China Economic Review 80 (2023) 102000

Contents lists available at ScienceDirect

China Economic Review

journal homepage: www.elsevier.com/locate/chieco

How can China's power sector reform reduce carbon emissions? A long-term competition perspective

Chenxi Xiang, Xinye Zheng, Lunyu Xie *

School of Applied Economics, Renmin University of China, Beijing, China

ARTICLE INFO

JEL code:
Q41
Q48
Q54

Keywords:
Power sector reform
Carbon emission
Generation competition
Renewable energy
Price dividend
Carbon pricing

ABSTRACT

Challenges coexist with opportunities for achieving carbon neutrality through power sector reform. Based on the ongoing reform in China and generator-level data in 2019, we identify three channels through which the reform could affect carbon emissions. We analyze the theoretical mechanisms under a long-term average cost competition framework, evaluate the emission reduction potentials of the three channels, explore the obstacles in achieving these potentials, and propose corresponding solutions. We find the following: (1) By reshaping the generation competition between high-efficiency and low-efficiency coal-fired generators, the reform has the potential to reduce carbon emissions by 205.4 million tons. However, considering the high financial costs of high-efficiency generators, realizing the full potential is difficult. (2) Administrative promotion of renewable energy could reduce carbon emissions by 311 million tons, but with large implicit expenses, which makes the promotion unsustainable. (3) The price dividend induced by the reform could increase carbon emissions by 98.1 million tons. To achieve emission reduction potentials in the first two channels and offset the rebound effect in the third channel, we propose explicitly pricing carbon. Without other supporting measures, a carbon price of over 400 Chinese yuan per ton of carbon dioxide is essential for the reform to eliminate barriers to its implementation.

1. Introduction

China was responsible for 33% of the world's carbon emissions in 2020, and its power sector accounted for 43.1% of the country's total emissions (International Energy Agency, [IEA], 2022). The power industry is believed to have huge potential for emission reduction. Many countries have attempted to approach the goal of carbon neutrality through power sector reforms (Oscar, David, & Catherine, 2019). Some started from the supply side, improving fossil-fuel energy generation efficiency and encouraging the replacement of fossil-fuel energy with renewable energy (Lin & Zhu, 2019; Sarkodie, Adams, & Leirvik, 2020; Slate, Whitehead, Brownson, & Banks, 2019). Some studies have focused on the demand side, optimizing the electricity consumption structure to control total emissions (Cabeza & Chàfer, 2020; Wang et al., 2019; Yu, Zheng, Li, & Li, 2018). In 2015, China initiated a new round of power sector reform, aiming for a more efficient and environmentally friendly power industry. Distinguished from power sector reforms in other countries, China's reform in this round made efforts on both the supply and demand sides. The main measures included encouraging the development of high-efficiency generators by introducing market mechanisms, prioritizing renewable energy generation, and reducing electricity prices. Given the complexity and interaction of the measures, whether and how China's power sector

* Corresponding author.
E-mail address: lunyuxie@ruc.edu.cn (L. Xie).

https://doi.org/10.1016/j.chieco.2023.102000
Received 18 August 2022; Received in revised form 21 March 2023; Accepted 20 May 2023
Available online 23 May 2023

reform could reduce carbon emissions remains open for research.

Researchers have studied the impact of power sector reforms on carbon neutrality worldwide. Zarnikau (2011) found that power market reform in Texas in the United States made a significant contribution to its leading role in renewable power, which promoted the reduction of carbon emissions. Craig and Savage (2013) reported a potential 30–50 million ton decrease in carbon emissions after introducing market mechanisms into the power sector of the United States. Kuramochi, Wakiyama, and Kuriyama (2017) pointed out that power sector reform would be a key step toward Japan's emission reduction target in 2030. Ahn and Jeon (2019) concluded that power sector reform in South Korea reduced CO_2 emissions, and the main measures included expanding the use of renewable energy and imposing restrictions on the operation of coal power plants. Agyeman and Lin (2023) discovered that deregulation in the electricity market could promote innovation in carbon capture and storage in OECD countries in the European Union.

Research on China's power sector reform and carbon neutrality has increased in recent years. Some research has focused on the dispatch transition in the reform. For example, Wei et al. (2018) estimated the coal consumption change from the traditional "equal share" dispatch to economic dispatch, and found that the new approach would reduce fuel consumption by approximately 6%, thus reducing carbon emissions. Abhyankar, Lin, Liu, and Sifuentes (2020) investigated the benefits of economic dispatch in China and found a 7%–10% reduction in CO_2 emissions. Some research has focused on the impact of relevant policies on the reform. For example, using data from Guangdong, Pollitt, Yang, and Chen (2018) qualitatively provided an overview of the policies, operations, and potential effects of power reform. Other studies have assessed carbon pricing instruments. Cao, Ho, Ma, and Teng (2021) conducted an *ex post* evaluation of the effectiveness of China's pilot carbon emissions trading system and discovered its significant effect on increasing the production of non-coal-fired power plants. Li, Gao, Abdulla, Shan, and Gao (2022) investigated the synergistic effects of power sector reform and carbon pricing in the China Southern Power Grid and concluded that if there was no concurrent power market reform, moderate carbon pricing alone would not be sufficient to effectively reduce carbon emissions.

In contrast to the existing literature, which generally focuses on specific measures in the reform, we systematically investigate the effects of power sector reform on carbon emissions. Based on the institutional background and long-term equilibrium framework, we first identify three channels through which reform could affect carbon emissions and investigate their interactions. The first channel encourages replacing low-efficiency generators with high-efficiency ones by introducing market mechanisms, referred to as the "reshaping generation competition" channel. The second is giving renewable energy administrative priority in generation, referred to as the "promoting renewable energy" channel. The last channel involves reducing electricity prices. Then, combined with the generator-level data in 2019 in China, we establish formulas to estimate the carbon reduction potential of the three channels, as well as the obstacles in the process. Finally, considering the complexity of the emission reduction process through power sector reform, we specifically propose the corresponding solution. We find that the "reshaping generation competition" channel and "promoting renewable energy" channel could reduce CO_2 emissions by 205.4 and 311 million tons, respectively, while the "reducing electricity price" channel would increase emissions by 98.1 million tons. However, under average cost competition, replacing low-efficiency generators with high-efficiency generators is difficult, and the administrative priority of renewable energy would lead to high implicit costs. Based on the simulation results, we propose that carbon pricing at the level of 400–600 yuan/tCO_2 is needed to achieve the full carbon reduction potential of the reform.

This study contributes to the literature in three ways. First, it provides a more comprehensive understanding of the potential effects of China's power sector reform on carbon emissions.

Second, we perform a detailed *ex ante* assessment of the potential effects of the reform. Compared to *ex post* analysis, which previous literature mostly uses, *ex ante* analysis combined with scenario discussion can illustrate various potential carbon effects of the reform. Using *ex ante* analysis, this study proposes a new perspective on the evaluation of reform effects and reveals potential problems in China's power sector reform and emission reduction.

The final contribution is that we build a unified framework of long-term equilibrium to analyze the reform's carbon effects. The existing research mostly adopts a short-term marginal cost competition framework, which is widely used in full marketization contexts in places such as the United States and Europe (Hiebert, 2002). However, China's electricity market differs from that of these countries, and China's reform still contains some central planning-dominated methods (Lin, Kahrl, Yuan, Liu, & Zhang, 2019; Wei & Zheng, 2017). Using the long-term average cost competition framework could explain specific obstacles in the reform process and shed light on utilizing power sector reform to reduce carbon emissions in countries whose market mechanisms have not yet been fully developed.

The remainder of this paper is organized as follows. Section 2 describes the background of China's power sector reform and carbon emissions, Section 3 introduces the theoretical mechanisms explaining the reform's effect on carbon emissions, Section 4 presents the formulas and data that are used to quantify the emission reduction potentials and underlying obstacles of the reform, Sections 5 and 6 present the findings and discuss solutions to eliminate the obstacles and maximize the reform's carbon emission reduction effects, and Section 7 concludes with policy implications.

