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Green and Low-Carbon Development Path of Boiler Equipment in China

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Abstract: Boilers are special equipment with high energy consumption and are widely used in electric power, heating, steel, and other industries, as well as in daily life. They represent a significant part of the infrastructure for guaranteeing economic development and improving people's lives. However, the energy consumption, air pollution, and carbon emissions of boilers are large. Therefore, a transformation to green and low-carbon boiler equipment is crucial for realizing carbon peaks and carbon neutrality. In this paper, power station boilers and industrial boilers are discussed from the perspectives of energy conservation and carbon emission reductions from the boiler equipment. The development trend of boiler equipment in China is summarized, and existing problems are analyzed. Based on the characteristics of power stations and industrial boilers and considering the stages of production, use, and inspection, as well as the factors of the fuel supply, operating conditions, and operation level, green and low-carbon development paths are proposed for boiler equipment. These include upgrading power station boilers, transforming industrial boilers to low-carbon types, employing green development in boiler manufacturing, and use- and management-level improvements. Corresponding measures are discussed. Finally, countermeasures and suggestions are proposed from three perspectives: strengthening scientific and technological innovation; perfecting public service systems; and improving laws, regulations, and standards systems to provide a reference for promoting a transformation and upgrade of the boiler equipment manufacturing industry and develop green and low-carbon boiler equipment.

Keywords: boiler equipment; low-carbon development; energy conservation and efficiency promotion; fuel structure adjustment; intelligent operation

1 Introduction

Boilers are widely employed in electric power, heating, petrochemical, chemical, iron and steel, non-ferrous metals, paper-making, and other industries, as well as in daily life. They represent important infrastructure for ensuring national economic development and improving people's lives. In addition, they are the main energy-consuming equipment and important air pollutants and carbon emission sources, respectively. According to the application classification, boilers are mainly divided into power station boilers and industrial boilers. Based on a rough estimation, the energy consumption of boilers in 2020 exceeded 1.8×10^9 tce. Therefore, improving the boiler energy efficiency, optimizing the fuel structure, reducing CO_2 emissions, and realizing green and low-carbon quality have important supporting significance for China to achieve its goals regarding carbon peaks and carbon neutralization.

The power station boiler is one of the three main pieces of equipment in coal-fired thermal power plants. To achieve the carbon peaking and carbon neutralization goals and reduce the carbon emissions from thermal power, it is necessary to continuously increase the proportion of clean energy power generation [1]. In the future, the installed capacity and electricity of coal power are expected to gradually experience "power capacity increase and

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generation control," "power capacity control and generation reduction," and "power capacity reduction and generation reduction" [2], respectively, implying that the roles played by power station boilers in power production will gradually change. Power station boilers will "strictly control the increment, actively reduce the quantity, and optimize the stock" by accelerating the upgrading and transformation towards energy saving and efficiency improvements. It has been suggested to reduce CO_2 emissions by using mixed combustion of coal, sludge, domestic waste, and other biomass [3], thereby taking a path of low-carbon development.

According to the requirements of the *Carbon Peaking Action Plan before 2030* issued by the State Council of China, it is necessary to promote energy conservation and efficiency enhancements in key energy-using equipment and to comprehensively improve the energy efficiency standards of industrial boilers. Studies have been conducted to construct carbon emission measurement indicators for industrial boilers. They analyzed the effectiveness of carbon reduction measures in the industrial boiler industry and proposed strategies for adjusting and optimizing the fuel structure [4]. Other studies have proposed maximizing the energy-saving potential by promoting green upgrades and improvements in key energy-consuming equipment such as boilers [1].

In this study, aiming to determine a high-quality development path for boiler equipment in China, the two types of boilers (power station boilers and industrial boilers) are discussed, starting from the perspectives of energy saving and carbon reduction in boiler equipment. In addition, the development trend and current problems of China's boiler equipment are summarized, and a green and low-carbon development path for boiler equipment and demand suggestions are proposed. The green and low-carbon development path and demand suggestions are expected to provide a reference for the green and low-carbon development of China's boiler equipment under the requirements concerning carbon peaks and carbon neutrality.

2 Development trends and existing problems of boiler equipment in China

Boilers are currently the most important energy consuming and carbon emission equipment in China. Since the 11th Five-Year Plan, China has intensified efforts toward boiler energy saving and emissions reduction. Correspondingly, China has implemented a series of policy measures such as those concerning coal power structure optimization, transformation, and upgrading, coal-fired industrial boiler energy conservation, and environmental protection comprehensive improvement projects, thereby significantly improving the levels of boiler energy conservation and environmental protection. As shown in Fig. 1, owing to the elimination of a large number of small-capacity coal-fired industrial boilers, boilers in China showed an evident downward trend after 2014. By the end of 2020, the number of boilers in China was approximately 3.56×10^5, including 1.36×10^4 power station boilers and 3.42×10^5 industrial boilers. The overall number of boilers decreased by 44.5% compared with the peak in 2013, mainly owing to the significant decrease in industrial boilers. The production changes in industrial boilers in China from 2011 to 2021 are shown in Fig. 2. In 2014, the production of industrial boilers in China reached a peak of approximately 5.58×10^5 t/h, and then remained at approximately 4×10^5 t/h without a significant decrement. It can be observed that the initiatives of coal-to-gas, coal-to-electricity, and replacing small with large to improve boiler production remain considerable.

