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REVIEW ARTICLE

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Energy conservation in China's coal-fired power industry by installing advanced units and organized phasing out backward production

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Abstract Coal-fired power is the main power source and the biggest contributor to energy conservation in the past several decades in China. It is generally believed that advanced technology should be counted on for energy conservation. However, a review of the decline in the national average net coal consumption rate (NCCR) of China's coal-fired power industry along with its development over the past few decades indicates that the upgradation of the national unit capacity structure (including installing advanced production and phasing out backward production) plays a more important role. A quantitative study on the effect of the unit capacity structure upgradation on the decline in the national average NCCR suggests that phasing out backward production is the leading factor for the decline in the NCCR in the past decade, followed by the new installation, whose sum contributes to approximately 80% of the decline in the national average NCCR. The new installation has an effective affecting period of about 8 years, during which it would gradually decline from a relatively high value. Since the effect of phasing out backward production may remain at a certain degree given a continual action of phasing out backward capacity, it is suggested that the organized action of phasing out backward production should be insisted on.

Keywords coal-fired power, energy conservation, net coal consumption rate, new installation, phasing out backward production, unit capacity structure

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1 Introduction

As the main energy resource, coal resource accounts for approximately 70% of the overall energy consumption in China [1,2]. The annual coal consumption for power generation has surpassed 1.3 billion tons of standard coal since 2015 [1], from which about 80% of the electricity was generated in the past several decades [3]. Coal-fired power industry is no doubt the biggest engine for the development of China in, but not limited to industry, construction, transportation, agriculture and daily life.

Along with the rapid development of industrialization, the demand for energy resources accelerates, and China has become the world's largest energy consumption country since 2010 [4]. While the energy supply is limited [5], the demand for energy conservation is getting bigger and bigger. Since the Comprehensive Work Plan of Energy Conservation and Emission Reduction (2007 No. 15) was issued by the State Council in 2007 1) , energy conservation has been paid more and more attention in coal-fired power industry. To cope with the energy security problem, a revolution of energy production and consumption was proposed in China in 2014 2). To mitigate climate change, China-US Joint Announcement on Climate Change was also issued in 2014 3)[6], where China's fossil consumption is supposed to reach the peak in about 2030 [2]. All in all, energy supply, energy security, and energy conservation have been increasingly concerned over the world [7].

Considering the resources endowment in China, the special status of coal resource in China's primary energy consumption is hard to be changed in the near future 4).

1) The State Council. Comprehensive Work Plan of Energy Conservation and Emission Reduction ([2007] No. 15) (in Chinese)
2) Xi J. Actively promoting China's energy production and consumption revolution. 2014 (in Chinese)
3) China-US Joint Announcement on Climate Change. 2014
4) BP Energy Outlook/Country and regional insights— China. 2017

Although renewable energy sources have been extensively exploited in recent years, their unstable characteristics determine that they could not play the leading role in China's energy structure [8]. Unlike the electricity generated from renewable energy resources which fluctuates heavily and can hardly be predicted [9], the electricity generated from coal-fired power industry can be easily regulated [10].

Coal-fired power industry, as the biggest fossil fuel consumer, has always been the main contributor to the energy conservation in the past several decades in China [11]. The energy conservation of coal-fired power industry is mainly achieved by the improvement of plant efficiency, which refers to the ratio of net power supply over the overall heat consumption. In the power industry, plant efficiency is used to be denoted by the net coal consumption rate (NCCR, referring to the standard coal consumption rate for unit power generation, g/kWh). By the end of 2017, the national average NCCR of the thermal power units in China had been reduced to 309 g/kWh, accounting for only 27%, 66%, and 81% of those values after the establishment of the People's Republic of China (1949), before the reform and opening-up (1978), and the reformation of electric power system (2002), respectively [12,13]. The NCCR of an advanced coal-fired power unit in China has been reduced to less than 260 g/kWh (48.12% based on the low heat value, LHV) [14]. As the coal-fired power industry plays an irreplaceable role in China's energy and power structure, its continual contribution to the national energy conservation is an important strategic issue for energy security.

A review of the literature indicates that the structure up-gradation has always been concerned in the power industry. Strategies like promoting advanced ultra-super-critical coal-fired power technology [15], phasing out outdated power capacity [16], and developing renewable energies [17] are widely proposed. Many studies related to structure optimization of power sources [18], power generation deal [19], and renewable energy replacement prediction [20], have been conducted and predicting models in carbon constraint model [21] have been developed in the past decades. However, few discussions related to specific energy conservation value have been found. Other researches in this field mainly focus on specific technologies, like advanced-ultra super critical power generation technology (A-USC) [22,23], higher temperature/pressure materials [24,25], hybrid power generation technologies [26], double reheat technology [27], low-temperature economizer [28], etc. These technologies might be effective for some specific units, while as far as a nation's total coal-fired power industry is concerned, their influence might be less.

