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REVIEW ARTICLE

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An overview of the development history and technical progress of China's coal-fired power industry

Abstract As the main power source of China, coal-fired power industry has achieved a great progress in installed capacity, manufacturing technologies, thermal efficiency, as well as pollutant control during the past century. With the fast development of renewable energies, coal-fired power industry is experiencing a strategic transformation. To specify the development of coal-fired power industry, its development history is reviewed and the technical progresses on aspects of thermal efficiency, pollutants control and peaking shaving capacity are discussed. It is concluded that the role of China's coal-fired power source would be transformed from the dominant position to a base position in power source structure. Considering the sustainable development of coal-fired power industry in energy conservation, emission control, and utilization of renewable energies, it is suggested that the national average thermal efficiency should be improved by continual up-gradation of units by using advanced technologies and eliminating outdated capacity. Moreover, the emission standard of air pollutants should not be stricter any more in coal-fired power industry. Furthermore, the huge amount of combined heat and power (CHP) coal-fired units should be operated in a decoupled way, so as to release more than 350 GW regulation capacity for the grid to accept more renewable energy power.

Keywords coal-fired power, development strategy, eliminating outdated capacity, peak shaving, emission reduction, renewable energy

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1 Introduction

Coal is the main fossil fuel in China, accounting for approximately 70% of the national energy consumption [1,2]. Over the past century, about 80% of the electricity was generated from thermal power plant on average [3], as shown in Fig. 1, where coal-fired power accounts for approximately 85% of the thermal power generation[1)].

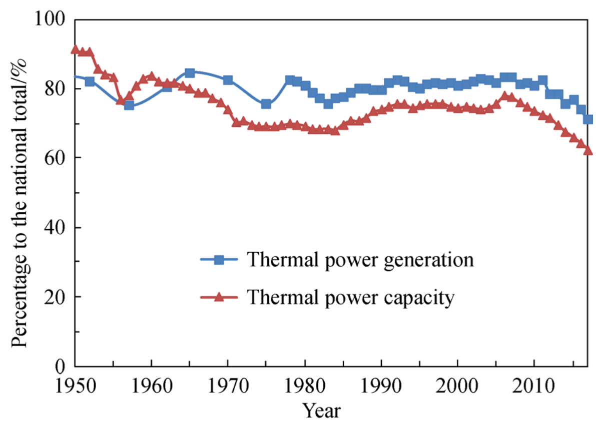

Fig. 1 Generation and capacity shares of thermal power units

According to statistics, the overall standard coal consumption reached 2.68 billion tones in 2015, around half of which were used for power generation [1]. As the main power supplier, coal-fired power industry contributes a lot to the development of national industry, construction, transportation, agriculture, and daily life. It is believed that a healthy coal-fired power industry in China is the basic safeguard for the rapid growth of economy and improvement of people's living standard.

Thanks to the continual progresses in the coal-fired power technology, the national average thermal efficiency of coal-fired power plants increases greatly over the past

1) National Power Industry Statistics Bulletin (1950–2018). National Energy Administration, Beijing, 2017 (in Chinese)

few decades. By the end of 2017, the national average net coal consumption rate (NCCR) of the thermal power units in China had been reduced to 309 g/kWh, which accounts for 27%, 66%, and 81% of those in 1949, 1978 and 2002 respectively [4,5]. The NCCR of the state-of-the-art coal-fired power units in China has been reduced to less than 260 g/kWh (48.12%, LHV) [6].

Coal-fired power industry used to be the main contributor of air pollutants emission in China for a long time [7–9]. However, influenced by the increasingly strict emission standards issued by the Chinese government, the national annual total pollutants emission in coal-fired power industry has declined greatly in the past few years. As the ultra-low emission standard has been implemented since 2014, which requires the emission content of SO_2, NO_x and dust in coal-fired power plant should be less than 35, 50 and 10 mg/m^3, the total emission in coal-fired power industry in 2017 accounts only for approximately 10% of that in 2007[1)]. Coal-fired power industry was no doubt the biggest contributor to the energy conservation and pollutants emission reduction in the past two decades.

To cope with the climate change, China-US Joint Announcement on Climate Change was released by China and the US in November 2014[2)][10]. Consequently, China targets for increasing the share of non-fossil fuels energy in primary energy consumption to around 20%, and peaking its greenhouse gas emission in 2030. During the past several years, a rapid growth in renewable energy utilization has been seen in China [11]. For example, the installed capacities of wind and solar power had reached 164 and 130 GW by the end of 2017, which accounted for about 9.2% and about 7.3% of China's total installed power capacity respectively[3)]. It is generally believed that coal consumption will reach its peak at a certain point in the near future [2], and coal-fired power will follow this path soon afterwards.

However, as the result of the resources endowment in China, the dominance of coal resource in primary energy consumption is hard to be changed in the near future[4)]. Unlike the fluctuating and unpredictable characteristics of the power generated from renewable energy resources [12], the coal-fired power can be easily regulated. As more and more renewable energy power units have been installed, the coal-fired power industry would play an increasingly important role for the peak shaving in the grid [13].

Coal-fired power industry is experiencing a great change nowadays. Considering the significant role of coal-fired power in the power structure of China, it is of great importance to specify a sustainable development strategy. While the research in this field mainly concentrates on clean coal technologies, like ultra-supercritical technology, CFB technology, IGCC (integrated gasification combined cycle), and CCS (carbon capture and storage) [8,14], it is generally concluded that advanced technologies in coal-fired power generation [7], pollutant-control, CO_2 capture, storage and utilization should be concerned in coal-fired power industry [8]. However, as reviewed by previous studies, the energy efficiency penalty for the CCS could be a decrease of approximately 10% [15], which is too much to be accepted as most of the energy efficiencies of existing coal-fired power units are only between 30% and 45%.