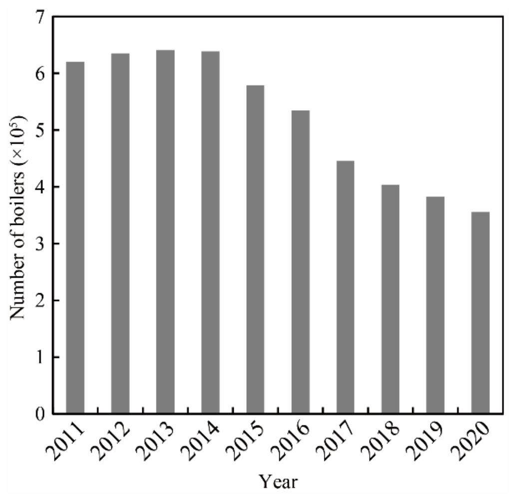

Fig. 1. Variation of boilers in China from 2011 to 2020.

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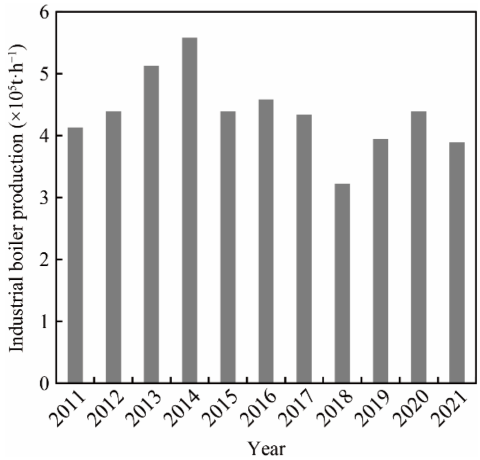

Fig. 2. Variation of industrial boilers in China from 2011 to 2021.

2.1 Development trend of boiler equipment in China

2.1.1 Development trend of power station boiler equipment

Power station boilers continue to develop toward larger capacities, higher parameter values, and lower emissions. They have reached a main steam pressure of 31–35 MPa, temperature of 600–615 °C, reheat steam temperature of 620–630 °C, and to higher parameter values of 650 °C and 700 °C forward [5]. In recent years, the thermal power structure of China has significantly changed, and the proportion of ultra-supercritical units has significantly increased (Fig. 3). By the end of 2020, the capacity of thermal power units of 600 MW and above in China accounted for 46% of the total installed thermal power capacity, with the proportion of 1000 MW-class ultra-supercritical units exceeding 12%. In terms of the average coal consumption of the thermal power supply, it continued to decline from 330 g/(kW·h) in 2011 to 305.5 g/(kW·h) in 2020 [5]. It is expected that the energy efficiency level of the thermal power units will continue to improve. By 2025, the national average coal consumption of the power supply will be further reduced to below 300 g/(kW·h).

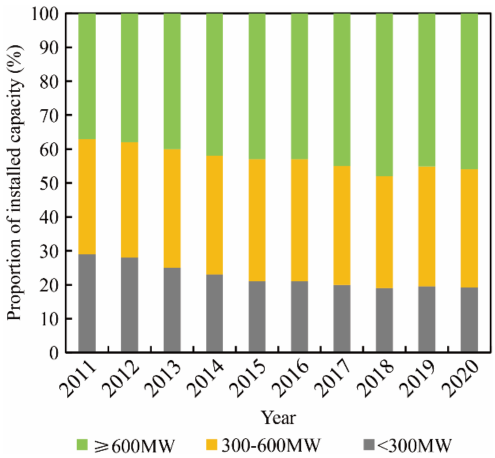

Fig. 3. Variation of thermal power structure in China from 2011 to 2020.

Compared with primary reheat units, secondary reheat units can reduce power supply coal consumption by approximately 8–10 g/(kW·h). In that regard, 1000-MW grade 600 °C/620 °C/620 °C ultra-supercritical secondary reheat units were put into operation in 2016, with a power supply coal consumption of 266.18 g/(kW·h). The first international Anhui Pingshan 1350-MW high-low arrangement ultra-supercritical secondary reheat unit was also put into operation. The Datang Yuncheng 630 °C ultra-supercritical secondary reheat power generation project was listed as a national power demonstration project in 2017; the relevant parameters were 35 MPa/615 °C/630 °C/630 °C. In the future, the use of a secondary reheat unit with ultra-high parameters should remain an important development direction for power plant boiler equipment [6]. Numerous studies had also been conducted on efficient combustion and multi-field collaborative pollution control in high-parameter boilers to achieve safe, efficient, clean, and optimal control of boiler combustion processes with multiple objectives [7]. In addition, the emissions values for soot, sulfide, and nitrogen oxides from coal-fired thermal power units have continued to decline. The emissions of soot, SO_2, and NO_2 in 2017 were 0.06 g/(kW·h), 0.26 g/(kW·h), and 0.25 g/(kW·h), respectively [8]. Biomass power generation has also developed rapidly. By the end of 2020, the installed capacity (including waste incineration power generation) had reached 2.95×10^7 kW, accounting for 1.34% of the national installed power generation capacity.

