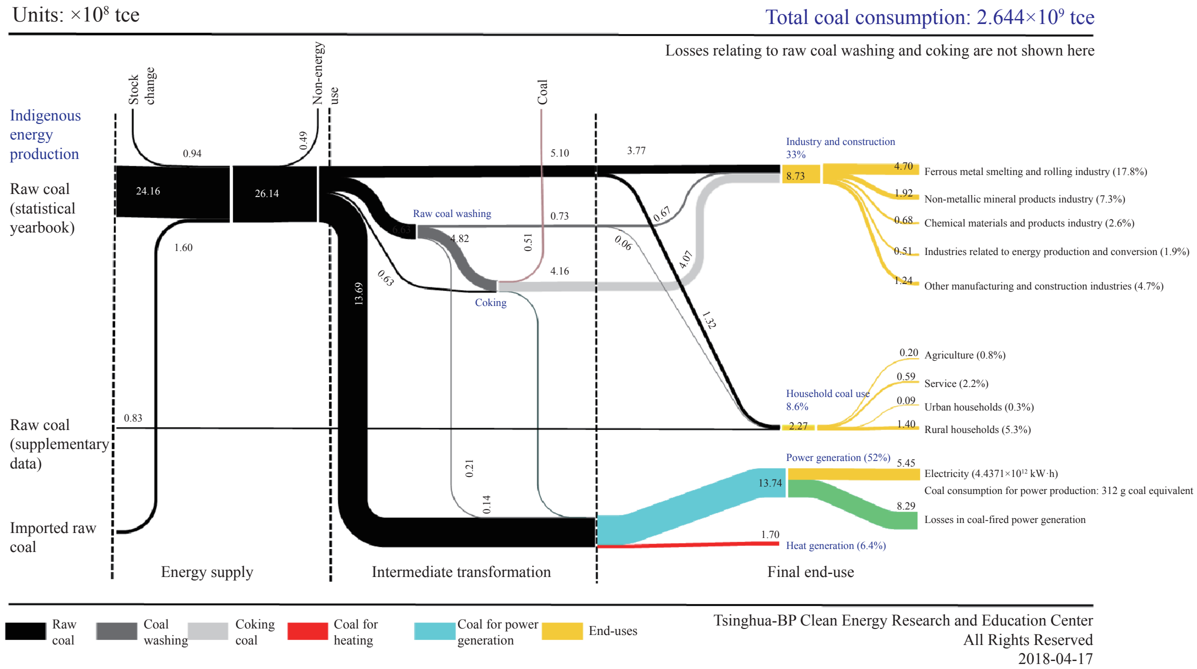

Fig. 1. The energy allocation Sankey diagram of coal usage in China in 2016.

combustion (more than 80%), but when not used in centralized power generation, a significant proportion is used in a dispersed manner in industrial and household applications.

1.2 Importance of clean coal combustion technologies

Severe air pollution in China has catalyzed "decoalification" trends in Chinese society. Furthermore, in accordance with environmental protection strategies, China has long-term plans to impose stringent controls on the scale of coal usage and reduce the proportion of coal used in its primary energy mix. For example, the National Energy Administration (NEA) and National Development and Reform Commission (NDRC) have proposed that non-fossil fuel sources should account for more than 50% of China's primary energy mix in 2050 [2], and Dai et al. [3] have projected that to reshape China's energy sector, non-fossil fuel sources will account for 55% of the energy mix by 2050, while the proportion relating to coal will decrease to 20.1% (according to coal equivalent calculations).

However, objective analysis needs to recognize that coal will continue to dominate energy production in China in the short-to-medium term, and an excessive focus on "decoalification" will cause significant harm to securing basic energy supplies such as electricity and heating. Therefore, with respect to China's domestic conditions, it is necessary to develop cleaner coal combustion technologies in the short-to-medium term. During the Central Economic Work Conference (CEWC) in 2015, General Secretary Xi Jinping stated, "We are currently reducing the proportion of coal (in the energy mix), but China is still a coal country. For a long period of time, even in the long-term, coal will continue to dominate our energy structure; it is just its proportion that will decrease. We will not shift our attention away from coal. Instead, we should consider how to optimally use coal, and focus on the use of new technologies to solve the clean coal combustion problem" [4]. In addition, the Chinese Academy of Engineering has published the *Strategic Research on Promoting Energy Revolution of Production and Consumption*, which proposes that the proportion of coal will be reduced to approximately 40% by 2050 [5], and this figure considers China's energy security needs.