Considering the significant role of coal-fired power industry in China's energy conservation, it is of great importance to clarify its efficiency improvement process (i.e., the NCCR decline) in the past, and work out an effective and applicable scheme for its continual energy conservation. Accordingly, the decline in the national average NCCR of China's coal-fired power industry is first reviewed. Then the relationship between the up-gradation of unit capacity structure (including installation of advanced units and phasing out of backward production) and the decline in the national average NCCR in the past few decades is analyzed. Finally, the influences of new installation and phasing out of backward production are investigated, and strategies for energy conservation of the coal-fired power industry are proposed.

2 Decline in national average NCCR

Since the earliest power generating assembly emerged in China in 1879 [12,29], China's power industry has undergone about 140 years. From the late Qing Dynasty to the end of the Republic of China, the national installed coal-fired capacity increased gradually from 0 GW to 1.69 GW, and the national average NCCR declined gradually from above 1800 g/kWh to about 1130 g/kWh (11% in LHV) [12]. As the statistical data of that era is very limited, this section would mainly focus on the period after the foundation of the People's Republic of China (PRC). With regard to several landmark events related to the power industry in China, the time after the foundation of the PRC is divided into the preliminary construction stage (1949–1978), the reform and opening-up stage (1979–2002), and the stage after the reform of the electric power system (2003–now).

2.1 Preliminary construction stage

The preliminary construction stage in this paper refers to the time after the foundation of the PRC to the time before the reform and opening-up. After the foundation of the PRC, the coal-fired power industry was first recovered from the devastation of the Wars. With the help of Soviet Union, a lot of large capacity coal-fired power plants were reconstructed or constructed. By importing manufacturing technologies of medium pressure and high pressure coal-fired power units from Czechoslovakia and Soviet Union respectively, the national manufacturing industry increased gradually from nothing.

As China's coal-fired power capacity accounts for most of the thermal power capacity (88%–99%), the national statistical data of coal-fired power units have not been recorded separately in a long period of time, thereby they are generally represented by those of the overall thermal power units. Figure 1 shows the development of the national installed thermal power capacity and its average NCCR in the preliminary stage [12]. It can be seen from Fig. 1 that the rapid development periods of the installed capacity are located mainly in 1953–1960 and 1969–1978 while the rapid decline in the national average NCCR are located mainly in 1949–1958 and 1962–1966. The rapid development of the national installed capacity is not always connected with the rapid decline in the national NCCR as can be seen from the lines in Fig. 1.

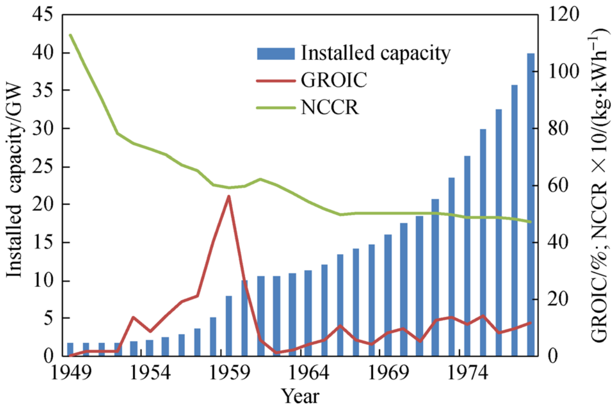

Fig. 1 Development of China's thermal power industry during 1949–1978

The first sharp drop in the national average NCCR of the coal-fired power industry occurs during 1949–1952, without any promotion from the increased national installed capacity as can be seen from the bar and line in Fig. 1. An analysis of the historical data demonstrates that this sharp drop in the national average NCCR is mainly achieved by a recovery of the industrial production from the devastation of wars, including the improvement of the annual utilization hours (AUH) of the equipment, the reduction in service power consumption rate (SPCR), and the enhancement of operational management [12]. Subsequently, aided by Soviet Union, the national installed thermal power capacity increased sharply from 1.78 to 3.62 GW during 1952–1957 while the national average NCCR decreased steadily from 785 to 651 g/kWh.

Afterwards, the national installed thermal power capacity skyrocketed from 3.62 to 9.98 GW during 1958–1960. The deterioration in the Sino-Soviet relations in 1960 saw the independent development of the power industry. Due to rough design, inferior manufacturing, and non-standard operation, most of the installed coal-fired units could not run properly. Consequently, even though the growth rate of the installed capacity (GROIC) was very high, the national average NCCR decreased only in the first two years, and then became to rebound.