2.1.2 Development trend of industrial boiler equipment

Industrial boilers are gradually developing toward cleaner, larger, and higher efficiency. The variations in fuel types for industrial boiler product testing from 2012 to 2021 are shown in Fig. 4. Among them, the number of coal-fired industrial boiler products has decreased significantly, to less than 50 units per year since 2018. Natural gas was the most dominant fuel type among new industrial boiler products in recent years, followed by biomass. By eliminating a large number of outdated coal-fired boilers, the fuel structure for industrial boilers has been fundamentally enhanced. Gas boilers have accounted for over 50% of the total number of industrial boilers (Fig. 5). The variation in the maximum rated thermal power of industrial boiler product testing in recent years is shown in Fig. 6. The maximum rated thermal power or evaporation capacity of industrial boilers of various fuel types are consistently increasing. At present, the maximum rated thermal power of coal-fired industrial boilers has reached 168 MW, and gas-fired industrial boilers have reached 116 MW. The maximum rated evaporation capacity of electric-heating industrial boilers is 80 t/h. The variations in the thermal efficiency of the industrial boiler product testing are shown in Fig. 7. Before 2017, the average testing thermal efficiency of industrial boiler products showed an evident rising trend, mainly owing to the yearly decrease in the number of coal-fired boiler tests and yearly increase in the number of gas boiler tests. After 2018, it showed a stable trend. At this time, the automation level of industrial boilers had been continuously improved, and the situations regarding high energy consumption and heavy pollution had been significantly improved.

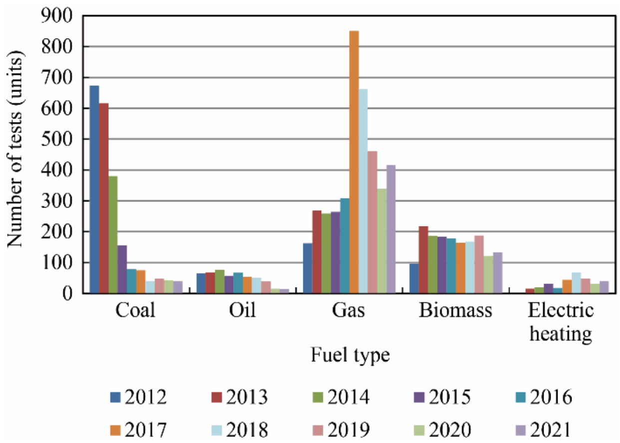

Fig. 4. Variation of fuel type for industrial boiler product testing.

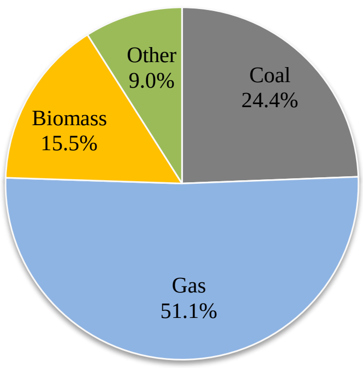

Fig. 5. Fuel structure of industrial boiler.

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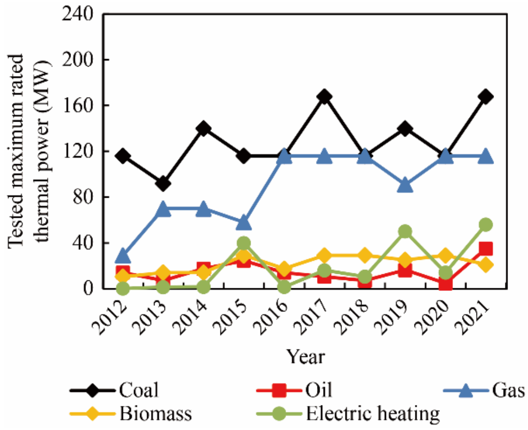

Fig. 6. Variation of maximum rated thermal power tested by industrial boiler products.

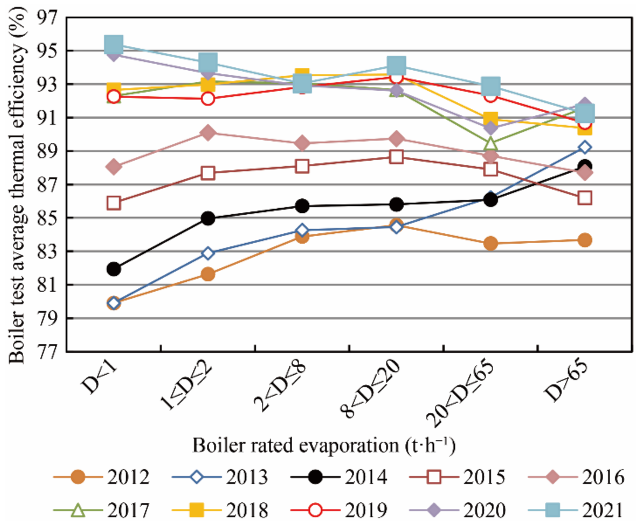

Fig. 7. Thermal efficiency variation of industrial boiler product test.