2 Research methods

Technology roadmaps are tools widely utilized globally to support the development and implementation of strategic plans [6]. In recent years, technology roadmaps have been broadly applied in various fields, including the formulation of company strategies [7], scientific innovations [8], energy planning [9], and urban planning [10]. The International Energy Agency (IEA) published a guide for technology roadmaps in 2014 [11] and stated that roadmaps can delineate inter-task relationships and near-term, medium-term, and long-term focal points for action. A well-designed technology roadmap can describe the objectives, milestones, gaps, barriers, action items, priorities, and timeline of a plan. Therefore, five-year plans and strategic plans for technological development in China can also be regarded as technology roadmaps with Chinese characteristics, as they generally include a description of the plan's current problems, strategies, strategic objectives and tasks, and safeguarding measures.

However, relatively few studies have been conducted on developing technology roadmaps for clean coal combustion, both in China and internationally. To compensate for this and enable formulation of a technology roadmap for clean coal combustion, numerous Chinese experts in clean coal combustion participated in the project entitled "Research on the Directions and Roadmap of Clean Coal Technology Developments" (sub-topic No. 6 of the "Strategic Research about Technology Directions and Systems for the Energy Technology Revolution of China" consultation project of the Chinese Academy of Engineering) from January 2015 to November 2017. The following contents about the strategic ideas and strategic objectives, current state of technological developments in China and abroad, future technology directions, priority areas, and key technologies for clean coal combustion in China are presented here with respect to the results of the project.

3 Results

3.1 Strategic ideas and strategic objectives

China's strategic ideas and objectives for the development of clean coal combustion technologies include: first, absorbing international experiences, to maximize coal use for large-scale power generation to facilitate the implementation of clean coal combustion; and at the same time, considering China's specific conditions and national policies, to account the use of energy-efficient, clean and cost-efficient technologies in small-to-medium coal combustion equipment as an important priority.

The strategic ideas and objectives are based on both China's domestic conditions and the experiences of developed countries, such as the U.S. and countries in Europe, where coal is mainly used in large-scale power production. Historical efforts to improve the environmental friendliness of the coal power generation industry in recent years have greatly reduced its atmospheric emissions, and the primary focus of coal-related environmental work in China has now shifted towards coal use in manufacturing industries and household applications.

3.2 Current status quo of technological developments in China and internationally

The current status of technological developments in China and internationally (as of October 2016) in six clean coal combustion-related technologies are summarized in the following paragraphs.

(1) Coal-fired Industrial Boilers: 85% of all coal-fired industrial boilers in China are chain grate boilers, which have low average single-furnace capacities. In addition, the overall technological level and operational efficiency of industrial boilers in China is poor, and their average heat efficiency is only 60%–65%, which is 20% lower than international advanced levels. Furthermore, there is a lack of associated effective pollutant control measures for such boilers.

(2) Household Coal Use (primary production, tertiary production, and household usage): The technological foundations in this respect are very weak in China, and it is difficult to obtain consistent data relating to scattered coal usage.

(3) Ultra-Supercritical (USC) Technologies: The 600 °C single-reheat USC units of China are among the best in the world in terms of coal consumption per unit of electricity and power generation efficiency. There are only twenty-five 600 °C double-reheat USC units in the world, and six of these are operating in China. However, only one 650 °C USC unit, the SKR-100, exists in the world, and this was developed in Russia. Furthermore, 700 °C USC power plants are now under development, and China has already begun working on this technology.

(4) Pollutant Control Technologies for Coal Power Generation: With respect to air pollution management and control, China is already internationally advanced and is a world leader in certain aspects. In terms of wastewater management, China is generally close to the level of developed countries but lags behind in zero wastewater discharge technologies, particularly in relation to the discharge of desulfurization wastewaters. With respect to solid waste management, China has reached internationally advanced level in terms of the large-scale comprehensive utilization of fly ash and the desulfurization of gypsum, but is behind in high value-added usage.