2. Institutional background

2.1. Power sector reform in China

China has had a long process of power sector reform since 1985. Before 1985, no private enterprises were involved in power generation in China. After 1985, to alleviate power shortages, the Chinese government allowed many public and private investors to participate in power generation, although the power sector remained under a vertical integration structure. In 2002, to preliminarily break the monopoly, China's power industry was reorganized, and power generation was separated from the power grid. Power dispatch was in the form of "equal share" dispatch, which assigned the same annual operating hours to generators of similar types and ages. Thus, this is a planning-dominated dispatch approach. In addition, power generation enterprises continued to implement government-regulated electricity prices, and transmission, distribution, and sale were still vertically integrated.

China started a new round of power sector reform in March 2015, with the announcement of "Opinions on Further Deepening Power Sector Reform" (hereinafter referred to as the No. 9 Document). The reform of this round aimed to break the vertical integration of the power sector, build competitive markets in competitive fields (e.g., power generation and consumption), and implement effective regulation in monopolistic fields (e.g., power transmission and distribution). Specifically, the reform proposed seven major policy objectives: releasing generation and consumption plans, straightening out the electricity price formation mechanism, improving power trading, establishing a relatively independent power trading platform, promoting reform on the sales side, allowing fair access to the power grid, and strengthening power supervision.

China's new power sector reform shares certain common targets with reforms in developed countries. In terms of improving market competition, the reform aims to break vertical integration. Similarly, the EU Electricity Act explicitly aimed to separate competitive power generation and sales markets from monopolized transmission and distribution (Jamasb & Pollitt, 2007; Pollitt, 2008). There was also a similar reform process in the United States, making existing integrated utilities sell a large number of power generation assets and gradually extending the sales competition from large manufacturers to small users. In terms of natural monopoly supervision, China clarified the transmission and distribution prices. Similarly, the United Kingdom successfully separated power grid charges from competitive field charges by introducing incentive regulations.

China's power sector reform is also distinguished from that of other countries in many respects. In terms of dispatching rules, developed countries, such as Europe and the United States, mostly adopted the economic dispatch approach, where generating units participate in production according to the merit order of costs. In China's reform, part of the generation is still allocated by the government, namely, the generation quota, and the residual is assigned according to economic dispatching. In terms of market competitors, renewable energy in Europe and the United States have participated in market competition, but China's renewable energy sector retains an advantage in power generation through administrative priority and subsidies (National Development and Reform Commission, [NDRC], 2015). In terms of electricity price adjustments, China's electricity price reform faces more difficulties. In China, 71% of the electricity demand comes from the manufacturing industry, while in the United States, only 25.71% comes from the manufacturing industry (Pollitt, Yang, & Chen, 2017). Therefore, electricity price adjustments are expected to have large impacts on China's industry. Meanwhile, owing to political and economic factors, the residential electricity price in China is much lower than that in the United States, which would also highly constrain price adjustment in China.

2.2. *Performance of China's new power sector reform on carbon emissions*

China's new power sector reform has contributed to reshaping generation competition, promoting renewable energy, and reducing electricity prices through both market and policy mechanisms. These contributions are expected to not only make the power industry more efficient but also have an underlying effect on carbon neutrality. However, realization of carbon reduction potential faces certain

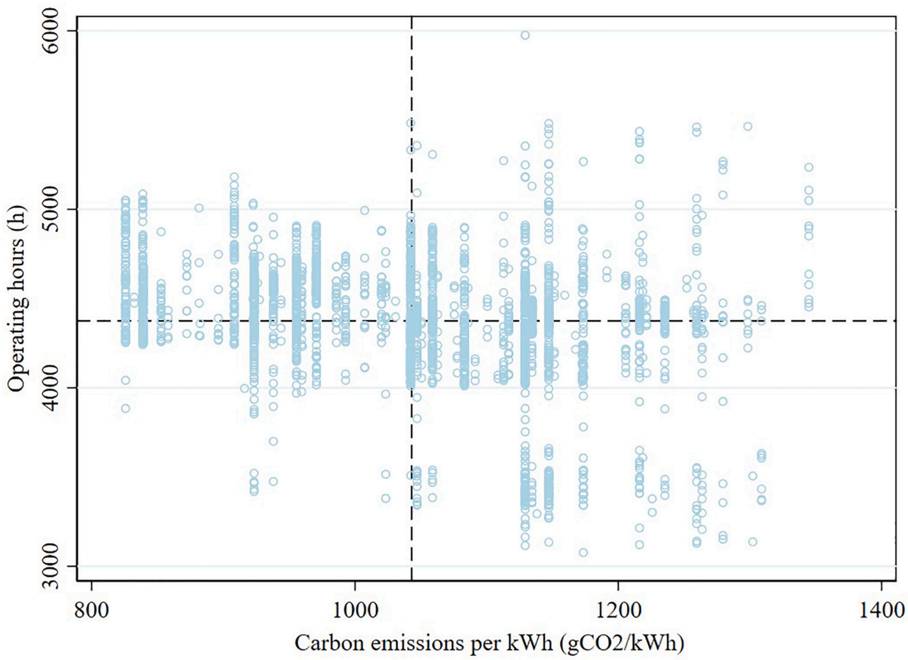

Fig. 1. Efficiency and operating hours of coal-fired generators in China in 2019. The black dotted line in the figure is the average level of emission factors (carbon emissions per kWh) and operating hours.

obstacles. Below, we discuss three contributions and the accompanying obstacles.

First, by introducing market mechanisms into generation dispatch (i.e., economic dispatch), the reform reshaped generation competition, and high-efficiency coal-fired generators with lower emissions are expected to replace low-efficiency coal-fired generators with higher emissions because high-efficiency generators usually consume less coal and thus have an advantage in fuel costs (Ding & Yang, 2013). If the substitution of these two types of generators is achieved successfully, carbon emissions in power generation can be reduced spontaneously.

However, based on power plant data, we find that from 2015 to 2019, the heat rate (per kWh coal use) of coal generation in China dropped at a lower speed (from 315 gce/kWh to 306.4 gce/kWh) than that before the reform (from 333 gce/kWh to 315 gce/kWh during 2010–2015). As shown in Fig. 1, among all the coal-fired generators in 2019, many low-efficiency generators with higher carbon emissions still obtained high operating hours (dots in the upper-right quadrant), and some high-efficiency generators only had low hours (dots in the lower-left quadrant). The mismatch between energy efficiency and operating hours has not been resolved by this reform.

Second, the No.9 Document and its supporting documents emphasized the establishment of a priority system for renewable energy power generation and encouraged replacement of coal-fired power with renewable energy sources using economic incentives such as subsidies. Enterprises that have their own coal-fired power plants and are located in areas with abundant renewable energy are encouraged to buy power from renewable sources instead of generating it on their own. The "administrative" priority of renewable energy accelerated the increase in its generation. We observe that the incremental share of renewable energy generation rose rapidly after the reform. Wind power generation increased by an average of 54.9 billion kWh annually from 2015 to 2019, while the average annual increase during 2010–2015 was 27.2 billion kWh. The average annual increment in solar photovoltaic (PV) generation from 2015 to 2019 was 46.1 billion kWh, nearly seven times that in 2010–2015. Although renewable energy sources have not yet been subject to generation competition in China, which contrasts with traditional power market reforms in developed countries, their "administrative" priority in generation is also helpful in reducing carbon emissions (European Environment Agency, [EEA], 2018).

In addition to policy incentives, the "A-J effect" (Averch & Johnson, 1962) caused by the new cost-plus pricing system created by the reform also contributes to the development of renewable energy. The A-J effect occurs because the power grid is more inclined to purchase renewable energy which involves a larger grid investment compared to fossil fuels. Under the rate-of-return regulation, the allowable return changes with capital. When the fair rate of return cannot be accurately determined in the presence of information asymmetry, regulated enterprises prefer overinvestment to obtain higher profits.

However, administrative priorities can cause problems. China's renewable energy sector has not been subject to market competition for many years for several reasons, including, but not limited to, immature technology, high investment costs, high transmission costs, and provincial barriers (Song, Bi, & Wei, 2019; Xia & Song, 2017). When an energy source that currently has no absolute cost advantage is given priority to generate electricity, it is bound to distort market competition.