Thereby, this paper mainly focuses on the development of advanced technologies, pollutant control, and grid peak shaving of coal-fired power industry. Based on a brief review of the development history of coal-fired power industry in China, the related technologies and strategies involved in unit efficiency, pollutants control, and regulation capacity are investigated respectively. Accordingly, some sustainable development strategies related to energy conservation and emission reduction of coal-fired power industry are proposed.

2 A brief history of China's coal-fired power

The earliest power generating assembly was installed in China in 1879, when a British engineer named J. D. Bishop lighted the first electric arc lamp by adopting a self-excited DC generator driven by a steam engine in Shanghai [4,16]. Through the ages of late the Qing Dynasty and the Republic of China, the national installed coal-fired capacity increased to 1.68 GW. Meanwhile, most of the steam engines were replaced by steam turbine in coal-fired power plants, and the state-of-the-art unit capacity also increased from 100 kW to 50 MW. Consequently, the NCCR of the state-of-the-art unit were largely reduced from 1350 to 500–600 g/kWh (20%–25% in LHV) [4].

After the establishment of the People's Republic of China (1949), the development of the power industry was brought into a new era. By referring to another two landmark events of the "Reform and Opening-up" and the "reform of electric power system," this new era is divided into three periods: the preliminary construction period (1949–1978), the reform and opening-up period(1979–2002), and the period after the reform of electric power system (2003–the present).

2.1 Preliminary construction period

The preliminary construction period refers to the first 30 years after the foundation of the People's Republic of China. During this time, the coal-fired power industry was first recovered from the devastation of the wars. Then

1) Annual Development Report of China's Power Industry. China Electricity Council, Beijing, 2018 (in Chinese)
2) China-US Joint Announcement on Climate Change. 2014
3) National Power Industry Statistics Bulletin. National Energy Administration of China, Beijing, 2018 (in Chinese)
4) BP Energy outlook/country and regional insights—China. 2017

assisted by the former Soviet Union, a lot of backbone coal-fired power plants were reconstructed or constructed, including the power plants in Fuxin, Fushun, Hulan Ergi, Xi'an, Zhengzhou, Chongqing, Taiyuan and Jilin. Besides, a great progress had also been made in the national manufacturing industry during this time. By importing manufacturing technologies of medium pressure coal-fired power units from the former Czechoslovakia in 1952 and those of medium and high pressure coal-fired power units from the former Soviet Union in 1953, the medium pressure 6 MW, medium pressure 12 MW, and the high pressure 25 MW coal-fired power units were developed in 1956, 1957, and 1958 respectively. Then the national installed thermal power capacity increased gradually from 1.69 GW in 1949 to 3.62 GW in the end of 1957.

As a result of the deterioration of Sino-Soviet relations in 1960, the Chinese government had to develop the power industry independently. As a consequence, the domestic manufacturing technologies of coal-fired power equipment were developed rapidly. During the Great Leap Forward Movement, the national installed thermal power capacity quickly increased to 10.66 GW in 1962. However, as a result of rough design, shoddy manufacturing, and violation operation, most of the coal-fired units could not run properly. Fortunately, the operation, maintenance, and management in coal-fired power plants were greatly improved during the adjustment period of national economy (1961–1965), and many delayed projects were reconstructed in this time. Subsequently, the domestic manufacturing technologies of 25, 50, and 100 MW units were gradually developed with competent performance compared to the imported units [17]. Then the national coal-fired power industry gradually stepped into the right track via a self-reliance way. By the end of 1965, the national installed thermal power capacity had increased to 12.06 GW.

However, the newly recovered power industry was struck again by the 10-year Great Culture Revolution (1966–1976). Apparently, many achievements were made during this period. For example, the domestic super high pressure 125 and 200 MW, and subcritical 300 MW units were successfully put into operation in 1969, 1972, and 1974 respectively; and the 19.11 GW new thermal power units were installed. However, accidents frequently occurred during the daily operation, and many new installed units could not operate at the nominal load in this time.

China's power industry, starting from scratch, had achieved many historical breakthroughs through 30 years of technology introduction, assimilation, and self-development. Figure 2 shows the national total installed power capacity and thermal power capacity from 1949 to 1978. As can be seen from the histograms, thermal power was always the backbone of China's power industry in this period. As the line chart shows in Fig. 2, there are generally two fast development periods of thermal power industry

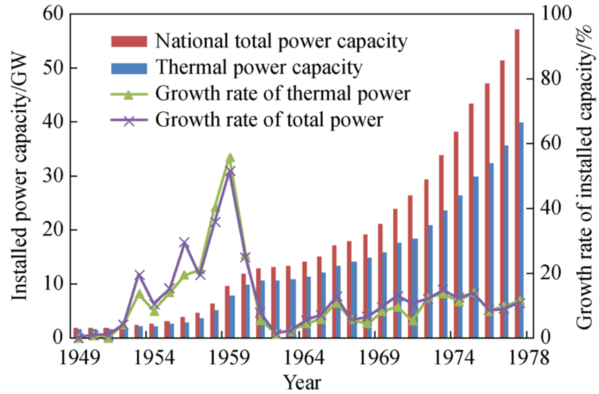

Fig. 2 Development of China's installed power capacity during 1949–1978

during the preliminary construction time. The first period locates from 1953 to 1960, when the coal-fired power capacity shot up with an average annual growth rate of 24.9% and a maximum growth rate of 56.1% in 1959. The second period locates from 1966 to 1976, with a moderate average annual growth rate of about 9.5%. While these two periods were both strongly influenced by large political movements, i.e. the Great Leap Forward Movement and Great Culture Revolution respectively, the general situation of China's power industry in this period foreshadowed a new run of technology introduction afterwards.