Note: D indicates the rated evaporation capacity of the boiler.

2.2 Problems existing in boiler equipment in China

In terms of power station boilers, the levels of energy saving and environmental protection in power station boilers in China are relatively high. However, there are still problems, such as the limited proportion of large-capacity and high-parameter units, a certain gap between the average power supply coal consumption and advanced units, and a large number of coal-fired power station boilers still having room for energy-saving and efficiency improvements. As power stations represent the major carbon-emitting industry, it is imperative to increase the proportion of clean energy generation and reduce the number of coal-fired power station boilers to achieve the goal of carbon neutrality. Simultaneously, it is also necessary to improve the flexibility of coal-fired units to solve the problem of insufficient consumption capacity for new energies.

For industrial boilers, owing to uneven design and manufacturing, and operation and management levels, the average operating thermal efficiency has a large gap from the design value, and there remains a certain amount of energy waste. Simultaneously, owing to the characteristics of industrial boilers including large quantities, wide areas, and scattered use, the application of carbon capture, utilization, and storage (CCUS) technology is more difficult. Thus, the situation facing the development of low carbon is more complex. For this reason, it is necessary to comprehensively consider various factors such as the fuel supply, operating conditions, and operation level, and to propose a reasonable and feasible carbon emission reduction path for industrial boilers.

3 Green and low-carbon development path of boiler equipment

3.1 Development direction

China's carbon neutrality goal requires complete decarbonization of the power system while electrifying the entire economic sector as much as possible. Therefore, the proportion of new energy sources will increase rapidly in the future, whereas coal power will gradually change from the main power source to a basic and regulating power source [9]. Before 2030, the installed capacity and power generation of coal power will still increase to a certain extent. Different researchers have predicted coal power generation and its proportion for 2060 [2,10–13]. Although the results from the predictions are different, overall, the coal power generation is expected to peak in 2025–2030 before the installed capacity, and the corresponding carbon emissions are expected to peak at approximately 4×10^9 t. Then, coal power generation will enter a rapid decline stage, although the reduction will tend to slow down after 2050. The proportion of coal power generation is expected to decrease annually. In 2030, the proportion of coal-fired power generation is expected to be 40%–55% and will drop to under 5% in 2060. The carbon emissions in 2060 will be approximately 5.3×10^8 t, and the installed capacity of coal power will be approximately 4×10^8 kW. Most of the coal power units presently in service were commissioned after 2000 and will enter the retirement peak in 2035–2050. The subsequent new coal power units will be in service until 2055. By cooperating with CCUS technology, the retained installed coal power capacity can provide an application space for advanced and efficient power generation technologies, such as adopting ultra-supercritical power generation technology with ultra-high parameters and supercritical CO_2 cycle power generation technology. Therefore, for power station boilers, the development direction mainly includes: (1) conducting a flexible transformation and manufacturing all coal-fired power units to provide a flexible regulation capacity to realize new energy consumption while ensuring energy supply security; （2） promoting biomass pure combustion power generation and biomass coupling power generation technology according to local conditions to exploit the advantages of biomass carbon neutrality; (3) further improving the energy efficiency levels of units and exploiting the carbon reduction contribution of the energy consumption reduction, implementing energy-saving and efficiency transformations and improving the use management level for stock units, and adopting advanced and efficient power generation technology for the new units; and (4) applying CCUS technology to realize coal-fired power generation decarbonization.

The green and low-carbon development of industrial boiler equipment will be coordinated with the power station boilers. In accordance with the *National Implementation Plan for the Transformation and Upgrading of Coal Power Units* issued by the National Development and Reform Commission and the National Energy Board, during the 14th Five-Year Plan period, the heating transformation will be further promoted, and the heating and industrial steam supply small boilers will be actively shut down. The number of industrial boilers will further decline, and coal-fired industrial boilers will remain the focus of elimination. The consumption of natural gas and biomass will continue to increase, and the demand for energy storage owing to grid shaving and the integration of centralized renewable energy will provide a new path for the adjustment of the industrial boiler fuel structure. The zero-carbon fuel created by hydrogen energy technology can be mixed with natural gas for combustion. In addition, a heat storage industrial electric boiler can be widely employed with the adjustment of the energy structure of the power system and improvement of the electrification level of the industrial sector. In accordance with the deployment of the *Carbon Peaking Action Plan before 2030* issued by the State Council, it is also necessary to comprehensively improve the energy efficiency standards for industrial boilers. Hence, for industrial boilers, the development direction mainly includes: adjusting the fuel structure to achieve carbon reduction at the source, upgrading energy efficiency standards and usage management to further improve boiler energy efficiency, and realizing a process for carbon reduction.