Third, the new round of power sector reform reduced electricity prices through regulation, accompanied by a few market methods. Price dividends are good news for market entities, but not for the environment. Lower electricity prices reduce the costs of manufacturing enterprises that take electricity as one of their main inputs, and the reduced cost stimulates production (Shi, Wang, et al., 2018), thereby causing more carbon emissions. Fig. 2 shows primary aluminum (an energy-intensive product) as an example and demonstrates this potential effect. There is a steep increase in production around 2015. Although the government also adopted policies to curb the development of energy-intensive industries in other fields, such as export restrictions, here we only discuss the impact of power sector reform on carbon emissions.

3. Theoretical framework

In view of the gap between the expected emission reduction effects and the actual performance of the reform, we adopt the framework of long-term average cost competition. In the power market, the generators that can participate in power generation and the amount of electricity they can generate are determined by the equilibrium of market supply and demand. In addition, the supply curve is closely related to costs. In the short run, costs can be divided into variable costs (e.g., coal consumption cost for power generation) and fixed costs (e.g., financial cost of constructing a generator). The variable cost is also called the marginal cost, and generators are assumed to bid on it. In the long term, all costs are variable. With the entry and exit of generators,[1] the marginal cost competition among generators in the short term is converted to competition based on the average cost. Considering the characteristics of power generation, the marginal cost is assumed to be constant, because the cost of additional fuel is constant for one more kWh of generation, while the average cost should be downward sloping with the initial one-time investment divided by power generation. As production increases, the average cost decreases and approaches the marginal cost but never crosses it. By changing the supply curve, the new power sector reform leads to different equilibrium power quantities and power structures, resulting in a change in carbon emissions.

Generally, under market-oriented dispatching, competition among generating units is based on the merit order of their marginal costs, which constitutes the common framework of most power market research. In China's context, however, the power sector has both market and planning attributes, which can be seen from the "generation quota + economic dispatch" approach. When the government and enterprises participate in decision-making about the generation order of generating units, they consider not only the

[1] In the past, withdrawing a generator after it was built was difficult. However, with the increasingly fierce market competition and government support for phasing out generators with low capacities, the number of retired generators increased after 2007.

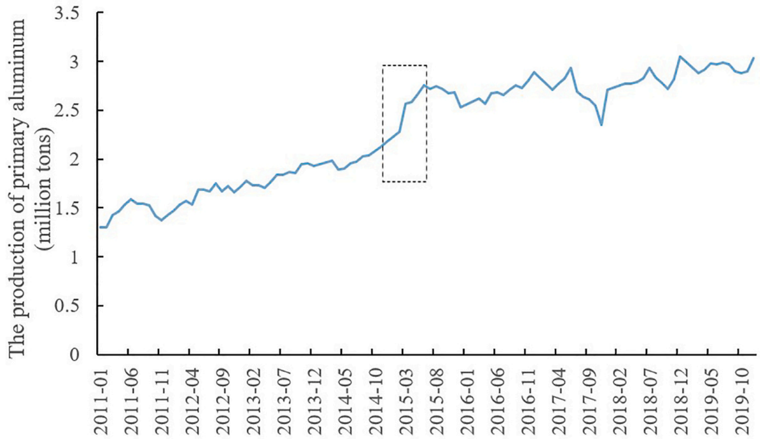

Fig. 2. The potential stimulus of price dividend to energy-intensive industries.

marginal cost but also the fixed cost, such as early-stage investment in construction. For example, with the development of technology, some renewable energy sources have gained an advantage in marginal cost, but the government has to consider construction, transmission, and other costs in overall planning. Some coal-fired generators with higher efficiency but larger investments in fixed assets face the same problem. This is probably why there are still some phenomena that cannot be explained by marginal cost competition after the reform, such as the mismatch between energy efficiency and operating hours, as shown in Fig. 1. In this context, the long-term average cost competition framework could provide an explanation.

Therefore, in this section, we propose a unified long-term average cost competition framework to theoretically explain the effects of the three channels discussed in the previous section on carbon emissions and consider their combined effects with scenario simulations.

3.1. Competition between high- and low-efficiency generators

High- and low-efficiency generators are distinguished based on their carbon emissions. High-efficiency generators use advanced technology with lower coal consumption and emission factors, whereas low-efficiency generators use relatively old technology with higher coal consumption and emission factors. Therefore, as shown in Fig. 3, high-efficiency generators have a lower marginal fuel cost (MC_H) because they can generate more electricity with less coal. This is also the basis for the expectation in new power sector reform that high-efficiency generating units can win through market competition and replace low-efficiency ones.

However, in the long term, we must consider the fixed costs of the generators. Every generator has an initial construction cost and subsequent maintenance costs, which are called fixed asset costs. According to accounting rules, fixed assets depreciate over time, indicating that the older the generator, the lower its financial costs. This means that when the fixed costs of old low-efficiency generators are amortized, those new high-efficiency generators may still incur high financial costs. Therefore, although high-efficiency generators enjoy lower marginal coal costs, they usually have higher average costs.

As shown in Fig. 3, when the production quantity is low, the average cost of high-efficiency generators (AC_H) is higher than that of low-efficiency generators (AC_L). Only when the production quantity is large enough to reach the critical quantity (Q_c) can the average cost of high-efficiency generators (AC_H) become lower than that of low-efficiency generators (AC_L), and high-efficiency generators start to occupy the market. The type of generator that participates in production is determined by the relative location of the demand curve and critical point Q_c. When the demand is low (curve D), low-efficiency generators can meet the demand at a lower cost than high-efficiency generators.[2] In contrast, when the demand curve is at position D', the high-efficiency generators win. The realization of emission reduction depends on successful replacement of low-efficiency by high-efficiency units; however, it is uncertain whether this substitution can occur, as it depends on the demand curve and Q_c. This explains why we still observe some mismatch between the generators' efficiency and operation after the reform. We will further verify this phenomenon in a subsequent quantitative analysis.

3.2. Adding in renewable energy

With technology upgrades, the marginal cost of renewable energy is decreasing and may be even lower than that of coal-fired power in the future (Rao & Kishore, 2010). However, from the perspective of long-term competition, renewable energy usually has a higher investment cost and faces high transmission costs in China because of the location mismatch of capacity (concentrated in western China) and load (concentrated in eastern China). In this context, renewable energy remains costly at the current stage. As

[2] Only when the generation capacity of the lowest-cost generators can no longer meet the market demand, can generators with the next lowest cost be phased in.

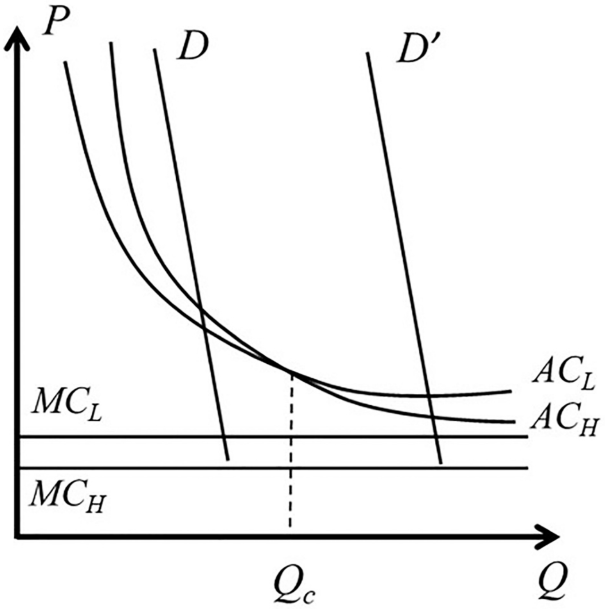

Fig. 3. Factors determining the competitiveness of coal-fired generators. AC_H and MC_H are the average and marginal costs of high-efficiency generators. AC_L and MC_L are the average and marginal costs of low-efficiency generators. D and D′ are two different market demands. Q_c is the critical quantity at which the competitiveness of the two types of generators changes.

shown in Fig. 4(a), the average cost of renewable energy (AC_R) is higher than that of coal-fired power (AC_C). Without policy support, coal-fired power would cover the entire market, which is q_C.