2.2 Reform and opening-up period

The reform and opening-up period refers to the period between the launch of the reform and opening-up policy in China in 1978 and the reform of China's electric power system in 2002. After the 10-year Great Culture Revolution and 2-year lingering, the domestic manufacturing technology of the power industry was too laggard to meet the requirement of a regular power supply. Power shortage arose to be a very serious economic and social problem [18]. As a consequence, many subcritical coal-fired power units of 300 MW class were imported from Japan and European countries. Besides, in order to import the manufacturing technologies of 300 and 600 MW subcritical coal-fired units, the technology transfer contracts of steam turbine unit and boiler were signed with Westinghouse Electric Corporation (WH) and Combustion Engineering Corporation (C-E) respectively in 1980, and the design technology of power station was imported from the EBASCO Engineering at the same time [19].

Stimulated by the reform and opening-up policy, China's economy increased rapidly in 1980s. As the industry needed time to be transformed from the extensive management in the Great Culture Revolution period, the construction of power industry fell badly behind at the early 1980s. Figure 3 demonstrates the national total installed power capacity and installed thermal power

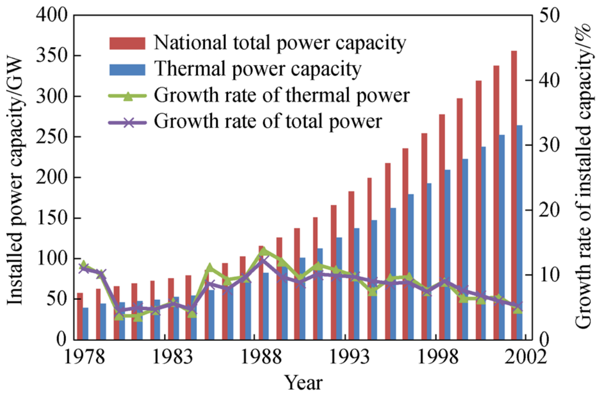

Fig. 3 Development of China's installed power capacity in 1978–2002

capacity from 1978 to 2002. As can be seen from the histograms, the average growth rate of installed thermal power capacity was only about 4.4% from 1980 to 1984, which was rather low compared to the fast recovery economy. Then, the power shortage problem became increasingly severe. As a consequence, a large amount of domestic made coal-fired power units were installed afterwards, including a considerable number of small coal-fired power units. As Fig. 3 indicates, an average growth rate of around 11% can be seen for the installed thermal power capacity after 1985. Inevitably, the safety problem of frequent accidents once again struck the power industry of China.

As the trial-production of the introduced type 300 and 600 MW subcritical coal-fired power units were successfully achieved in 1985 and 1987 respectively, the domestic made self-developed 300 MW boiler and steam turbine were put into operation in 1985 and 1987 respectively. Along with the mass production of the introduced type and self-developed subcritical coal-fired power units, the main power equipment manufacturers were gradually upgraded, and the status of China's power industry was gradually improved. Consequently, China's total installed power capacity and total power generation surpassed France, the UK, Canada, Germany, Russia, and Japan successively, and ranked only second to the US by 1996. The problem of power demand-supply balance was comprehensively solved for the first time [18].

However, power surplus emerged soon after the outbreak of Asian financial crisis in 1998. A large number of small low-efficiency units installed from 1985 to 1995 began to exhibit their deficiency, accordingly, low annual utilization hours (AUH) and high NCCR became the main problems in China's power industry [20]. As a result, the approval of new power project was strictly controlled by the central government in the following several years. Many small coal-fired power plants were shut down. Many power construction enterprises were even forced to disband. The development of coal-fired power industry was gradually slowed down, with an average growth rate of 6.1% from 1999 to 2002 as shown in Fig. 3.

2.3 Period after the reform of electric power system

With the continuous implementation of the reform and opening-up policy in economy, China's electric power system underwent several structural reforms, including the streamlining administration and delegating power in 1981–1985, the multi-agent power structure policy in 1986–1990, the establishment of state power corporation in 1997, and the reorganization of the state power corporation in 2002. The reorganization of the state power corporation in 2002 finally laid out today's electric power system, which is taken as a landmark in this paper.

As the economy recovered from the Asian financial crisis, the demand for electricity grew rapidly. The power industry was still in a contraction status, and the power construction capacity was in a valley as a result of several years' depression. Consequently, a power shortage emerged again in 2001, and the situation increasingly deteriorated in 2004, when the biggest power gap was up to 44.85 GW [21]. Thereafter, as depicted in Fig. 4, a blowout of China's power construction came up again from 2004 to 2007, especially for coal-fired power industry because of its short construction period. The maximum annual growth rate of coal-fired power capacity reached 23.7% in 2006, and the installed thermal power capacity was doubled within five years.

As the subcritical units of the introduced type and self-developed type were extensively applied for more than ten years, China's power manufacturing industry had accumulated a lot of design and manufacturing experience. To improve the thermal efficiency, the former State Development Planning Commission added the "Research Project of 600 MW Critical Coal-fired Power" to the "Science and Technology Breakthrough Project" of key technical equipment in the 9th Five-Year Plan of China. Soon after, the critical coal-fired power technology was introduced from Mitsubishi, Siemens, and Hitachi simultaneously in 2002; and the supercritical coal-fired power technology was introduced from Mitsubishi, Siemens, Alstom, and Hitachi in 2003. The first critical and supercritical units were put into operation in 2004 and 2006 respectively.