The next steady decline in the national average NCCR occurred during 1962–1966. Since the national economy entered the adjustment period (1961–1965), many delayed projects were reconstructed. The operation, maintenance, and management in coal-fired power plants were greatly improved. Besides, the domestic manufacturing technologies of 25, 50 and 100 MW units were developed with competent operating performances compared to the imported units [30]. As a result, the national average NCCR was steadily reduced without much new installed coal-fired power capacity.

However, the good time did not last long. During the ten years from 1966 to 1976, the newly recovered power industry was struck again. Even through many advanced technologies were developed, such as the domestic super high pressure 125200 MW, the subcritical 300 MW technologies, and the installation of 19.11 GW new thermal power units, the national average NCCR was not obviously reduced as a result of low-level management in the whole industry.

Before the reform and opening-up of China, China's economy experienced a 2 year lingering period. During this time, the coal-fired power industry was gradually adjusted again. Many unreasonable production modes were corrected, and many equipment problems were solved. Thereby, an obvious decline in national average NCCR is seen again from 1978.

On the whole, through about 30 years of technology introduction, assimilation, and self-development, although starting from scratch, great progress have been made in the coal-fired power industry of China. The national installed capacity of coal-fired power units grew from 1.69 to 39.84 GW, an increase of about 23 times while the national average NCCR fell from 1130 to 471 g/kWh, a reduce of about 60%.

2.2 Reform and opening-up stage

The reform and opening-up stage refers to the period between the implementation of the reform and opening-up policy and the reform of the electric power system (1978–2002). Driven by the rapid development of economy as the result of the reform and opening-up, the power shortage was getting increasingly severe [31]. Influenced by the 10 year's economic chaos before the reform and opening-up of China, the domestic manufacturing technology of the power industry was too backward, and the power source construction fell behind. Consequently, many subcritical coal-fired power units of 300 MW class were imported from Japan and European countries. To improve the overall manufacturing status of the coal-fired power industry, manufacturing technologies of 300 and 600 MW subcritical coal-fired power units were introduced from Westinghouse Electric Corporation (WH) and Combustion Engineering Corporation (C-E) [32].

Figure 2 exhibits the development of the national installed thermal power capacity and the average NCCR in the reform and opening-up stage, where the data refer to most of the units in service with a nominal load of above 6 MW [33]. As can be seen from the lines, the national average NCCR of coal-fired power units experienced a steady decrement after the reform and opening-up except the mid and later 1990s. Again, the development of the national installed capacity is not always consistent with the decline in the national NCCR, especially during 1985–1990.

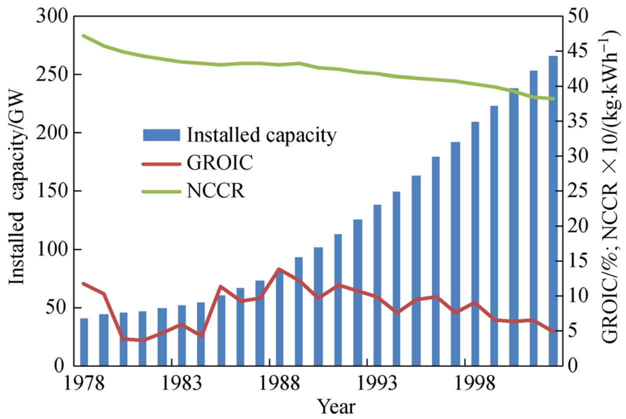

Fig. 2 Development of China's thermal power industry during 1978–2002

After the reform and opening-up policy, many new installed units were imported from Japan and European countries. Then the national average NCCR declined by 13–14 g/kWh annually in 1978–1979 as the GROIC is about 11%. As the GROIC dropped to about 4% in the following four years, the annual decline in the national average NCCR was still as high as 9 g/kWh in the 1980, although the annual decline was gradually reduced to 2 g/kWh in 1984. As stated in Section 2.1, the rapid decrement in the national average NCCR in the years around 1978 partially resulted from the bringing order out of the chaos before the reform and opening-up of China, where the enhancement of management and operational efficiency in the power system were thought to be the main factors leading to the improvement of the thermal efficiency in this period [12].

However, as the national thermal power capacity barely increased during 1980–1984, the power shortage problem became increasingly severe. Since the manufacturing technologies of introduced type 300 and 600 MW subcritical coal-fired power units had not been trial-produced, a large number of backward, small coal-fired power units were installed during 1985–1989. Consequently, the national average NCCR remained unchanged even though the average growth gate of the capacity was as high as 11.3% as shown by the GROIC line and capacity histogram in Fig. 2.