Power sector reform uses policy incentives to ensure rapid development of renewable energy. Instead of participating in market competition, renewable energy is given administrative priority in power generation, and coal-fired power meets the residual demand. As depicted in Fig. 4(b), the renewable energy capacity is fully utilized with policy support and provides power at the quantity $q_R{}'$. The rest of the market demand ($q' - q_R{}'$) is met by coal-fired power. As renewable energy has a lower emission factor, the reform is expected to reduce carbon emissions by administratively increasing the proportion of renewable energy in power generation. However, we also notice that this type of emission reduction is at the expense of increasing the cost of coal-fired power from p_C to $p_C{}'$.

3.3. When electricity price reduces

The reduction in electricity price indicates a cost decline on the supply side, regardless of whether this price dividend is achieved through the government's price reduction target, transmission and distribution supervision, or market-oriented transactions. In Fig. 5, the average cost of power generation shifts from AC to AC', leading the equilibrium to move along the demand curve to a larger quantity from q to q'. Generally, industries that are sensitive to electricity price change contribute the most to the demand increase, such as energy-intensive industries using electricity as an important input. When these polluting energy-intensive industries expand their production scale due to cost decline, carbon emissions increase as a result.

3.4. The combined impacts of the three channels

The original purpose of the new round of power reform is to reduce carbon emissions by increasing the proportion of high-efficiency generators and renewable energy. As shown in Fig. 6(a), after the reform, renewable energy is produced at quantity $q_R{}'$ and the residual power demand is met by high-efficiency generating units.

However, the reform's electricity price dividend changes the supply curves. The market equilibrium price decreases from p_E to $p_E{}'$, and the equilibrium quantity increases from q_E to $q_E{}'$ (see Fig. 6(b)). This increase in quantity leads to a rebound effect on carbon emissions. Here, since the priority of renewable energy for power generation is guaranteed by the government, the relative position of renewable energy and coal-fired power doesn't change with the price decline. Furthermore, when the average cost of high-efficiency power-generating units does not decrease sufficiently rapidly (see Fig. 6(c)), low-efficiency units can occupy the market, and the reform's carbon emission reduction effect is further weakened.

Based on the above equilibrium analysis, we discuss the effect of the reform on carbon emissions in three scenarios. As summarized in Fig. 7, each scenario includes four carbon emission levels: the pre-reform carbon emission level (red line), the post-reform expected carbon emission level (dark green line corresponding to the scenario in Fig. 6(a)), the post-reform carbon emission level considering the decline in electricity prices (medium green line corresponding to the scenario in Fig. 6(b)), and the post-reform carbon emission

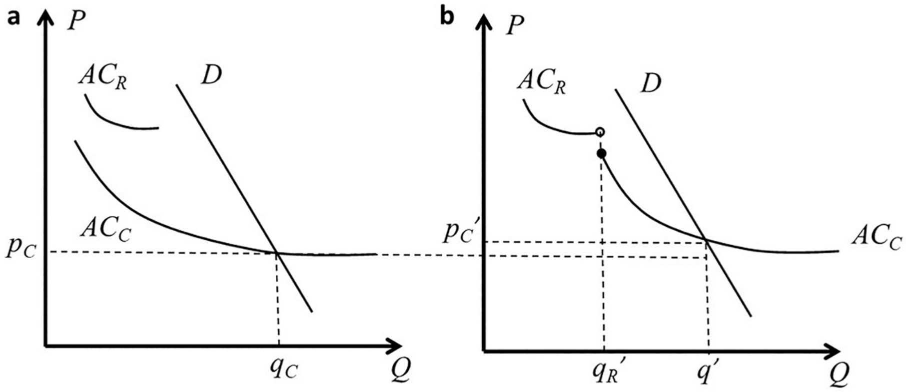

Fig. 4. The mechanism of reform in prioritizing renewable energy. (a) The average cost competition between renewable energy and coal-fired power without policy support. (b) The "competition" when renewable energy is given administrative priority.

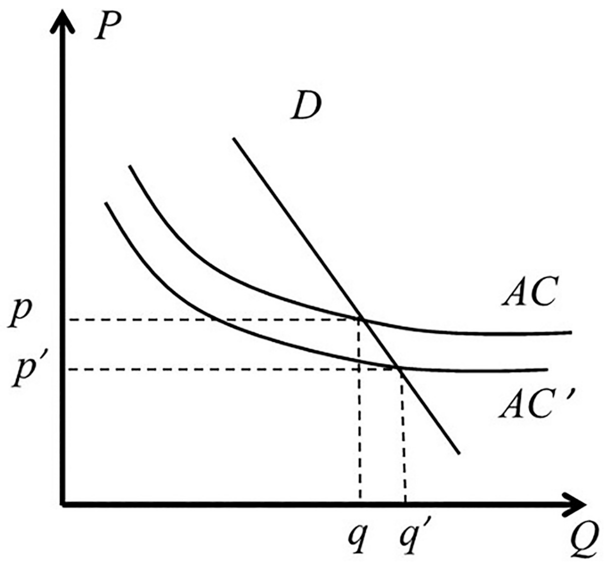

Fig. 5. The impact of electricity price reduction on equilibrium quantity.

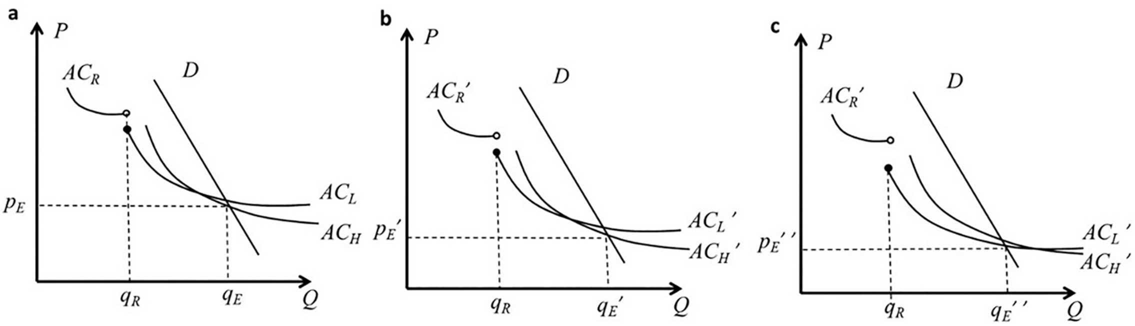

Fig. 6. Possible impacts of the new power sector reform on market equilibrium. (a) The expected impacts of the reform with high-efficiency generators and renewable energy promotion. (b) The possible actual impacts of the reform with electricity price declining. (c) The possible actual impacts of the reform when high-efficiency generators fail to replace low-efficiency ones. The p_E'' in Fig. 6(c) is not necessarily lower than the p_E' in Fig. 6(b). Their relative position depends on the relative position of AC_L, AC_H, and D.

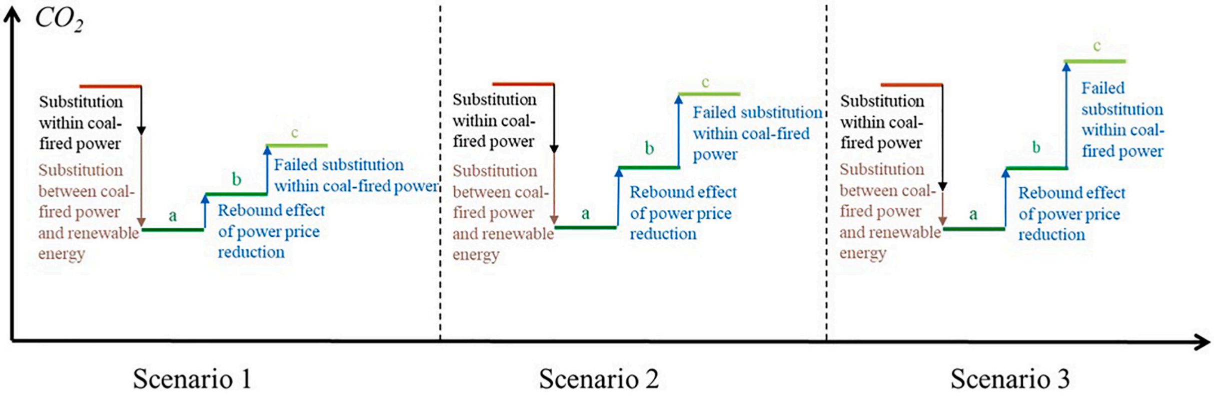

Fig. 7. Three scenarios analyzing the reform's carbon emission reduction effects. The red line indicates the carbon emission level before the reform, the dark green line indicates the expected carbon emission level after the reform, the medium green line indicates the carbon emission level after the reform considering the price decline, and the light green line indicates the carbon emission level after the reform considering the price decline and the failure of substitution within coal-fired power. The green lines from dark to light correspond to scenarios in Fig. 6 (a), (b) and (c), respectively. Scenarios 1 to 3 set different emission effects of the three channels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