To cope with climate change, the investment in renewable energy increased greatly after 2008 [22], which inevitably affected the development of the coal-fired power industry. Besides, since the power supply-demand balance was basically achieved after 2006, the structure optimization by shutting down small coal-fired power units was adopted again. As shown in Fig. 4, the growth rate of thermal power capacity has experienced a nearly continual decrement since 2010, and had reached 4.2% by the end of

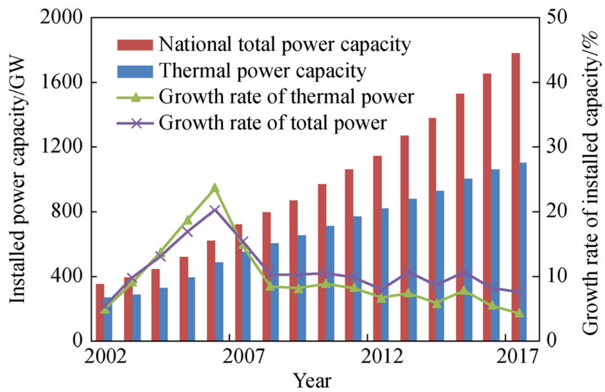

Fig. 4 Development of China's installed power capacity in 2002–2017

2017.

Even though the investment in the coal-fired power sector has slowed down gradually in the recent years, the base position of coal-fired power in the power sources of China could hardly be changed. Figure 5 exhibits the composition of China's installed power capacity by the end of 2017, where "Other" mainly refers to other thermal power sources like blast furnace top gas recovery turbine units (TRT), biomass units, and oil-fired units.

It can be seen from Fig. 5 that the installed coal-fired power capacity still accounts for 88.6% of the installed thermal power capacity and 55.2% of the national total installed power capacity. Unsurprisingly, the share of renewable energy power sources has increased to 35.7%. As renewable energy resources fluctuate heavily, coal-fired power source has to take the regulation responsibility in consideration of their compatible shares. Taking into account of China's energy structure, the national strategic vision and the characteristic of renewable energies, the status of coal-fired power source should be transformed from the dominant position to a base position.

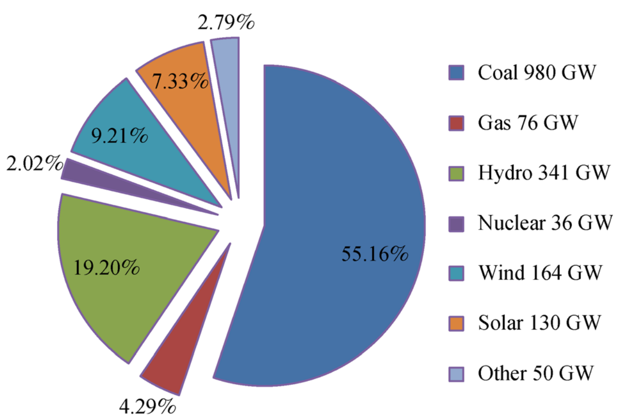

Fig. 5 Composition of China's installed power capacity in 2017

3 Technical progresses

The thermal efficiency is generally a basic index for the technical status of the coal-fired power industry. Besides, the pollutants emission of the coal-fired power industry is also vital as the coal-fired power industry is the biggest fossil fuel consumer in China. In view of the status of coal-fired power in China's power structure, its peak shaving capacity should also be concerned for a sustainable development of renewable energy. Thereby, the thermal efficiency, pollutants emission, and peak shaving capacity of China's coal-fired power industry are discussed in this section.

3.1 Thermal efficiency

The thermal efficiency of a coal-fired power unit refers to the ratio of net power supply to the overall heat consumption. In industrial process, thermal efficiency is always represented by NCCR for statistics convenience. Figure 6 illustrates the key indexes of China's coal-fired power industry during the past 40 years, including the national average NCCR, growth rate of installed coal-fired power capacity (ICPC), national average service power consumption rate (SPCR), and national average AUH. According to the statistical description by China Electricity Council, the data refer to most of the units in service with a nominal load above 6 MW[1)].

As shown in Fig. 6, the national average NCCR of coal-fired power units has experienced a nearly continual decrement after China's implementation of the reform and opening-up policy except the mid and late 1990s. The national average NCCR underwent six distinctive decrement periods, i.e. 1978–1984, 1990–1997, 1998–2001, 2002–2006, 2007–2008, and 2009–present, when the average annual NCCR decrement is about 7.4, 3.0, 5.8, 3.6, 11, and 4.0 g/kWh respectively. A conjoint analysis of the ICPC growth rate, SPCR, AUH, and their historical background as introduced in Section 2 indicates that the reasons for the decrement of the national average NCCR in different periods are rather complicated and different with each other.

In the first two years of the reform and opening-up period, as many new installed units were imported from Japan and European countries, the national average NCCR declined by 13–14 g/kWh annually as the ICPC increased at an annual rate of approximately 11%. As the ICPC growth rate dropped to about 4% in the following four years, the annual decline of national average NCCR dropped from 9 g/kWh in 1980, and gradually to 2 g/kWh in 1984. As the SPCR and AUH remained steady during this time, the improvement of management and operational efficiencies in the power system were also thought to be the key factors for the decline of the national NCCR in this

1) Statistics Bulletin on National Power Industry (1978–2017). China Electricity Council, Beijing, 2017 (in Chinese)

period.