(5) Water-Saving Technologies for Coal Power Generation: Water recovery from lignite is being developed and piloted in China and internationally. More than 10 thermal power units in China that are currently piloting this technology. With respect to water recovery from flue gas, condensate recovery is already being used in operations at the Karlskoga thermal power station in Sweden, and design works have begun for the construction of four 660 MW USC power stations in China. Membrane-based water recovery technology has achieved commercial application in gas-fired power plants outside of China but is still under development within the country.

(6) Carbon Capture and Storage (CCS) / Carbon Capture, Utilization and Storage (CCUS) Technologies: Development CCS and CCUS technologies is currently at different stages in various countries, and the focus is scattered between theoretical research, experimental research, and industrial and small-scale commercial application, as these technologies are only economically viable under certain conditions. The development of CO_2 pipelines and chemical looping combustion technologies in China is behind that of developed countries, such as the U.S.

In summary, China has reached an internationally advanced level (and is a world-leader in some respects) in USC technologies, water-saving technologies for coal power generation, and the management of waste from coal power generation, although further improvement or development in certain aspects is still required. However, there is a sizeable gap between China and other advanced nations in the development of coal-fired industrial boilers, household coal use, and CCS/CCUS technologies.

3.3 Future technology directions

Based on the above status quo and technological needs of China, we propose the following technology directions for future clean coal combustion developments:

(1) Coal-Fired Industrial Boilers: The development trend for coal-fired industrial boilers should lean towards larger boiler sizes and intellectualization to realize higher levels of automation. Relevant industries should be encouraged to use clean and efficient technologies such as energy-saving, low-emission, circulating, fluidized, bed boilers and stoker-fed boilers with integrated flue gas desulfurization/dedusting/denitrification systems. The coal consumption of industrial boilers should also be reduced through the substitution of coal with gas/electricity, waste heat utilization, and waste reuse.

(2) Household Coal Use: The intensive production, sale, and use of high-quality/clean coal briquettes should be extensively promoted. Centralized production and delivery systems should be developed, such as coal production and delivery centers, supply networks, delivery systems for agricultural villages, and supply platforms for advanced household coal-fired stoves. In addition, the use of decoupling combustion technology in household applications should be encouraged, and the substitution of coal with gas, electricity, and renewable energies should be promoted in accordance with local conditions.

(3) USC Technologies: The development, refinement, and propagation of 600 °C/610 °C/620 °C 1000 MW USC double-reheat units should be continued, and the development and application of elevated turbine generator (T-G) unit technologies for 600 °C USC double-reheat units should be accelerated. In addition, research and piloting works for 650 °C thermal power plants should be initiated as soon as possible, to enable their propagation and application in a timely manner. Heat resistant alloys for 700 °C USC power plants should be developed, and experimental validation should be performed on the key components of these power plants. The development of primary and auxiliary equipment for 700 °C USC steam turbines should be prioritized to enable the piloting of 700 °C USC power plants and to gain a full understanding of 700 °C USC steam turbine technology.

(4) Pollutant Control Technologies for Coal Power Generation: New pollutant control technologies with higher levels of performance and cost efficiency should be developed for waste management, as should multi-pollutant control technologies. In addition, "conventional processing + preprocessing + evaporative crystallization" technologies for desulfurization wastewaters should be developed for wastewater management. In the management of solid waste, the use of desulfurization gypsum to improve soil should be promoted (200 000 acres have already been successfully improved using this approach), as well as the use of high-alumina fly ash to produce aluminum oxide. Refined applications for desulfurization gypsum and fly ash should be developed to enable the production of high value-added products.

(5) Water-Saving Technologies for Coal Power Generation: Mature technologies, such as dry ash handling, dry slag handling, and auxiliary air-cooling, should be applied broadly in air-cooled power plants. In addition, lignite and flue gas water removal technology should be piloted in 600 MW steam turbine power plants to facilitate their propagation.