level considering both the price decline and the failure of high-efficiency coal-fired generators to replace low-efficiency ones (light green line corresponding to the scenario in Fig. 6(c)). Scenarios 1–3 in Fig. 7 show a progressive emission reduction effect by adjusting the degree of carbon emissions of different channels. A comparison between the red and light green lines shows the combined effects of the reform under different scenarios. Whether the total effect is positive or negative depends on the relative magnitude of the carbon emission reduction caused by the substitution within coal-fired power and substitution between renewable energy and coal power, compared to the carbon emission increase caused by the rebound effect of electricity price decline and the failure of substitution within coal-fired power.

4. Formulas and data

In this section, we establish formulas to explore the carbon emission reduction potential and assess the possible obstacles of the three channels introduced above. It should be noted that this is an *ex ante* analysis rather than an *ex post* quantification. We analyze what will happen if the corresponding scenario occurs.

4.1. Formulas

4.1.1. Channel of reshaping generation competition

By promoting market competition, this reform attempts to replace low-efficiency coal-fired generators with high-efficiency generators, thus reducing carbon emissions. We define a generator to be high-efficiency if its per kWh carbon emissions are below the average level; otherwise, it is a low-efficiency generator. The amount of carbon emission reduction depends on the difference in carbon emission factors between high- and low-efficiency generators as well as the number of generators to be replaced. The formula used is as follows:

$$CER_1 = AEF_{\text{high}} \times TG_{\text{replaced}} - \sum_{i=1}^{n} EF_{i,low} \times G_{i,low} \tag{1}$$

where CER_1 is the amount of carbon emission reduced from the "reshaping generation competition" channel; AEF_{high} is the average emission factor of the alternative high-efficiency generators; TG_{replaced} is the total replaced power generation; assuming there are n low-efficiency generators being replaced, $EF_{i,low}$ and $G_{i,low}$ are the emission factor and generation of the i^{th} low-efficiency generators, respectively; and $\sum_{i=1}^{n} EF_{i,low} \times G_{i,low}$ is the current total carbon emissions of the low-efficiency generators that will be replaced. Here, we consider five scenarios in which different proportions of low-efficiency generators are replaced by high-efficiency generators. The five scenarios are that 10%, 20%, 30%, 40%, or all of the least efficient generating units are replaced by 10%, 20%, 30%, 40%, or all of the most efficient units, respectively.

According to the analysis in Section 3.1, the realization of the carbon reduction potential in the first channel depends on whether replacement can occur, which depends on the comparison between the average costs of the low- and high-efficiency units. The average cost of a generating unit mainly includes coal cost (variable cost) and financial cost (fixed cost). The per-kWh coal cost is equal to the marginal cost, as it describes the cost of additional fuel for one more kWh of power generation:

$$CC_i = \frac{EF_i}{Eff_{ic}} \times P_i \tag{2}$$

where CC_i is the per kWh coal cost of generator i, EF_i is the emission factor of generator i, Eff_{ic} is the carbon emission coefficient of the coal used in generator i, varying among different coal types $c \in \{Lignite, Bituminous, Subbituminous, Anthracite\}$; P_i is the coal price of the province where generator i is located.

The financial cost is related to the generator's construction investment, and declines with time in terms of depreciation. The annualized financial cost at year t ($F_{i,t,b}$) is calculated as follows:

$$F_{i,t,b} = \frac{NInv_b}{NCap_b} \times (1 - r \times (t - b)) \tag{3}$$

where b in Eq. (3) is the year when generator i is constructed; $NInv_b$ and $NCap_b$ are the new fixed asset investments and the new capacity of coal-fired power in year b, respectively; we took $\frac{NInv_b}{NCap_b}$ as the investment cost per unit installation of generator i constructed in year b; r is the depreciation ratio. We assume that the net residual value rate and depreciation period of the generating units are 3% and 20 years, respectively; thus, the depreciation ratio r is (1%–3%)/20 = 4.85%. Generally, the service life of coal-fired power units is more than 40 years; however, in terms of accounting standards, the amortization of fixed assets will end within 20 years. This is why some old low-efficiency generators have a significant cost advantage over new high-efficiency ones. Generators built in the same year are considered to have the same financial costs.

Given that the financial cost decreases with an increase in operating hours, there exists a critical point (h^*) at which the average costs of the high-efficiency generators and the low-efficiency generators intersect. Based on this critical point, we can evaluate the realization likelihood of replacement. If h^* is within the reasonable range of generator operating hours, the replacement of low-efficiency generators by high-efficiency generators could occur; otherwise, the replacement would not be realized. The formula used to determine the critical point is:

$$ACC_{high} + \frac{AF_{high}}{h^*} = ACC_{low} + \frac{AF_{low}}{h^*} \tag{4}$$

where ACC_{high} and ACC_{low} in Eq. (4) represent the average coal costs of the high- and low-efficiency generators in the replacement. Similarly, AF_{high} and AF_{low} are the average financial costs of high- and low-efficiency generators, respectively.

4.1.2. Channel of promoting renewable energy

The carbon emission reduction potential of promoting renewable energy comes from the difference between the emission factors of coal-fired power-generating units and renewable energy production:

$$CER_2 = \sum_{m=1}^{M} G \times SC_m \times (LCef_m - LCef_c) \tag{5}$$

where CER_2 is the amount of carbon emission reduced from the "promoting renewable energy" channel; m represents different types of renewable energy[3]; G is the total generation; SC_m is the proportional increase of renewable energy m in total generation (for simplicity, we regard this structure change as the replacement of coal-fired power by renewable energy); $LCef_m$ and $LCef_c$ are the life-cycle carbon emission coefficients of renewable energy m and coal power, respectively.

Under government support, the generation of renewable energy can always be satisfied, so the realization of carbon emission reduction potential can be guaranteed, which is different from uncertainty in the "reshaping generation competition" channel. Nevertheless, we should not ignore the welfare loss caused by this distortion of market competition.

4.1.3. Channel of reducing electricity price

Electricity is one of the most important inputs in energy-intensive industries and is sensitive to electricity price changes. When the price declines, the production of these energy-intensive industries expands, and thus, carbon emissions increase. We calculate the change in carbon emissions induced by this channel, as follows:

$$CER_3 = e \times \frac{\Delta p}{p} \times CE_{ei} \tag{6}$$

where CER_3 is the amount of carbon emissions induced by the "reducing electricity prices" channel, CE_{ei} is the general carbon emission of energy-intensive industries, $\frac{\Delta p}{p}$ is the change in electricity price caused by the reform, and e is the elasticity (price responsiveness) of industries' output relative to electricity price. The CE_{ei} here refers to the carbon emissions of the entire industry chain of energy-intensive industries, which not only includes carbon emissions caused by the production growth of industries but also the carbon

[3] We mainly focus on wind and solar photovoltaic power in this study, since hydropower's proportion of total electricity generation has not changed much after the reform, and the total amount of geothermal and biomass energy is still relatively low.

emissions caused by increasing power inputs.

4.2. Data

To capture the characteristics of the power market and analyze the effect of the three channels, we use data from China in 2019, which are the most recent unit-level power generation data available to us.