In 1985–1989, many small coal-fired power units with a relatively lower thermal efficiency were installed as the result of the severe power shortage. Consequently, the national average NCCR of coal-fired power units did not decline, given the fact that the annual average growth rate of ICPC as high as 11.3%. Thanks to the mass production of the introduced type and self-developed subcritical coal-fired power units, the thermal efficiencies of new installed coal-fired power units were greatly improved. Thereafter, the national average NCCR of the of coal-fired power units began to decline steadily in 1997, but the annual decline was gradually reduced to 2g/kWh after 1995 as the influence of new technologies weakened.

Since the demand-supply balance was basically achieved in mid 1990s, the central government began to pay more attention to the structure optimization of the power industry and the improvement of management and operation efficiencies. Thereafter, the State Power Corporation was established in 1997, and the policy of "replacing small units by large ones" was immediately introduced by the State Power Corporation. Two years later, the implementation advice on shutting down small thermal power plants was issued by the former State Economic and Trade Commission of China. As a result, small coal-fired power units with a capacity of 12.26 GW were shut down by the end of 2001 [23]. Besides, the national average SPCR was reduced significantly in this period. Accordingly, the national average NCCR of coal-fired power units declined by 6 g/kWh annually in 1998–2001[1)].

After the Asian financial crisis, the rapid growth of economy demanded a great of electricity. However, it took time for the power industry to recover from the depression. As a consequence, a power shortage emerged again in 2001, and worsened in the following several years. Undoubtedly, the shutting down of small thermal power units was suspended, and a large number of new small coal-fired power units were gradually installed from 2003 on. Meanwhile, the AUH increased immediately after 2002, and the service power consumption rate began to increase as the AUH arrived at a high value as shown in Fig. 6. Accordingly, the annual decline of national average NCCR was reduced to 2 g/kWh in 2002 and the annual decline of national average NCCR coal-fired power units was only 3 g/kWh, given the fact that the growth rate of thermal power capacity was as high as 23.7% in 2006. The new installation of subcritical power units had almost lost its effectiveness in reducing the national average NCCR then.

As the power shortage problem was gradually solved after 2006, the "Suggestion on Accelerating the Shutdown of Small Thermal Power Units was issued by the State Council in January 2007. The central government began to restore the policy of shutting down small coal-fired power units in a more aggressive way. Consequently, the shutdown capacities of small coal-fired power units were as high as 14.36 GW and 16.69 GW in 2007 and 2008 respectively, which was significant for the decline of national average NCCR. Besides, since the domestic critical and supercritical coal-fired power units were mass produced step by step, and the growth ratio of ICPC was still high, the annual decline of national average NCCR of coal-fired power units reached 11 g/kWh in these two years, as shown in Fig. 6. As the shutdown capacity of small coal-fired power units declined after 2009 and the influence of new installed critical/supercritical units was gradually decreased, the annual decline of national average NCCR of coal-fired power units was gradually reduced.

Moreover, since the issue of the Comprehensive Work Plan of Energy Conservation and Emission Reduction by the State Council in 2007, the work on efficiency enhancement has been increasingly concerned by coal-fired power industry. Thereafter, many energy-saving technologies have been adopted in coal-fired power plants. As Fig. 6 shows, the national average SPCR has been gradually reduced in the past decade. For this reason, the national average NCCR of coal-fired power units continually declines at an annual average value of about 3 g/kWh in recent years, despite the low AUH in the past few years, as shown in Fig. 6.

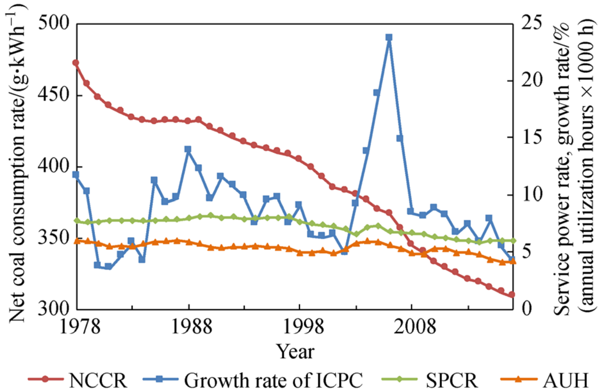

Fig. 6 Key indexes of China's installed coal-fired power units

A thorough investigation of the development of China's coal-fired power industry in the past 70 years demonstrates that the national average thermal efficiency of the coal-fired power industry, represented by the national average NCCR, is mainly influenced by installing new advanced units, eliminating outdated capacity, adopting energy conservation technologies, and improving the management and operation efficiencies.

Generally, a new generation units has an influence cycle of around 5–7 years on the decline of national average

1) Statistics Bulletin on National Power Industry (1978–2017). China Electricity Council, Beijing, 2017 (in Chinese)

NCCR, whose effect will last around 5–10 g/kWh during the first several years and will then decrease gradually. The effect of eliminating outdated capacity on the decline of national average NCCR depends on the closed capacity and the corresponding backwardness. Generally, an annual decline of 5–10 g/kWh could be achieved given eliminating a considerable capacity of outdated production. Comparatively, the effects of adopting energy conservation technologies and improving management and operation efficiencies are apparently less, but their influence cycles are longer.

3.2 Performance on emission reduction

Coal is the main fossil fuel in China, and around half of them are used for power generation. When coal is burnt in boilers, a great deal of dust, SO_2, and NO_x are produced, which are the main air pollutants in the environment. The first national standard covering emission control of coal-fired power plant was issued in 1973 [24], where the emissions, other than the emission concentrations of dust, SO_2 and NO_x were limited. The first special emission standard of air pollutants for coal-fired power plants was issued in 1991 [25], when the dust emission concentration was first limited according to different boundary conditions. This standard was first revised in 1996 [26], when the emission of SO_2 and NO_x were first limited by both emission and emission concentration. Thereafter, the emission standard of air pollutants for thermal power plants was revised twice in 2003 [27] and 2011 [28] respectively. The worldwide strictest ultra-low emission standard was put into implementation in 2014 by the Action Plan on Upgrading and Reconstruction of Coal-fired Power Industry for Energy Conservation and Emission Reduction (2014–2020) in 2014[1)].