3.2 Development path

According to the characteristics of power station boiler and industrial boiler equipment, the development path comprehensively considers production, utilization, inspection, testing, and other aspects, as well as the fuel supply, operating conditions, operation level, and other factors. Based on the transformation and upgrading of power station boilers, low-carbon transformation of industrial boilers, green development of boiler manufacturing, improvement in boiler utilization management levels, and other aspects, the boiler equipment green low-carbon development path is analyzed and explained below (Fig. 8).

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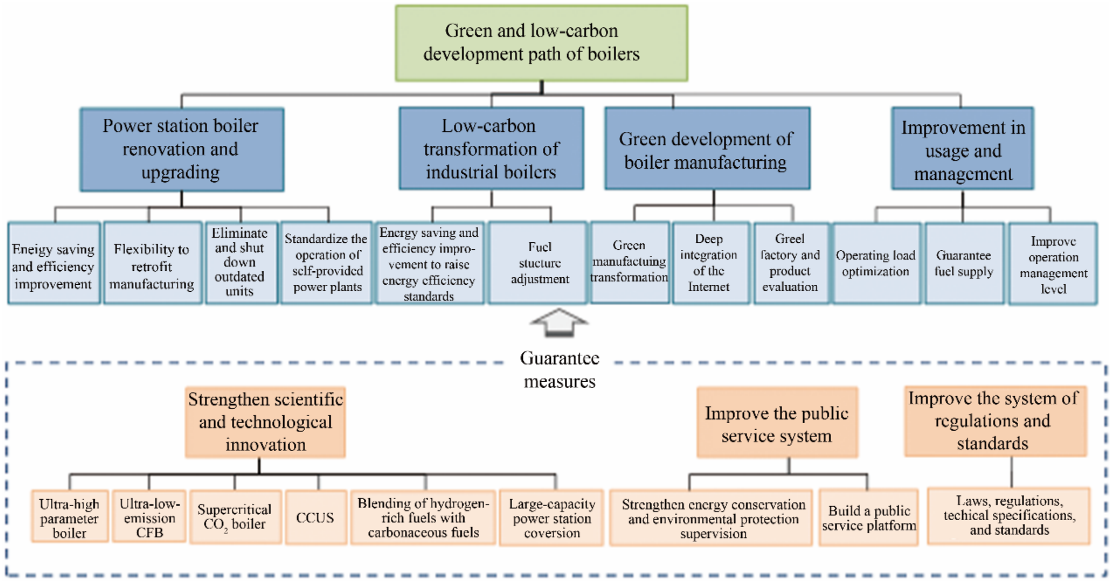

Fig. 8. Green and low-carbon development path for boilers.

3.2.1 Renovation and upgrading of power station boilers

Energy-saving and efficiency-enhancing transformations should be continuously promoted. By the end of 2019, the scale of energy-saving renovations of coal power units in China had exceeded 7×10^8 kW. The energy-saving and efficiency-enhancing renovations of boilers mainly included efficiency-improvement renovations of conventional boilers, comprehensive upgrading and renovation of high-temperature subcritical boilers, deep utilization of flue gas waste heat, and heating supply renovation. During the 14th Five-Year Plan period, the transformation scale of coal power units with a power supply coal consumption above 300 g/(kW·h) will be no less than 3.5×10^8 kW. The reduction of coal consumption in the power supply is expected to decrease the CO_2 emissions from electricity by approximately 7×10^7 t.

The implementation of flexibility transformation and manufacturing should be accelerated. In particular, it should focus on the flexibility transformation of coal power units of 300 MW and below, and promote the flexibility transformation of 600-MW subcritical coal-fired power units in areas with difficulties in peak shaving. For pure condensing units, the boiler and turbine should be decoupled through coupled heat storage technology, so that the load change is not affected by the minimum steady combustion load of the boiler and the peak shaving depth is further reduced [14,15]. For cogeneration units, the core issue in the peak-shaving capacity enhancement during the heating period operation lies in thermal decoupling. At present, most domestic coal-fired boilers have a low load stabilization capacity of 40%–50% of the rated load; this can be lowered to 20%–30% of the rated load through retrofitting [11]. In January 2022, the 660-MW generator unit of Datang Qinling Power Plant achieved a stable operation at 10% of the rated load. During the 14th Five-Year Plan period, China is expected to complete the flexibility transformation of the 2×10^8 kW coal power units in stock and to reach the flexibility manufacturing scale of 1.5×10^8 kW coal power units.

Backward power station boiler production capacity should be further eliminated. For areas with a large stock of power station boilers, such as Shandong, Jiangsu, Guangdong, and Inner Mongolia, the efforts to eliminate backward coal power production capacity should continue to increase. The low-parameter small-capacity power station boilers will be further eliminated and shut down, and the coal power industry structure will continue to provide high-capacity, high-parameter optimization adjustments. The shut-down units meeting the requirements for energy efficiency, environmental protection, safety, and other policies and standards will be included as an emergency backup. During the 14th Five-Year Plan period, the country will form and maintain an emergency reserve capacity of 1.5×10^7 kW.