With the mass production of introduced type and self-developed subcritical 300 and 600 MW coal-fired power units, the thermal efficiency of new installed coal-fired power units were greatly improved. Thereafter, the national average NCCR of coal-fired power units began to steadily decline in 1997, although the annual decline was gradually reduced to 2 g/kWh after 1995.

Since the demand-supply balance was achieved after mid 1990s [31], the GROIC was gradually reduced after 1997. However, as the government began to optimize the structure of power sources, the implementation advice on shutting down small thermal power plants was issued by the former State Economic and Trade Commission in 1999, and small coal-fired power units with a capacity of 12.26 GW were shut down by the end of 2001 [34]. As a result, the national average NCCR of coal-fired power units declined at an annual average of 6 g/kWh during 1998–2001 [33].

However, as the continual fast growth of power industry and outbreak of Asian financial crisis in 1998, power surplus appeared. Besides, a great number of small coal-fired power units with low heat efficiency were installed from 1985 to 1995. Consequently, low annual utilization hours (AUH) and high NCCR became the main contradictions in the power industry of China [35]. Accordingly, the approval of new power project was strictly controlled by the government in the following several years. Many small coal-fired power plants were also shut down. Many power construction enterprises were forced to disband. The development of the coal-fired power industry was gradually decreased, with an average growth rate of 6.1% from 1999 to 2002, as depicted in Fig. 3.

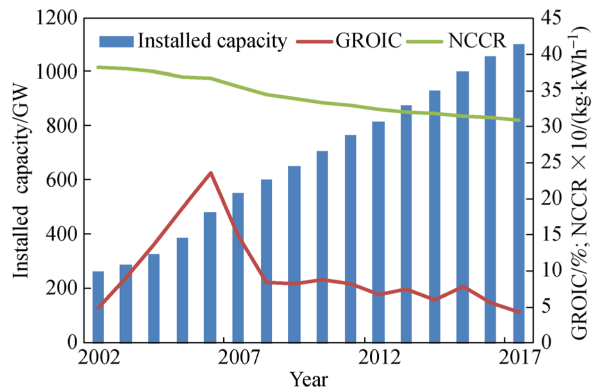

Fig. 3 Development of China's installed power capacity during 2002–2017

2.3 Stage after the reform of electric power system

The State Power Corporation was first established in 1997, and then divided into two grid corporations and five power generation corporations in 2002. As the reorganization of the State Power Corporation in 2002 finally laid out the pattern of today's electric power system. The stage after the reform of electric power system in this paper refers to the time after 2002.

As shown in Fig. 3, the national average NCCR has experienced a continuing decline after the reform of the electric power system, which could be divided into three distinctive periods of 2002–2006, 2007–2008, and 2009–present. The average annual NCCR decrement is 3.6, 11, and 4.0 g/kWh.

As the economy recovered from the Asian financial crisis, the demand for electricity increased sharply. Since it took some time for the power industry to recover from the depression, the power shortage emerged in 2001, and worsened during the following several years [36]. Thereby, the shutting down of backward production was suspended, and a blowout of coal-fired power unit installation appeared again after 2004. Even though the mass production of domestic critical coal-fired power units were achieved after 2005, the most increased units were still not advanced enough compared to the main existing units. As a result, the annual average decline in the national average NCCR of coal-fired power units was only 3.6 g/kWh from 2002 to 2006, given the annual average growth rate of thermal power capacity was as high as 16.3%.

As the demand-supply balance was achieved again after 2006, the Opinions on Accelerating the Shutdown of Small Thermal Power Units was issued by the State Council in January 2007. Accordingly, the policy of shutting down backward coal-fired power units was restored by the central government in a more aggressive way. It was reported that the phasing out capacity of small coal-fired power units reached 20.44, 18.51, and 18.13 GW in 2007, 2008, and 2009 respectively. Besides, the mass production of domestic supercritical coal-fired power units was achieved after 2007. In addition, since the Comprehensive Work Plan of Energy Conservation and Emission Reduction was issued in 2007 by the State Council, the efficiency enhancement has been increasingly concerned by the power industry. Thereafter, many energy-saving technologies have been adopted in coal-fired power plants.

As a result, the annual decline in the national average NCCR of coal-fired power units reached 11 g/kWh in these two years. However, as the capacity of phasing out backward coal-fired power units declined after 2009, and the effectiveness of new installed critical/supercritical units gradually disappeared, the annual decline in the national average NCCR of coal-fired power units was gradually decreased. However, as the effect of adopting energy-saving technologies continues, the national average NCCR of coal-fired power units continuously declines at an annual extent of about 3 g/kWh in recent years.