To improve the environment, prevent and control air pollution, ensure public health, the Environmental Protection Law of the People's Republic of China (Trial) was enacted in 1979. Along with the emission standards being revised again and again, the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution was enacted in 1987, and then revised in 1995, 2000, and 2015 respectively. Besides, the Environmental Protection Law of the People's Republic of China was officially enacted in 1989, and then revised in 2014. The enactment and issue of these laws have guaranteed the implementation of the continually updated emission standards in coal-fired power industry.

The limits of air pollutants for newly installed coal-fired power units specified in different emission standard versions are displayed in Fig. 7. It can be seen from Fig. 7 that the national emission standards for coal-fired power units are increasingly stringent. The latest ultra-low emission standards require that the emission concentrates of dust, SO_2, and NO_x in coal-fired power plants should be not more than 10, 35, and 50 mg/Nm^3 respectively. These emission allowances are respectively about 5%, 3%, and 8% of the corresponding values in the 1996 edition.

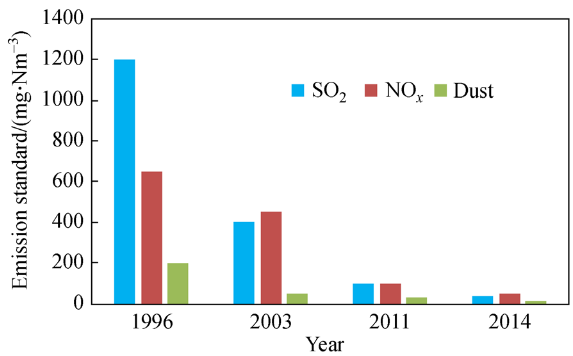

Fig. 7 Emission standards of air pollutants for new installed coal-fired power plants

Influenced by the increasingly stringent emission standards and corresponding laws, the emissions of dust, SO_2, and NO_x in the coal-fired power industry have experienced an increasingly decrease in recent years. The Annual Development Report of China's Power Industry issued by the Electricity Council[2)] shows that the emissions of dust, SO_2 and NO_x in China's coal-fired power industry are only about 0.26, 1.2 and 1.14 million tons in 2017, which account for only about 2%, 7% and 7% of the national total emission respectively. Compared to the emissions in 2007, the annual pollutants emissions are reduced by 93%, 90%, and 86% respectively. It is obvious that coal-fired power industry is not the main industrial source of air pollutants anymore.

3.3 Peak shaving capacity

With the fast development of renewable energy power generation, the grid regulation capacity is growing correspondingly. By jointly analyzing the 13th Five-Year-Plan on energy development, and related researches on the prediction of China's power structure[3)], the national installed power capacity is assumed to arrive at 2.1, 3.1, and 4.5 TW in 2020, 2030, and 2050 respectively in a

1) Action plan on upgrading and reconstruction of coal-fired power industry for energy conservation and emission reduction (2014–2020). National Development and Reform Commission of the People's Republic of China, Ministry of Environmental Protection of the People's Republic of China, National Energy Administration of the People's Republic of China, Beijing, 2014 (in Chinese)
2) Annual Development Report of China's Power Industry. China Electricity Council, Beijing, 2018 (in Chinese)
3) The 13th Five-Year Plan for Energy Development in People's Republic of China. National Development and Reform Commission of the People's Republic of China, Beijing, 2016 (in Chinese)

medium development scenario[1)] [29–30]. The overall share of the renewable power sector, including water power, wind power, and solar power will gradually increase to 35%, 37%, and 43% in 2020, 2030, and 2050 respectively. Meanwhile the share of the coal-fired power sector will be gradually reduced to 52%, 43%, and 33% correspondingly.

As the installed and exploitable capacity of peaking load power like pumped-storage power is limited in China [31,32], coal-fired power, as the main power source, has to undertake more and more peak shaving obligation in the coming future. A typical daily load curve of the Jing-Jin-Tang Power Grid in China indicates that the peak-valley difference is around 30% [33]. As the national total installed capacity of stable power sources, including thermal power and nuclear power, is about 1142 GW in China in 2017 and considering the regular maintenance, 90% of this table power capacity is assumed to exactly meet the peak load requirement of the grid. It can be inferred that about 308 GW regulation capacity is needed for a regular peak-valley regulation in the grid. Then how much of the regulation capacity is left for the renewable energy power sources?

As energy conservation and emission reduction are of increasing concerned, the combined heat and power (CHP) generation has experienced a fast development in China, as shown in Fig. 8. As can be seen from Fig. 8, around a half of the ICPC in China (about 500 GW) refers to CHP units in 2017, including about 350 GW central heating supply units and about 150 GW industrial steam supply units. However, most of the CHP units run according to the rule of "determining the power generation by heating load" [5]. As a result, most of the CHP units barely participate in peak regulation during the heat supply period. A survey shows that the overall regulation capacity of CHP units in China is less than 100 GW, which seriously affects the overall regulation capacity of coal-fired power industry.