The operation of coal-fired self-provided power plants should be further regulated. For example, there is a need to comprehensively clean up illegal coal-fired self-provided power plants and to guide self-provided power plants and clean energy to provide alternative power generation. This will increase energy savings and emissions reductions from self-provided coal-fired power units. The self-provided units that meet the conditions for elimination should be eliminated and shut down within a time limit. Self-provided units with high emissions and energy consumption levels should implement ultra-low emissions technology and energy-saving transformations.

Biomass pure-burning power generation and biomass coupling power generation technology should be developed according to local conditions. China's biomass resources can be applied with an energy development potential of approximately 4.6×10^8 tce, and the replacement of coal burning can achieve nearly 1.3×10^9 t of CO_2 emissions reduction. Currently, the Shandong, Guangdong, and Jiangsu provinces have large installed capacities for biomass power generation. In the future, provinces with rich biomass resources, such as Henan and Heilongjiang, will further promote and apply biomass pure-fired power generation and biomass-coupled power generation technologies. Owing to the scattered biomass sources, small unit scale, and high investment per kilowatt, the power generation cost for pure biomass burning power generation technology is currently high. The supporting policy for biomass-coupled power generation technology is also unclear. By providing a solution to the problem of biomass energy measurement, it can be expected to be applied within a certain range.

3.2.2 Low-carbon transformation of industrial boilers

The adjustment of the industrial boiler fuel structure should continue to be promoted to achieve a carbon emissions reduction at the source. The number of coal-fired industrial boilers should continue to further decrease. The number of gas-fired boilers should continue to increase, and biomass and coal-fired coupled biomass technology should be widely employed. Compared with power station boilers, industrial boilers have less fuel consumption and lower parameters, and there are no problems such as difficulties in the fuel source and/or serious fouling and corrosion under high-temperature conditions. Therefore, the application of biomass resources in the field of industrial boilers is promising. As shown in Fig. 4, since 2015, biomass has become the industrial boiler fuel type with the largest number of tests for boiler products in addition to natural gas; this also confirms the great potential of continuing to promote biomass pure combustion and coupled combustion in the industrial boiler field in the future. Moreover, the low-carbon transformation of industrial boilers should also be developed in synergy with energy storage technologies such as blending (mixing) hydrogen into natural gas and using mature natural gas pipeline networks to achieve large-scale transportation of hydrogen [16,17]. If 10% of industrial natural gas consumption can be replaced by the use of hydrogen fuel, the annual CO_2 emissions can be diminished by more than 2×10^7 t. In addition, the proportion of electric energy in the terminal energy consumption structure will continue to rise. It is expected to increase to 30% in 2025, surpassing coal as the most dominant terminal energy consumption species [18,19]. It will further increase to 55% in 2050 [10]. Based on the development demand for industrial terminal electrification and demand for peak and valley electricity regulation under a power supply system dominated by new energy, electric heating boilers, especially thermal storage industrial electric boilers, will continue to rise in the proportion of industrial boilers. In addition, the boiler capacity will continue to increase. With the gradual decarbonization of the power system, the role of electric heating boilers in reducing carbon will become increasingly prominent.

The level of energy efficiency of industrial boilers should be further improved, and carbon emissions process control should be implemented. By revising the mandatory standards such as those for energy efficiency limits and energy efficiency levels for industrial boilers, the entry threshold regarding the energy conservation and environmental protection of boilers will be raised. Correspondingly, a catalog of high-efficiency boilers will be released to promote high-efficiency boiler products. Stakeholders should promote the elimination and renovation of old and inefficient boilers and prevent eliminated boilers from reentering the market. If the average operating efficiency of industrial boilers is further improved by approximately 5% through energy savings and efficiency enhancements, the annual CO_2 emissions can be reduced by up to approximately 8×10^7 t.

3.2.3 Green development of boiler manufacturing

Green manufacturing should be implemented during boiler manufacturing. To ensure the functionality, quality, and cost of products, boiler manufacturing enterprises should comprehensively consider the environmental impacts and resource efficiency of the manufacturing system to minimize environmental pollution throughout the life cycles of products, from design, manufacture, and use to scrap. This could render such products harmless or minimize harm to the ecological environment, improve resource utilization, and reduce energy consumption and carbon and pollutant emissions. The green manufacturing of boilers includes five parts: green design, clean production, green logistics, green operation, and reuse.

The depth of integration with the Internet should be strengthened. Against the background of manufacturing transformation and upgrading and the rapid development of intelligent manufacturing, boiler manufacturing

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enterprises should accelerate the implementation of Internet Plus manufacturing demonstration projects, provide automation and an intelligent transformation of production lines, and improve the level of automation.

Evaluations of green factories and green products should be actively conducted. Boiler manufacturing enterprises should identify deficiencies and improve through third-party evaluations to achieve their energy-saving and low-carbon transformations. For example, enterprises can establish a product database, track products, regularly conduct problem diagnoses, and propose targeted energy-saving, carbon-reducing, and pollutant-reducing recommendations.