3 Analysis of main affecting factors

The continual development of the advanced manufacturing technology of high efficient coal-fired power units is the basic driving force for efficiency improvement, i.e., the NCCR decline of the power industry. A thorough investigation of the development of China's coal-fired power industry in the past 70 years demonstrates that, although the adoption of energy conservation technologies and the enhancement of management and operational efficiency are effective in certain periods of time, the unit capacity structure does play the most important role in the decline in the national average NCCR.

Generally, the unit capacity structure is mainly affected by the installation of advance units and the phasing out of backward ones [34]. Therefore, the relationship between unit capacity and NCCR is first introduced. Then, the development of the unit capacity structure of China's coal-fired power industry is addressed. Afterward, based on the statistical data of the national average NCCR, the operational average NCCR of different typical units, the new installed capacity and phasing out backward capacity of different unit capacity class in each year from 2006 to 2016, and the effects of new installed units and phasing out backward production in each year are calculated and analyzed.

3.1 Relationship between unit capacity and NCCR

In a Rankine cycle, the thermal efficiency of the system is mainly determined by the initial and terminal steam conditions, as well as the internal efficiency. Besides, boiler efficiency and service power consumption rate (SPCR) are also key factors affecting the thermal efficiency as far as a whole coal-fired power plant is concerned. As the terminal steam conditions are limited by the environmental temperature, attempts have been made to improve the thermal efficiency of a unit mainly by improving the initial conditions, the internal efficiency and boiler efficiency, as well as by reducing the SPCR. Generally speaking, the initial steam conditions (including initial steam pressure and temperatures), internal efficiency of a steam turbine, and boiler efficiency are improved simultaneously along with the development of coal-fired power industry. Meanwhile the SPCR is reduced accordingly.

Based on a statistical analysis of the nation-wide on service coal-fired power units, the annual average performances of different typical condensing units are estimated, as listed in Table 1, where N refers to the nominal load, P_m refers to the main steam pressure, T_m refers to the main stream temperature, T_r refers to the reheat steam temperature, T_{dr} refers to the double reheat steam temperature, HR refers to the heat rate, and η_b refers to the boiler efficiency. As can be seen from Table 1, along with the increase of nominal unit capacity, the NCCR decreases greatly. The NCCR of a typical 6 MW is approximately two times of that of a state-of-the-art unit. However, their relationship is not linear. Figure 4 illustrates the relationship between the annual average NCCR and the nominal capacity of a unit. By adopting the least square method, their relationship can be well fitted by a power function as shown in Fig. 4, where y denotes the annual average NCCR, and x denotes the nominal capacity.

3.2 Development of unit capacity structure

Before the foundation of the PRC in 1949, most of the unit capacities in the coal-fired power industry were below 2 MW. With the rapid development of coal-fired power

Table 1 Annual average performances of different typical condensing units

N/MW	P_m/MPa	T_m/°C	T_r/°C	T_{dr}/°C	HR/(kJ·kWh^{-1})	η_b/%	SPCR/%	NCCR/(g·kWh^{-1})
6	3.43	435			13600	90	10	573
12	3.43	435			12500	90	10	527
25	8.826	535			10500	90	10	442
55	8.826	535			10000	90	9	417
100	8.826	535			9500	90	8	392
200	13.24	535	535		8550	90	7	341
300	16.7	540	540		8300	91.5	6	328
600	24.2	566	566		7850	92	5.4	309
1000	26.25	600	600		7600	93.5	4.2	290
1000	31	600	610	610	7350	94.5	3.9	276

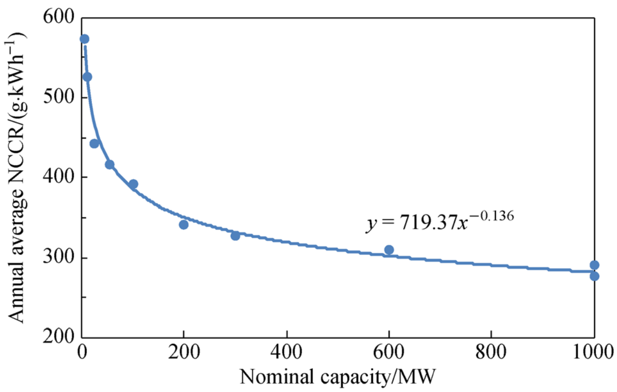

Fig. 4 NCCR versus nominal capacity of a unit

industry after 1949, the unit capacity of new installed units increased gradually from 2 MW to 6–12, 25, 50, 100, 125, 200, and 300 MW. By the end of 1980, the national total coal-fired power capacity had reached 45 GW, including 7 units of 300 MW and above, 17 units of 200–250 MW, and 112 units of 100–200 MW [12]. After the reform and opening-up, many subcritical coal-fired power units of 300 MW class were imported from Japan and European countries on the one hand, and the manufacturing technologies of subcritical 300 and 600 MW coal-fired power units were introduced from West House on the other hand.