For the “reshaping generation competition” channel, we use data on coal-fired generating units over the country in 2019. We collected data from the Global Coal Plant Tracker (GCPT) and China Electricity Council (CEC). The Global Coal Plant Tracker (2022) provides information on China's existing coal-fired power units generating 30 MW and above, including variables such as capacity, carbon emission factor (per kWh carbon emission), coal type, construction year, and retirement year. The heat rate of the generator can be inferred from the emission factor and coal type using the Intergovernmental Panel on Climate Change's recommended carbon emission coefficient for various fuels.

We refer to the 2019 China Power Industry Statistics published by the China Electricity Council (2019) for operating hours. The Statistics report the operating-hour intervals of generators with different capacities. We randomly and evenly distributed the operating hours in the interval to generators with the corresponding capacities. Clarifying the operating hours can help in calculating the generation and carbon emissions of each generator.

We merged the two datasets and obtained a sample of 2937 coal-fired power-generating units in 2019. As shown in Table A1, the total generation of these units is approximately 4524.7 billion kWh, which is very close to the generation data for coal-fired power announced by the CEC in 2019 (4553 billion kWh). The average heat rate of the coal-fired generators in 2019 is 1043 gCO_2/kWh. Based on the definition of generator efficiency, the sample has 1480 and 1457 generators of high and low efficiency, respectively, and their average emission factors are 946 gCO_2/kWh and 1141 gCO_2/kWh, respectively.

For the “promoting renewable energy” channel, we use the total generation in 2019. Structural changes can be set at different levels to evaluate the emission reduction effect under different renewable energy development scenarios. In this paper, we take the generation proportion increase in renewable energy (wind power, solar photovoltaic, etc.) from 2014 to 2019.

For the “reducing electricity price” channel, we use the data of overall carbon emissions of energy-intensive industries from the Carbon Emission Accounts and Datasets, which covers not only the emissions from the industries' production, but also the emissions caused by inputs such as electricity, so as to capture the changes of emissions on both the supply side and demand side under the price dividend. Similarly, the price change is set to vary to reflect the different rebound effects.

Table 1 summarizes the specific parameters used in the evaluation.

Table 1
Parameters in the evaluation.

	Parameter	Value	Source
Channel 1: Reshaping generation competition	Coal price in 2019 in different provinces (P_i)	Varying among provinces	NDRC
	Carbon emission coefficient of different coal (Eff_c)	Varying among coal types	IPCC
	New fixed assets investment and new capacity of coal-fired power in year b ($NInv_b$ and $NCap_b$)	Varying with the year	CEC
Channel 2: Promoting renewable energy	Total generation (G) in 2019	7326.9 billion kWh	CEC
	Power structure change (SC_m) (from 2014 to 2019)	2.72% in wind power; 2.64% in photovoltaic	CEC
	Life-cycle carbon emission coefficients ($LCef$)	820 g/kWh for coal-fired power; 12 g/kWh for wind power; 45 g/kWh for photovoltaic power	World Nuclear Association
Channel 3: Reducing electricity price	General carbon emissions of energy-intensive industries in 2019 (CE_{ei})	8006.76 million tons	CEADs
	Change in electricity price ($\frac{\Delta p}{p}$) (from 2014 to 2019)	−5.57%	NEA
	Elasticity of industries' output relative to electricity cost (e)	−0.22	Elliott, Sun, and Zhu (2018)

(1) The parameters in Table 1 only show one possibility of reform and carbon emissions, and can be adjusted according to the needs of the scenario setting. (2) According to Elliott et al. (2018), a 10% decline in electricity price could increase the probability of firms switching their production to more energy-intensive production by approximately 2.20%. As an expansion of the scale of industrial activity, it demonstrates that the elasticity e, the degree of responsiveness of energy-intensive industries to price changes, is −0.22. NDRC, National Development and Reform Commission; IPCC, Intergovernmental Panel on Climate Change; CEC, China Electricity Council; CEADs, Carbon Emission Accounts and Datasets; NEA, National Energy Administration.

5. Results

5.1. The carbon emission reduction potential of the reform

First, we evaluate the theoretical potential of these three channels in reducing carbon emissions. For the “reshaping generation competition” channel, we set five replacement scenarios to discuss the emission reduction effect. As shown in Fig. 8, high-efficiency generators have a lower emission factor than low-efficiency ones, but the gap decreases with an increase in the substitution ratio. Based on the difference in the emission factor between the two types of generators, we find that carbon emission reduction would be between 63.5 million tons for a 10% replacement of low-efficiency generators and 205.4 million tons for a complete replacement, equivalent to 0.6%–2.1% of the total carbon emissions in China in 2019, and 0.2%–0.6% of total global carbon emissions in the same year (IEA, 2020).

For the “promoting renewable energy” channel, with the assumption of a proportional increase of wind and solar photovoltaic power in total generation, we calculate the carbon emission reduction to be 311 million tons.

For the “reducing electricity price” channel, we focus on the six most energy-intensive industries in China (chemical, non-metallic mineral products, ferrous metal smelting, non-ferrous metal smelting, petroleum processing, and electric power production). In 2019, these six industries accounted for 82% of the total emissions of all industries. With the elasticity in Table 1, we can attribute 1.6% of the increase in production by energy-intensive enterprises to the reduced electricity price. Consequently, 98.1 million tons of carbon emissions would be induced.

Table 2 summarizes the potential carbon emission effects of the three channels.

5.2. Obstacles in carbon emission reduction

As shown above, power sector reform could reduce or increase carbon emissions. In practice, it remains unclear whether the potential of emission reduction can be fully realized and how much the emission induced can be offset.

For the “reshaping generation competition” channel, it is not guaranteed that high-efficiency generators will win over low-efficiency ones in the long run. High-efficiency generators usually have higher financial costs (fixed costs), and are therefore likely to have higher average costs. To test this conjecture, we sort the generators in order from high to low efficiency and depict their coal and financial costs in Fig. 9. This shows that the efficiency level is negatively correlated with coal costs and positively correlated with financial costs.

In average cost competition, high-efficiency generators can gain a cost advantage only when the operating hours are sufficiently large. However, as shown in Fig. 10, the cost of high-efficiency generators is higher than that of low-efficiency ones in all five scenarios. In Scenario 5, where we assume that all low-efficiency generators are replaced by high-efficiency generators, the critical hour level (approximately 12,000 h) is the lowest among the scenarios, but still far more than the maximum hours of a year (8760 h = 24 × 365). This high critical hour level implies that the high-efficiency generator could not win the market competition without some intervention.

To further explore the feasibility of replacing low-efficiency with high-efficiency generators, we discuss the differences between the cost curves of the two types of generators in different provinces. Fig. A1 ranks the provinces in order of critical hours under Scenario 5. The results show that replacement between the two types of generators within 8760 h can only occur in Yunnan, Zhejiang, Sichuan, Shanghai, and Guangxi. These five provinces can be divided into two categories. One comprises the provinces rich in renewable energy sources such as hydropower, including Yunnan, Sichuan, and Guangxi. These provinces do not depend on coal power for generation,

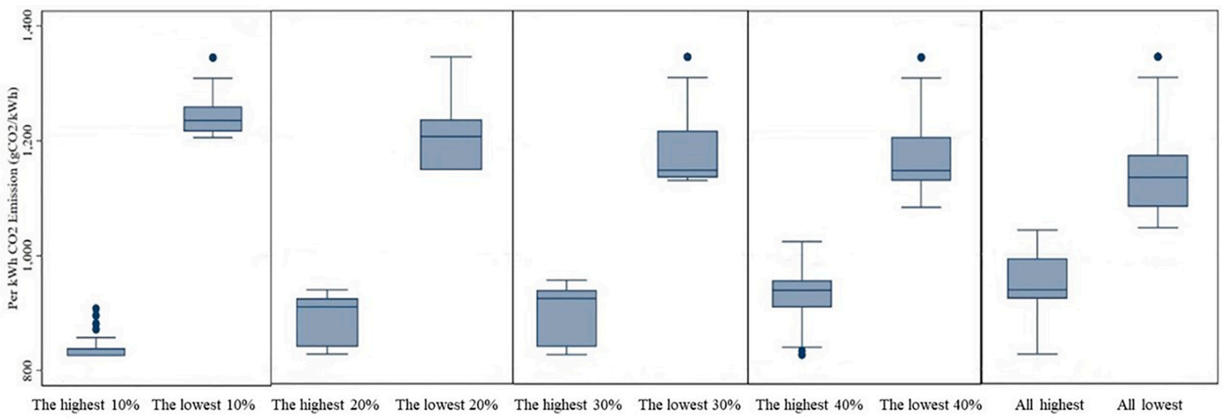

Fig. 8. Differences in emission factors in five scenarios. In Scenarios 1 to 4, the least efficient 10%, 20%, 30%, and 40% of generators are assumed to be replaced by the most efficient 10%, 20%, 30%, 40% of generators, respectively. In Scenario 5, all the low-efficiency generators are assumed to be replaced by high-efficiency generators. The graphs compare the emission factors of the replaced and the replacing generators in the five different scenarios.