(6) CCS/CCUS Technologies: The development and piloting of CCS/CCUS technologies should continue. Furthermore, the development of CO_2 pipeline networks should be accelerated, as should the construction of industrial demonstration projects with regional source-to-sink matching.

3.4 Priority areas and key technologies

Based on the China's current socioeconomic development trends, priority areas for the above-mentioned technology directions are as follows. (1) Optimization of coal end-use: based on controlling coal usage scales in industrial coal-fired boilers and household coal use, rapid and substantial improvements should be made in the energy efficiency of industrial coal-fired boilers and associated emissions, and in coal quality and the technological level of household coal use. (2) Increasing the efficiency of coal power generation: the development of high-efficiency USC technologies should be used to drive improvements in the efficiency of coal power generation. (3) Flexible peak shaving for coal power generation: the peak shaving problem in power generation should be mitigated to some extent without compromising boiler combustion efficiency. (4) The development of green coal technology: ultra-low emissions from coal-fired power plants, near-zero wastewater discharge, and comprehensive solid waste utilization should be implemented, and the application of water-saving technologies in coal power generation should be promoted. Research on low-carbon coal power generation technologies should also be strengthened.

The key technologies required for these priority areas are as follows: (1) advanced coal-fired industrial boilers, and high-quality/clean coal briquettes and stoves for household usage; (2) the development and demonstration of double-reheat USC technology, elevated T-G unit technology, and 650 °C/700 °C USC steam turbines; (3) technologies for decoupled heat and electricity production and power plant optimization; (4) water-saving technology, ultra-low emissions technology, zero wastewater discharge, and large-scale solid waste reuse technology for coal power generation; (5) the construction of CO_2 pipeline networks and CCS/CCUS technologies; and (6) system integration improvements and the development of next-generation coal power generation technologies that have near-zero carbon emissions and are clean, energy efficient, and resource efficient.

4 Technology roadmap

Based on the information presented above, a technology roadmap was formulated for clean coal combustion technologies up to 2050, as shown in Fig. 2. The underlying principles behind this roadmap are to advance research and development, demonstration and deployment, and commercialization of key technologies associated with the four above-mentioned priority areas in a stage-by-stage manner. In addition, basic research on next-generation, near-zero emissions, clean, efficient, and water-saving coal power technologies that combine CCS/CCUS, flexible peak shaving, and other advanced technologies should be strengthened, and should begin as soon as possible to enable realization of disruptive coal power technologies by 2050.

5 Suggestions for implementation of technology roadmap

This study proposes five strategies to assist in implementing the technology roadmap shown in Fig. 2, and these are presented as follows:

(1) To reduce "coal animosity" and avoid the potential danger of public demands for "decoalification", work should be conducted to raise awareness and inform society that the use of coal is important for meeting the energy security needs of China.

(2) Governmental planning and guidance should be used to increase the proportion of coal used in centralized electricity and heat production. The objectives of China's five-year plans should ensure that coal use via centralized electricity and heat production accounts for a minimum of 65% of China's total coal consumption by 2030, and 75% by 2050, thus reducing pollution through the optimization of coal usage.

(3) New circulating fluidized bed technologies should be used in small-to-medium sized coal-fired industrial boilers as this would reduce the amount of pollution caused by industrial coal usage. Application of this simple engineering measure would "clean" coal-fired industrial boilers (particularly boilers with capacities below 100 t/h) in a reliable manner and mitigate the need for stringent monitoring demands or changes in coal rank.