3.2.4 Improving boiler use and management level

The factors that affect the energy efficiency level of boilers mainly include the operating load, fuel characteristics, and operation management level. The first objective is to improve the flexibility and intelligence of grid dispatching and industrial heat user-demand matching. By giving full play to the clean and efficient advantages of large-capacity and high-parameter boilers and their load-side regulating ability, boilers can operate under loads with as high energy efficiency levels as possible. The second objective is to ensure the fuel supply for coal-fired boilers. It should be ensured that power station boilers burn the designed coal and that industrial boilers burn the designed coal as much as possible to avoid the decline of boiler energy efficiency caused by fluctuations in fuel quality to the maximum extent. The third objective is to encourage users to adopt a professional operation mode and scientifically formulate an optimized operation program to optimize the boiler’s full working condition operation. The fourth objective is to improve the online detections and diagnoses of energy efficiency levels and emissions of boilers and to realize a digital and intelligent operation of boilers through technologies such as intelligent operation and maintenance and remote diagnosis.

For self-provided power station boilers, it is necessary to strengthen supervision to ensure that self-provided power plants strictly implement the latest air pollutant emissions standards and total control requirements for public coal-fired power plants. For industrial boilers, it is necessary to improve the requirements of the regulations and standards and assist with tax incentives. By dynamically adjusting the industry’s benchmarking index system and conducting the “leader” actions for boiler system energy efficiency, it is possible to encourage and guide the already-operating boilers to the benchmark energy efficiency. In addition, it is necessary to support low-efficiency and high-emission boilers in implementing energy-saving and pollution-reduction measures, and any carbon reduction renovations as planned.

4 Safeguard measures

4.1 Strengthening scientific and technological innovation

An industry–academia–research–application collaborative innovation system should be built. This system should focus on common key technologies and problems to accelerate the research and development and integrated innovation of key technologies and products for boiler energy saving and pollution and carbon reductions. This will make it possible to form advanced boiler energy-saving and emission-reduction technologies and complete sets of equipment with independent intellectual property rights.

The first objective is to accelerate the research on ultra-supercritical coal-fired power generation technology with ultra-high parameters. This technology is an important technology for realizing energy saving and emissions reductions in coal-fired power units, and its key constraint lies in the materials of the thermal components. The achievable net efficiency of a 650 °C generator set is not less than 47%, but the required heat-resistant materials are not yet fully mature, and it is still necessary to break through key technologies such as homogenous/dissimilar welding, hot and cold processing, and heat treatments for high-temperature components. The efficiency of 700 °C supercritical power generation technology can reach more than 50% [20]; accordingly, it is considered to be one of the major clean coal frontier technologies for 2035 [21]. Its high-temperature alloy materials and key high-temperature components such as in manufacturing, processing, welding, and inspection still require further investigation.

The second objective is to make further breakthroughs in circulating fluidized bed (CFB) power generation technology. This technology can solve the problems regarding the clean and efficient utilization and low-load stabilization of high-sulfur anthracite, high-moisture lignite, and low-calorific value coal [22], and can play an important role in absorbing inferior fuels, peak regulation, and biomass utilization. During the 14th Five-Year Plan period, further studies should be conducted on CFB boiler furnace limestone depth desulfurization and NO_x ultra-low emissions mechanisms, large CFB boiler material flow patterns, and other optimization designs to advance the key technologies in high-efficiency and low-cost power generation by ultra-low emission CFB boilers [23].

The third objective is to develop supercritical carbon dioxide power generation technology. Supercritical carbon dioxide cycle power generation technology could employ various energy forms such as coal, natural gas, nuclear energy, solar energy, biomass, and waste heat as heat sources. At 600 °C, the power supply efficiency of supercritical carbon dioxide cycle coal-fired power generation units could be increased by 3–5% relative to conventional water cycle generating units [11]. Thus, it is necessary to further strengthen the study of and engineering applications for key technologies of supercritical carbon dioxide boilers, unit system integration optimization, etc.

The fourth objective is to promote the research, development, promotion, and application of CCUS technology. For the coal-based industry and coal-fired power generation industry, the decarbonization process requires the cooperation of CCUS technology. At present, the overall scale of CO_2 capture technology is generally small, and the energy consumption and cost of capture are high [24,25]. For this reason, the research and development of cutting-edge technologies such as high-efficiency and low-energy CO_2 capture, large-scale transport and storage, storage monitoring and leakage warning systems, pressurized oxygen-rich combustion, and oil/gas/water/heat recovery by using CO_2 should be strengthened in the future. The carbon capture scale of coal power CCUS technology is expected to reach 3.7×10^7 t/a in 2030 [2].

The fifth objective is to strengthen the key technology research on hydrogen-rich fuels such as hydrogen and ammonia and carbon-containing fuel blending. At present, research on the influences of the combustion characteristics of hydrogen-doped natural gas is mainly focused on internal combustion engines, gas cookers, and gas turbines [26–29]. The application study of hydrogen-blended natural gas combustion in the field of industrial boilers is relatively weak, and there is an urgent need to research efficient and clean combustion technology and the equipment compatibility of gas with different blending ratios to lay a technical foundation for the application of hydrogen blending in large-scale natural gas pipelines. The study and development of key technologies and engineering applications for ammonia, natural gas-blended combustion, hydrogen/ammonia, and coal gas-solid two-phase blended combustion represent other directions for science and technology innovation.