Before the first introduced type subcritical 300 MW coal-fired power unit was put into operation in 1987, the national installed capacity of coal-fired power units had reached 72.7 GW, including 22 imported subcritical units of 300 MW and above, and 231 units of 100–300 MW. By the end of 1995, the national installed capacity of coal-fired power units had reached 163 GW, where the domestic made subcritical 300 and 600 MW units became the main contributor to new installed capacity. By the end of 2000, the national installed capacity of coal-fired power units had reached 238 GW, where the installed capacity of 300 MW units and above accounted for about 39%. Although most of the new installed coal-fired power units were of 300–600 MW, there are still a large proportion of the units which are below 300 MW.

The variation of the national installed capacities of different unit capacity classes and their percentages after 2000 is displayed in Figs. 5 and 6 respectively. It can be seen from Fig. 5 that the development of the national installed capacity is relatively slow during 2000–2004, and the national capacity of small coal-fired power units (below 100 MW, hereinafter referred to as small units) remained almost unchanged. Consequently, the proportion of 300 MW units and above accounted for about 40%, as shown in Fig. 6. During 2004–2007, the national installed capacity of small units declined slightly, while that of coal-fired power units of 300 MW units and above soared, where the new installed supercritical 600 MW class units contributed a lot after the successful trial-production of introduced type manufacturing technology in 2005. As a result, the proportion of small units declined drastically from 27.3% to 14.9%, and that of the of 600 MW units and above increase sharply from 10.7% to 25.6% (including 1.3% of 1000 MW units).

As a result of the dramatic achievement in phasing out backward production during 2007–2009, there appeared an obvious decline in the capacity of small units, as is seen from Fig. 5, while the capacity of the units of 600 MW class (600 MW $\leqslant N <$ 1000 MW) continuously increased, which dominated the overall capacity growth. Accordingly, the proportion of small units declined from 14.9% to 10.1%, and that of 600 MW class units increase greatly from 24.3% to 33.2%. Besides, since the first domestic made introduced type ultra-supercritical coal-fired power unit was put into operation in 2007, the capacity of 1000 MW class units began to steadily increase. Since 2009, the installed capacities of 300 MW class (300 MW $\leqslant N <$ 600 MW, including 350 MW supercritical units), 600 MW class and 1000 MW class ($N \geqslant$ 1000 MW) units have been steadily increased, and that of medium and small units

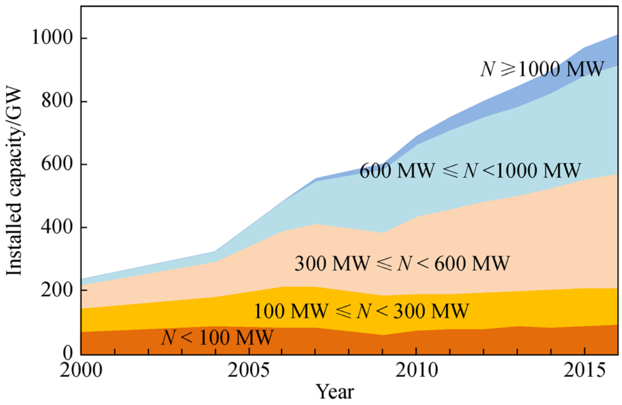

Fig. 5 Variations of installed capacity of different unit capacity classes after 2002

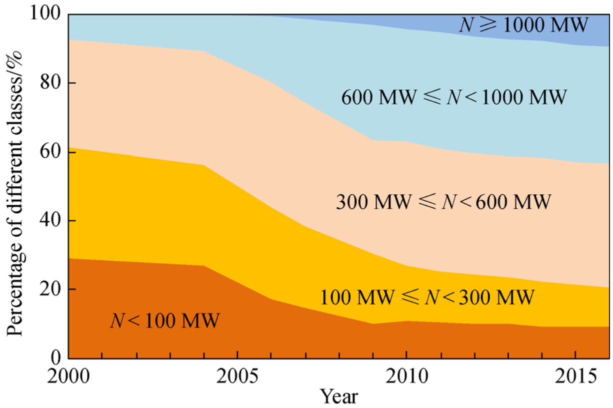

Fig. 6 Percentage variations of different unit capacity classes after 2000

(below 300 MW) has remained almost unchanged. As a result, the proportion of 1000 MW class units increased gradually from 3.1% to 9.6% (2016), while the proportion of medium and small units declined from 30.5% to 20.8% (2016).