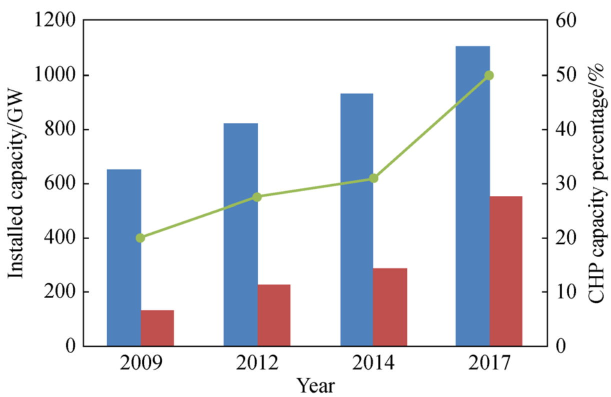

Fig. 8 Development of CHP units in China

Generally speaking, most of the conventional thermal power units, about 500 GW in 2017[2)], were designed to be regulated from 40% to 100% the nominal load. However, considering the operational factors of coal qualities, emission control, auxiliary equipment performances, and thermal control qualities, the existing coal-fired power units are generally regulated above 50% nominal load [33]. Thereby, a regulation capacity of about 250 GW is estimated for this section.

The above analysis suggests that the coal-fired power units have only about 40 GW extra regulation capacity left for the peak shaving of renewable energy. Besides, as China's economic development is slowed down in the new normal economy era, an obvious over investment has been witnessed in the coal-fired power industry [34], leading to an obvious decline in the national average AUH. If this over investment is considered, the available regulation capacity for the peaking shaving of renewable energy is very limited. The above analysis might explain the reason for the wide existing problem of abandoning wind and solar energy by the grid [35].

As the load of a steam turbine can be easily regulated to an extreme low or even zero condition, the regulation capacity of a coal-fired power unit mainly relies on the low-load performance of the boiler. Fortunately, most of the heat loads of CHP units are above the minimum loads required by the boilers. Therefore, it is generally applicable for a CHP unit to run in an extreme low or even zero load condition. According to a study, a full-load main-steam bypass (FLMB) is introduced to decouple the heat and power generation in CHP units [36]. By adopting this FLMB technology, the main-steam piping could be completely closed during the valley period of the grid, when the heat load is fully supplied by the main-steam bypass. By adopting this method, a large amount of regulation load could be released from CHP units compared to the "determining the power generation by heating load" scheme.

An aggregate analysis on the heat balance diagrams of typical steam turbines of different types shows that a central heat supply CHP unit generally could supply a power load of about 75% of the nominal load, and an industrial steam supply CHP unit generally could supply a power load of about 80% of the nominal load in the maximum extraction condition. If all of the CHP units are reconstructed using the FLMB technology, a regulation capacity of above 350 GW could be released by reducing the steam turbine load to zero.

1) National Electric Power Planning Research Center of China. Development forecast of medium and long term generation capacity and power demand in China. China Energy News, 2013-2-18 (in Chinese)

2) National Power Industry Statistics Bulletin. National Energy Administration of the People's Republic of China, Beijing, 2018 (in Chinese)

4 Conclusions and proposed strategies

Coal-fired power has always been China's main power source since its birth. As a result of the world wide continual progress in coal-fired power technologies, a great success has been made in China's coal-fired power industry, including manufacturing technology, thermal efficiency, as well as pollutants control. However, with the fast development of the renewable energies power generation, coal-fired power industry is facing a great strategic transformation. A comprehensive analysis leads to the conclusion that the role of coal-fired power should be transformed from the dominant position to a base one in China's power structure.

A thorough investigation of thermal efficiency, emission reduction, and peak shaving capacity suggests that a continual investment should be conducted on the new technologies of coal-fired power, so as to assure that a replacement cycle of the state-of-the-art coal-fired technology is not more than 7 years. The elimination of outdated capacity should be kept at a continual and steady path. Besides, the newly issued emission standard of air pollutants for coal-fired power industry is strict enough, which is meaningless to be even stricter. Moreover, combined heat and power (CHP) generation units should be reconstructed to operate in an decoupled way, so as to release more than 350 GW regulation capacity for the peak shaving of renewable energy.

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Notations

AUH	Annual utilization hours/h
CHP	Combined heat and power
DC	Direct current
FLMB	Full-load main-steam bypass
ICPC	Installed coal-fired power capacity/TW
LHV	Low heat value/kJ/kg
NCCR	Net coal consumption rate/($g \cdot kW^{-1} \cdot h^{-1}$)
SPCR	Service power consumption rate/%
TRT	Top gas recovery turbine units