Table 2
The carbon emission effects expected through the reform.

		Carbon emission reduction (million tons)
Channel 1	Scenario 1 (10% of replacement)	63.5
	Scenario 2 (20% of replacement)	120.8
	Scenario 3 (30% of replacement)	149.9
	Scenario 4 (40% of replacement)	201.6
	Scenario 5 (complete replacement)	205.4
Channel 2	Focusing on change in wind and solar photovoltaic power only	311
Channel 3	Carbon emissions induced by the price decline	−98.1

The combined carbon emission effects of the reform we obtained here are closer to Scenario 1 in Section 3.4.

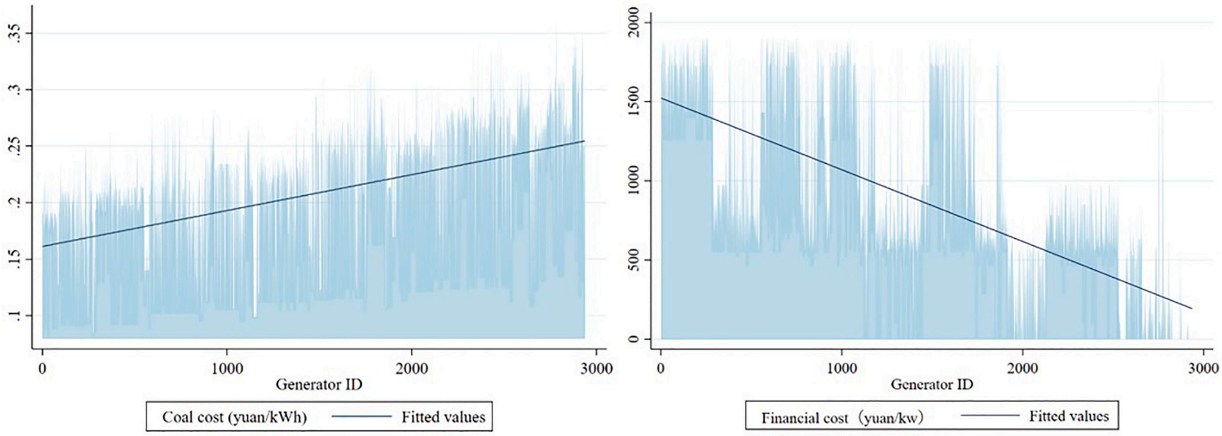

Fig. 9. The relationships between efficiency and coal and financial costs of coal-fired generators.

and the cost difference between high- and low-efficiency units is small. The other comprises the eastern coastal provinces, such as Zhejiang and Shanghai, which are more economically and technologically developed.

Fig. A1 also shows that most of the provinces where substitution is prone to occur (Zhejiang, Shanghai, Guangxi, etc.) have lower coal reserves, while the provinces where substitution is difficult to implement (Shanxi, Hebei, Guizhou, etc.) have higher coal reserves. Fig. A2 further confirms that provinces with abundant coal reserves are more likely to rely on coal power generation at an early stage, thus creating path dependence on low-efficiency units. The fixed costs of most low-efficiency units in these provinces have been amortized to zero, which constitutes an obstacle for new high-efficiency units to enter the market.

For the "promoting renewable energy" channel, the development of renewable energy seems to be on the way to carbon neutrality but will result in high implicit costs. A large number of subsidies increases fiscal pressure. According to Wang et al. (2018), China's total subsidies for wind and solar photovoltaic power generation in 2015 were as high as 60 billion to 70 billion yuan, far exceeding their environmental benefits (26.9 billion yuan). The additional costs imposed on coal-fired power are also high. For example, renewable energy reduces coal-fired plant generation hours and profit margins; furthermore, renewable energy is intermittent and therefore requires coal-fired power to provide auxiliary services.

6. Discussion

Considering the obstacles to reducing carbon emissions, corrective measures need to be taken, among which carbon pricing is one of the most direct and efficient methods (Klenert et al., 2018; Lontzek, Cai, Judd, & Lenton, 2015; Martin & Saikawa, 2017). First, by charging for carbon emissions, carbon pricing can increase the costs of low-efficiency coal-fired generators relative to high-efficiency generators because of differences in their emission factor, and thus help to achieve replacement in the "reshaping generation competition" channel. Second, carbon pricing converts the externalized subsidies into internalized costs in the "promoting renewable energy" channel. Carbon pricing increases the cost of coal-fired power generation by internalizing environmental losses, which consequently enhances the relative cost advantage of renewable energy. It can not only correct market prices and encourage renewable energy to improve production efficiency but also provide the government with an additional amount of revenue for redistribution. Third, carbon pricing in energy-intensive industries causes enterprises to bear the carbon emission costs caused by the corresponding output. The increase in cost would limit the production scale of these industries, so as to offset the negative effect on carbon emission reduction in the "reducing electricity price" channel.

The next question is, what level of carbon pricing can be effective? Taking the "reshaping generation competition" channel as an example, the carbon price should enable high-efficiency generators to win the market competition at feasible operating hours;

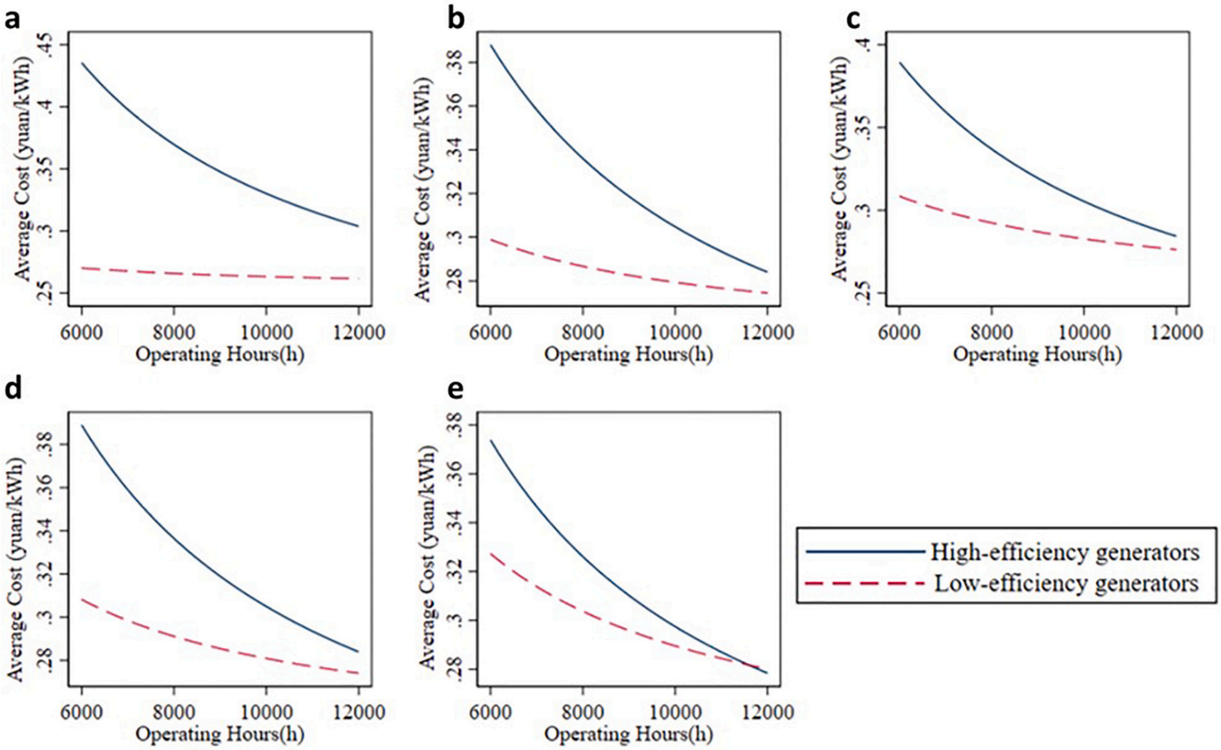

Fig. 10. Cost difference between high- and low-efficiency generators under different operating hours. The blue line is the average cost of high-efficiency generators and the red dotted line is that of low-efficiency generators. Plots a–e correspond to Scenarios 1–5, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