The sixth objective is to strengthen the research and development of key technologies for high-capacity electric heat conversion. At present, electric heating boilers are mainly small-capacity resistance boilers applying a 380-V low-voltage power supply, and the single unit capacity is generally under 2.8 MW. However, electrode boilers are not subject to restrictions on the electric heating element structure arrangement and heat density. They are more suitable for a large scale, usually using more than a 6-kV high-voltage power supply. Nevertheless, the basic research and key technology developments for large-capacity electrothermal conversion technology remain insufficient. There also remains a lack of relevant norms and standards. Nevertheless, there are certain safety hazards in practical application [30]. Therefore, it is necessary to strengthen the research on the key technologies for the electrothermal conversion of large-capacity high-voltage electrode boilers, electrical safety requirements, and high-efficiency and low-cost heat storage.

4.2 Improving the public service system

In this context, the first objective is to integrate multiple resources and build an industry–university–research–application exchange platform. To effectively support the green and low-carbon development of the boiler industry, it is necessary to bring together various elements such as technology, talents, information, policies, and funds, and to integrate the resources of the government, enterprises, professional service institutions, industry associations, scientific research institutes, and other parties to build a public service system for industry and enterprises. It is recommended to set up an exchange and cooperation platform for industry–university–research–application and technology promotion in the field of green low-carbon boilers. This can play a role in communication, coordination, and industry leadership. It can also help in the green low-carbon development of boiler equipment.

The second objective is to effectively and successfully perform the supervision and guarantee work regarding boiler safety, energy saving, and environmental protection. For the energy-saving and efficiency-enhancing transformations of power station boilers, supervision, inspections, and energy efficiency emission tests should be conducted both before and after the transformation. The system should actively respond to demands for deep peak shaving and conduct safety risk assessments, prevention, and control. Performing well the review and inspection of the emergency backup boilers ensures that emergency backup power could play its role. To strengthen the energy conservation and environmental protection supervision of self-provided coal-fired power unit boilers, energy

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efficiency emissions testing should be promoted. For industrial boilers, inspectors should conduct good energy-saving reviews of boiler design documents, energy efficiency testing of boiler products, and regular energy efficiency testing of boilers in utilization. This will support energy-saving supervision throughout the entire process of boiler design, production, and application.

The third objective is to strengthen the entire lifecycle management and service of boilers. Boiler manufacturing enterprises are gradually developing toward an integrated service of design + manufacturing + installation + maintenance. The aims are to enhance the supply system to meet the demands for adaptability and to build a digital platform for operation and control to manage the entire lifecycle of the boilers to provide value-added services for end users. Qualified third-party organizations could also provide entire process consulting, maintenance, renovation, specialized operations, and other services.

The fourth objective is to enhance the detection and evaluation capabilities for boiler carbon emissions. Research and development should be conducted on boiler greenhouse gas emission detection and full lifecycle carbon footprint quantification and evaluation technologies. Boiler energy saving, pollution reductions, and carbon reduction collaborative detection and evaluation systems should be further explored and researched. A green and low-carbon public service platform for boiler production and use units should be built to provide carbon emissions testing and carbon footprint accounting services.

4.3 Improving the system of relevant laws, regulations, and standards

In accordance with the "laws–administrative regulations–departmental regulations–safety specifications–reference standards" structure level of China's special equipment regulations and standards system, the boiler-related regulations and standards system should be improved. Timely revisions should be applied to the *Special Equipment Safety Law of the People's Republic of China*, *Energy Conservation Law of the People's Republic of China*, *Air Pollution Prevention and Control Law of the People's Republic of China*, *Regulations on the Safety Supervision of Special Equipment*, *Measures for the Supervision and Administration of Energy Conservation for Special Equipment with High Energy Consumption*, etc., to build a system of laws and regulations conducive to the green and low-carbon development of boilers. In the relevant technical specifications such as the *Technical Regulations for Energy Conservation and Environmental Protection of Boilers*, the contents regarding green manufacturing and boiler lifecycle carbon emission evaluations should be added in a timely manner. The formulation of standards such as those for boiler carbon emission quantification and evaluation methods should be accelerated. Timely revisions should also be made to boiler thermal efficiency indicators, boiler system energy efficiency indicators, and boiler energy efficiency testing methods, as well as to further improve standard systems, such as intelligent manufacturing and green manufacturing. A standards system should be established for the intelligent operation and supervision of boilers and acceleration of the alignment of quality and safety standards with international standards.

Boiler manufacturers and users should be encouraged to lead or participate in the formulation/revision of relevant national, local, and industrial technical standards. Enterprise and group standards can be formulated and combined with actual conditions. Key technologies with independent intellectual property rights can be incorporated into enterprise or group standards to promote the coordinated development of technological innovation, standards development, and industrialization.

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