References

1. National Bureau of Statistics of China. China Statistical Yearbook. Beijing: China Statistical Press, 2016 (in Chinese)
2. Han S, Chen H, Long R, Cui X. Peak coal in China: a literature review. Resources, Conservation and Recycling, 2018, 129: 293–306
3. Li D, Wu D, Xu F, Lai J, Shao L. Literature overview of Chinese research in the field of better coal utilization. Journal of Cleaner Production, 2018, 185: 959–980
4. Zhang B. China's Power Industry Chronicles. Beijing: Contemporary China Publishing House, 1998 (in Chinese)
5. China Electricity Council. The Power Industry Statistics Compilation in 2015. Beijing: China Electricity Council, 2016 (in Chinese)
6. Fan H, Zhang Z, Dong J, Xu W. China's R&D of advanced ultra-supercritical coal-fired power generation for addressing climate change. Thermal Science and Engineering Progress, 2018, 5: 364–371
7. Chen W, Xu R. Clean coal technology development in China. Energy Policy, 2010, 38(5): 2123–2130
8. Chang S, Zhuo J, Meng S, Qin S, Yao Q. Clean coal technologies in China: current status and future perspectives. Engineering, 2016, 2 (4): 447–459
9. Huang L, Hu J, Chen M, Zhang H. Impacts of power generation on air quality in China—part I: an overview. Resources, Conservation and Recycling, 2017, 121: 103–114
10. Zhao X, Wu L, Li A. Research on the efficiency of carbon trading market in China. Renewable & Sustainable Energy Reviews, 2017, 79: 1–8
11. Moosavian S M, Rahim N A, Selvaraj J, Solangi K H. Energy policy to promote photovoltaic generation. Renewable & Sustainable Energy Reviews, 2013, 25: 44–58
12. He Y, Pang Y, Li X, Zhang M. Dynamic subsidy model of photovoltaic distributed generation in China. Renewable Energy, 2018, 118: 555–564
13. Wang C, Zhao Y, Liu M, Qiao Y, Chong D, Yan J. Peak shaving operational optimization of supercritical coal-fired power plants by revising control strategy for water-fuel ratio. Applied Energy, 2018, 216: 212–223
14. Na C, Yuan J, Xu Y, Hu Z. Penetration of clean coal technology and its impact on China's power industry. Energy Strategy Reviews, 2015, 7: 1–8
15. Goto K, Yogo K, Higashii T. A review of efficiency penalty in a coal-fired power plant with post-combustion CO_2 capture. Applied Energy, 2013, 111: 710–720
16. Huang X. The status of electric-lamp industry from 1879 to 1911 in China and its industrial heritage. Journal of Inner Mongolia Normal University (Natural Science Edition), 2009, 38: 329–336 (in Chinese)
17. Du X. An Overview of the Academic Achievements of China's Famous Scientists in Twentieth Century (Energy and Mining Engineering Volume: Power and Electrical Science, Technology and Engineering). Beijing: Science Press, 2014 (in Chinese)
18. Wang B. Several problems of maintaining the balance of power supply and demand in China. Electric Power Technology and Economy. 2001, 5–8 (in Chinese)
19. Cheng J. History of Major Chinese Technical Equipment. Beijing: China Electric Power Press, 2012 (in Chinese)
20. Li H, Mao J. The present situation adjustment measures and policy advice of electric power industry. International Electric Power for China, 2000, (04): 4–9 (in Chinese)

21. Zhu Z. “Power shortage” = another “SARS”? China Report, 2006, (04): 29–38 (in Chinese)
22. Sahu B K. Wind energy developments and policies in China: a short review. Renewable & Sustainable Energy Reviews, 2018, 81: 1393–1405
23. Xue X, Li J, Geng Z, Zhu X, Zheng S. China’s action on shutting down small thermal power units. China Energy, 2003, (03):10–13 (in Chinese)
24. State Planning Commission of the People’s Republic of China, Basic Construction Commission of the People’s Republic of China, Ministry of Health of the People’s Republic of China. Industrial “Three Wastes” Emission Standards Trial Edition (GBJ4–73). Beijing: Standardization Administration of the People’s Republic of China, 1973 (in Chinese)
25. National Environmental Protection Agency of the People’s Republic of China. Emission Standards of Air Pollutants for Coal-Fired Power Plants (GB13223–91). Beijing: Standardization Administration of the People’s Republic of China, 1991 (in Chinese)
26. National Environmental Protection Agency of the People’s Republic of China. Emission Standard of Air Pollutants for Thermal Power Plants (GB13223–1996). 2nd ed. Beijing: Standardization Administration of the People’s Republic of China, 1996 (in Chinese)
27. State Environmental Protection Administration of the People’s Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China. Emission Standard of Air Pollutants for Thermal Power Plants (GB13223–2003). 3rd ed. Beijing: Standardization Administration of the People’s Republic of China, 2003 (in Chinese)
28. Ministry of Environmental Protection of the People’s Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China. Emission Standard of Air Pollutants for Thermal Power Plants (GB13223–2011). 4th ed. Beijing: Standardization Administration of the People’s Republic of China, 2011 (in Chinese)
29. Shan B G, Han X Y, Tan X D, Wang Y P, Zheng Y. Research on electricity demand of China during the 13th Five-Year Plan and Med-Term-& Long-Term Periods. Electric Power, 2015, 1: 6–10 (in Chinese)
30. Zhang X L, Liu J L, Wang K, Cui X Q, Zou J. Study on medium and long-term low-carbon development pathway of China’s power sector. China Population, Resources and Environment, 2018, 4: 68–77 (in Chinese)
31. Zeng M, Zhang K, Liu D X. Overall review of pumped-hydro energy storage in China: status quo, operation mechanism and policy barriers. Renewable & Sustainable Energy Reviews, 2013, 17: 35–43
32. Ding N, Duan J, Xue S, Zeng M, Shen J. Overall review of peaking power in China: status quo, barriers and solutions. Renewable & Sustainable Energy Reviews, 2015, 42: 503–516
33. Gu Y, Xu J, Chen D, Wang Z, Li Q. Overall review of peak shaving for coal-fired power units in China. Renewable & Sustainable Energy Reviews, 2016, 54: 723–731
34. Yuan J, Li P, Wang Y, Liu Q, Shen X, Zhang K, Dong L. Coal power overcapacity and investment bubble in China during 2015–2020. Energy Policy, 2016, 97: 136–144
35. Chen J, Liu W, Jiang D, Zhang J, Ren S, Li L, Li X, Shi X. Preliminary investigation on the feasibility of a clean CAES system coupled with wind and solar energy in China. Energy, 2017, 127: 462–478
36. Andersen T V. Integration of 50% Wind Power in a CHP Based Power System: a Model-based Analysis of the Impacts of Increasing Wind Power and the Potentials of Flexible Power Generation. Dissertation for the Master’s Degree. Kongens Lyngby, Copenhagen: Technical University of Denmark, 2009