3.3 Effect of new installation

As the relationship between unit capacity and their average NCCR is exhibited in Table 1 and Fig. 4, the effect of newly installed capacity of specific unit type on the national average NCCR could be easily calculated from Eq. (1). Accordingly, based on the average NCCR of newly installed coal-fired power units ($NCCR_{new}$), the newly installed capacity (IC_{new}, calculated by adding the national increased capacity and phased out capacity), the national average NCCR ($NCCR_{ave}$) and the national total capacity of coal-fired power units of each year (IC_{tot}), the effect of newly installed units on the national average NCCR is calculated (ΔNCCR). Figure 7 illustrates the effect of newly installed capacity on the decline in the national average NCCR and their relative data during 2006–2016. It can be observed from Fig. 7 that new installation is one of the main driving factors for the decline in the national average NCCR, especially during 2006–2009, where the effect of the new installation accounts for nearly half of the total NCCR decline. During the investigation, the accumulated effect of newly installed units on the decline in the national average NCCR amounted to 20 g/kWh, which was about 36% of the total NCCR decline.

$$\Delta NCCR = \frac{IC_{new}}{IC_{tot}}(NCCR_{new} - NCCR_{ave}). \quad (1)$$

However, the effect of the new installation on the national average NCCR decline suddenly increased in 2007 and steadily decreased afterward. A conjoint analysis of the development of the coal-fired power industry in the relevant period indicates that the mass production of domestic made (ultra) supercritical coal-fired power units is the primary reason. Besides, the booming of the new installation of coal-fired power units in 2006 and 2007 also accounts for the total NCCR decline and the effect of the new installation, as shown in Fig. 7.

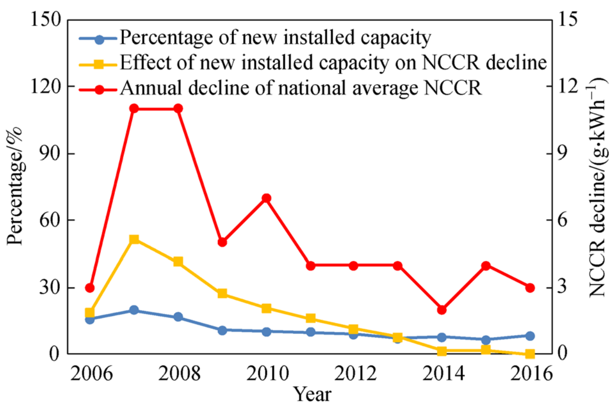

Fig. 7 Effect of new installed capacity on the decline in NCCR during 2006–2016

With the decline in the national average NCCR, the difference between the national average NCCR and the NCCR of the state-of-the-art unit decreased gradually. As a consequence, the effect of the new installation on the decline in the national average NCCR decreases correspondingly, given the same GROIC. As it always takes some time for the breakthrough of a new generation state-of-the-art technology, the effect of the new installation on the decline in the national average NCCR exhibits an obvious periodicity, usually with a cycle period of 10–20 years, as suggested by the practice in the past half century. However, as can be seen from Fig. 7, the effective period of the new installation on the decline in the national average NCCR only lasts for about 8 years, from 2006 to 2014.

3.4 Effect of phasing out backward production

Since implementation advice on shutting down small thermal power plants was issued by the central government in 1999, the organized action of phasing out backward production emerged in the power industry. Although this action was interrupted in early 2000 as the result of power shortage, it was restored in 2007 as the power-supply balance was achieved. Based on the relationship between unit capacity and the average NCCR in Table 1 and Fig. 4, the effect of phasing out backward production of specific unit type on the national average NCCR could be easily calculated from Eq. (2). By referring to the average NCCR of phasing out coal-fired power units ($NCCR_{out}$), the phasing out capacity (IC_{out}), the national average NCCR ($NCCR_{ave}$), and the national total capacity of coal-fired power units (IC_{tot}) of each year, the effect of phasing out capacity on the decline in the national average NCCR ($\Delta NCCR$) is calculated. Normally phasing out backward capacity is always followed by installing advanced units with corresponding or even a larger capacity at the same location, which is included in the new installation, but is not considered in this part.

$$\Delta NCCR = \frac{IC_{out}}{IC_{tot}}(NCCR_{ave} - NCCR_{out}). \qquad (2)$$

Figure 8 shows the effect of phasing out backward capacity on the decline in the national average NCCR and the relative data during 2006–2016. As can be seen from Fig. 8, phasing out backward production has an even larger impact on the decline in the national average NCCR, compared to the new installation as shown in Fig. 7. A great achievement on the decline in national average NCCR was made by phasing out backward production during 2007–2009, with an annual average NCCR decline of about 4.5 g/kWh. During the investigation, the accumulated effect of new installed units on the decline in the national average NCCR amounted to 27 g/kWh, which was about 46% of the total NCCR decline.