(4) The use of high-quality coal briquettes and specialized

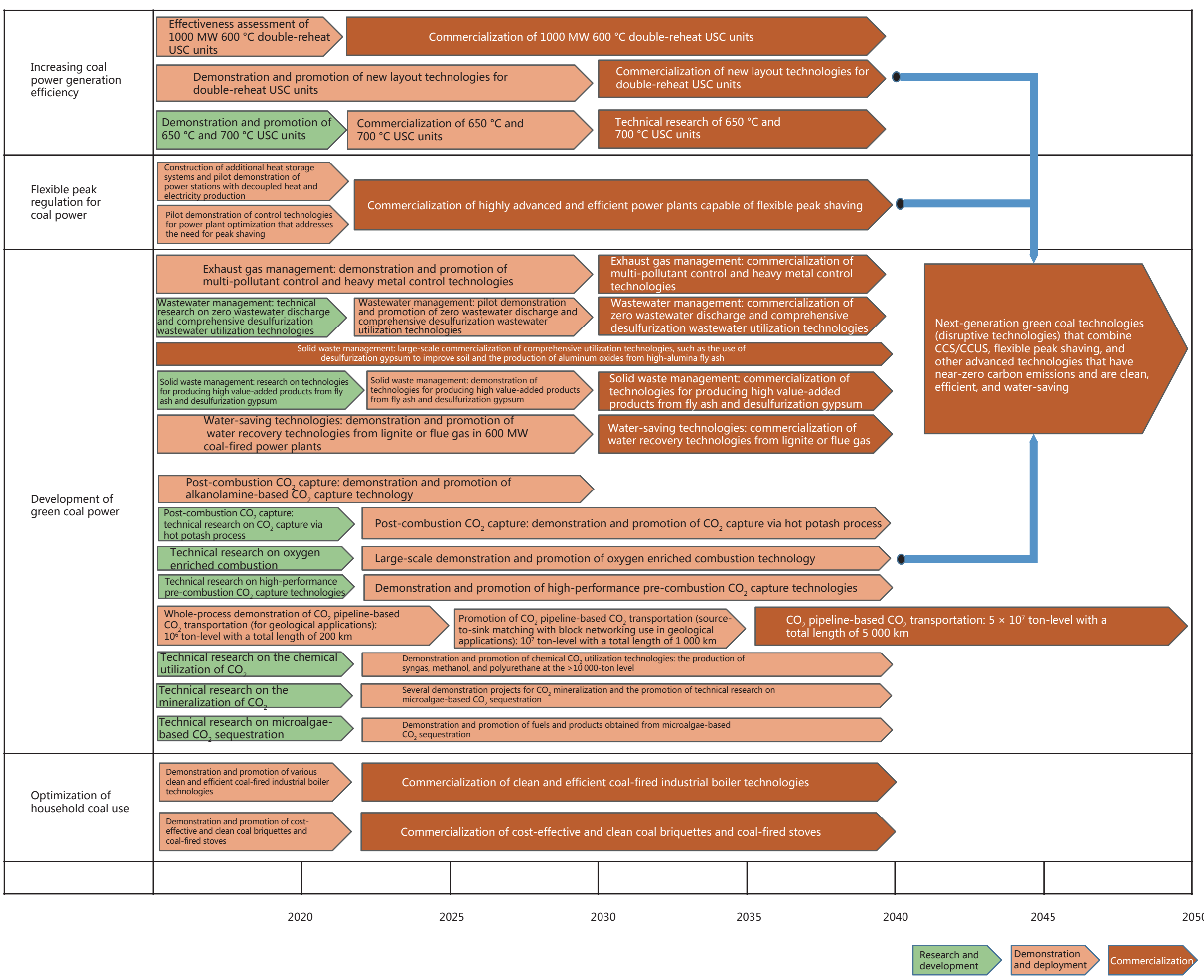

Fig. 2. Technology roadmap for clean coal combustion technologies up to 2050.

coal-fired stoves should be promoted for household coal usage, as this will reduce the amount of pollutants released in this mode of burning coal.

(5) Basic research on disruptive and forward-looking green coal power technologies should be prioritized and accelerated and national key technology R&D programs should be launched.

6 Conclusion and outlook

This work provides an initial outlook on the importance of clean coal combustion technologies and presents certain issues associated with formulating a technology roadmap for clean coal combustion in China. A technology roadmap for clean coal combustion technologies in China up to 2050 is then proposed, and five strategic suggestions are also proposed to aid implementation of this technology roadmap.

Although this work used systematic analyses and provides suggestions for developing a technology roadmap for clean coal combustion technologies, there are many uncertainties facing energy technology innovations and energy sector developments in China. We thus anticipate that the technology roadmap proposed in this study will be continuously refined and updated in the future, to ensure that clean coal combustion technologies in China will continue to develop in a healthy and sustainable manner.

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