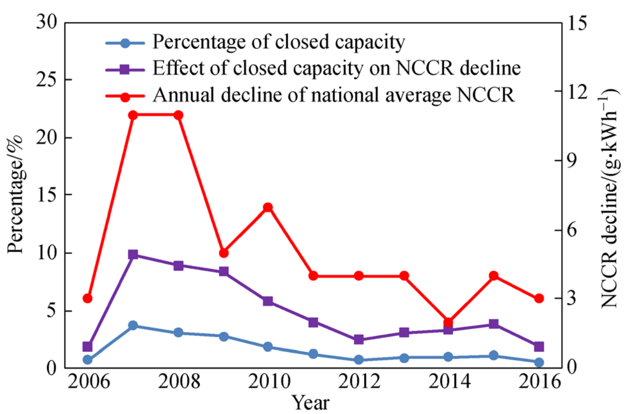

Fig. 8 Effect of phasing out capacity on the decline in NCCR during 2006–2016

Similar to the effect of the new installation, the effect of phasing out backward production on the national average NCCR decline also suddenly increased in 2007 and steadily decreased afterward. However, the difference is that the afterward effect does not decline to zero, but remains at a certain degree. By referring to the development of the coal-fired power industry in the corresponding period, the large capacity of shut down backward units during 2007–2009 accounted for the great achievement in the NCCR decline.

However, opposite to the case of the new installation, with the decline in the national average NCCR, the difference between the NCCR of backward units and the national average NCCR increases gradually. Therefore, the effect of phasing out backward production on the decline in the national average NCCR increases in some sense, given the same conditions of backward production. Then, the effect of phasing out backward production on the decline in the national average NCCR is mainly determined by the shutdown capacity and the average NCCR of those backward units. As the action of phasing out backward production is continually conducted during the past ten years, its effect on the decline in the national average NCCR remains at a certain degree recently.

4 Conclusions

Coal-fired power has always been China's main power source since the late Qing Dynasty. Thanks to its stable characteristics, the status of coal-fired power is hard to be changed in the near future, even though the renewable energy source is supposed to be exploited more extensively. As the result of the world wide continual progress in coal-fired power technology, great progress has been made in China's coal-fired power industry during the past century, as presented by the great reduction in the NCCR.

A brief review of the national average NCCR decline in China's coal-fired power industry along with its development over the past seventy years suggests that the up-gradation of the national unit capacity structure (including the installation of advanced units and phasing out of backward production) is the dominant factor for the decline in the national average NCCR.

Accordingly, the influence of the unit capacity structure up-gradation on the decline in the NCCR is studied quantitatively based on the national statistical data. It is found that, in the past decade, phasing out backward production was the leading factor for the decline in the national average NCCR, followed by new installation, which contributed to about 80% of the national average NCCR decline. However, the effect of new installation is large at first, but it declines gradually with an effective affecting period of about 8 years. Since the effect of phasing out backward production may remain at a certain degree given a continual conduction of phasing out backward capacity, a continual action of organized phasing out backward production is suggested to promote the energy conservation in the coal-fired power industry.

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Notations

AUH	Annual utilization hours
A-USC	Advanced-ultra super critical power generation technology
CHP	Combined heat and power
DC	Direct current
FLMB	Full-load main-steam bypass
GROIC	Growth rate of installed capacity/%
HR	Heat rate/($kJ \cdot kWh^{-1}$)
IC	Installed capacity/GW
LHV	Low heat value
N	Nominal unit capacity/MW
NCCR	Net coal consumption rate/($g \cdot kWh^{-1}$)
P	Pressure/MPa
PRC	The People's Republic of China
SPCR	Service power consumption rate/%
T	Temperature/°C
TRT	Top gas recovery turbine units
Greek letters	
Δ	The variation
η	Efficiency/%
Subscripts	
ave	National average value
b	Boiler
dr	Double reheat steam
n	Main steam
new	National new installed value
out	Phased out units
r	Reheat steam
tot	National total value

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