specifically, the critical hour level should be at least less than 8760 h. As Eq. (7) shows, after employing the carbon price, the average cost of high-efficiency generators should be lower than that of low-efficiency ones; therefore, the carbon price CP_{h_a} takes the value in Eq. (8):

$$ACC_{high} + CP_{h_a} * AEF_{high} + \frac{AF_{high}}{h_a} \leq ACC_{low} + CP_{h_a} * AEF_{low} + \frac{AF_{low}}{h_a} \tag{7}$$

$$CP_{h_a} \geq \left[\left(ACC_{high} + \frac{AF_{high}}{h_a} - \left(ACC_{low} + \frac{AF_{low}}{h_a} \right) \right) \right] \Big/ \left(AEF_{low} - AEF_{high} \right) \tag{8}$$

where we use the average operating hours of coal-fired generators in 2019 (h_a) as a representative for feasible operating hours at the current technical level and economic conditions, and it takes a value of 4375 h in the calculation.

Fig. 11 summarizes the simulation results for the average cost curves with carbon pricing. It shows that the carbon price should be set above 637.98 yuan per ton (tCO_2) to replace the least efficient 10% of the generators with the most efficient 10%, and above 463.19, 489.76, 555.10, and 422.01 yuan/tCO_2, respectively to achieve replacement in the other four scenarios. These values lie in the range of carbon pricing in all countries in 2019, but are much higher than China's current carbon pricing (World Bank, 2019). Cui, Song, and Jiang (2022) arrived at a similar conclusion when evaluating the impact of China's electricity market integration on the cost-effectiveness of carbon pricing. They found that the carbon price needs to be as high as 400 yuan/ton to begin achieving an overall carbon reduction in the context of the provincial market. In a case study of Guangdong, Lin, Kahrl, Yuan, Chen, and Liu (2019) claimed that a carbon price of 50–200 yuan/tCO_2 has no impact on carbon reduction; only when the carbon price increases to 500 yuan/tCO_2 can the emission reduction potential be achieved, but the cost pressure will also increase sharply.

7. Conclusion

Aiming at the goal of "achieving carbon peak by 2030 and carbon neutrality by 2060," China has taken many measures for carbon emission reduction. Effective methods of achieving carbon reduction in the power sector have attracted widespread attention, as this sector emits 43% of the country's carbon dioxide. The new round of power sector reform in China has changed the original inefficient power operation mode, which has great potential for emission reduction. However, in this process, we must be aware of the obstacles and find corresponding solutions to help achieve the carbon targets better and faster.

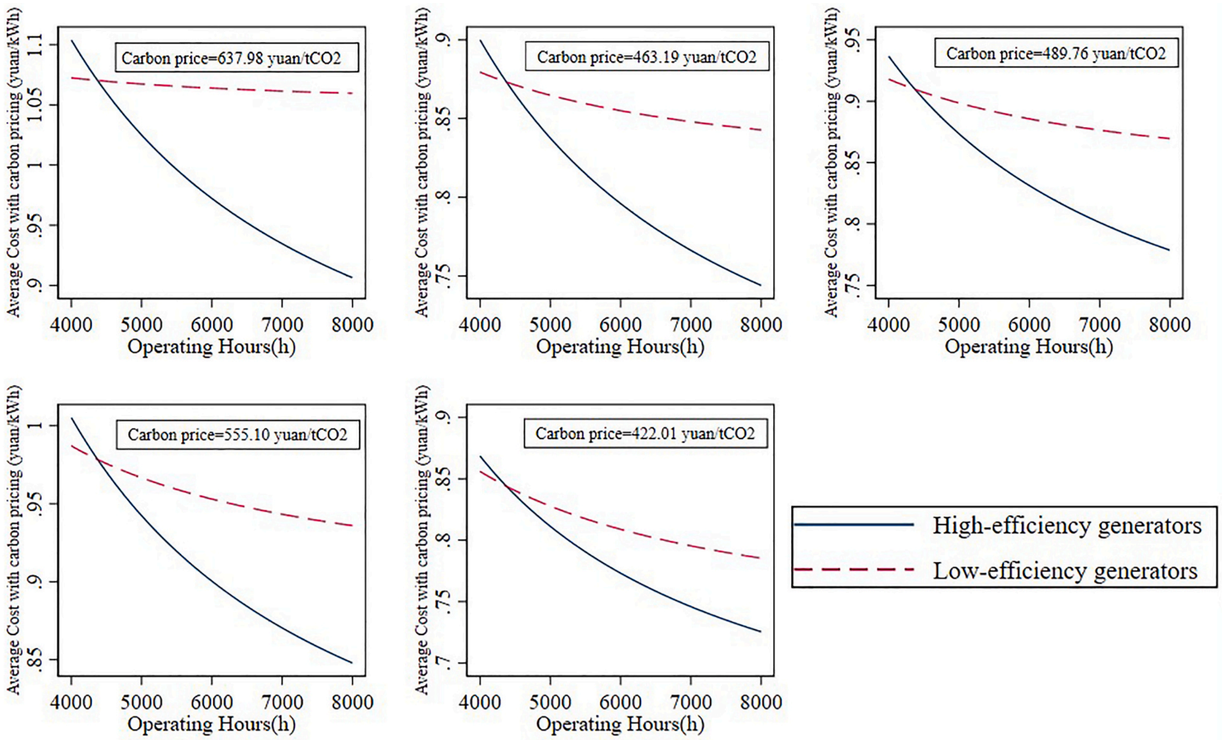

Fig. 11. Carbon price required for replacement in the five scenarios.

In this study, we examine the impact of China's new power sector reform on carbon emissions. We identify three channels through which ongoing power sector reform influences carbon emissions and investigate their interactions. By introducing the average cost competition framework, we can present the logic of the three channels in emission reduction and clarify potential problems. Then, we perform an *ex ante* analysis. Using generator-level data from 2019, we evaluate the carbon emission reduction potentials of the three channels and quantify the obstacles in achieving this potential. We further assess the carbon pricing level that could help eliminate obstacles.

We find that the reform-induced competition between high- and low-efficiency generators has the potential to reduce 205.4 million tons of carbon emissions, but the high financial costs of high-efficiency generators hinder the replacement: The administrative promotion of renewable energy as part of the reform can reduce carbon emissions by 311 million tons, but will bring about issues of high implicit costs and welfare losses. The price dividend is a side effect of the reform: The lower electricity price after the reform indirectly leads to an increase in carbon emissions by 98.1 million tons, as energy-intensive industries consume more electricity and produce more in response to the decreased power price. In summary, the new round of power sector reforms in China can achieve a certain emission reduction effect, but its potential has not been fully implemented.

Based on the above findings, we propose three ways to mitigate the obstacles in achieving the full potential of the current power sector reform. The first is to further improve market competition. Generally, competition among power units is based on marginal costs. One of the reasons we introduce the framework of average cost analysis is that competition among generators in China after the reform is not entirely market-oriented. Part of the dispatch is still controlled by the government and renewable energy has not yet been exposed to market competition. The "semi-planned and semi-market" dispatch approach will hinder the realization of market potential, thus reducing the corresponding emission reduction effect. Therefore, it is important to further improve market mechanisms in the power sector.

The second is to adopt corresponding auxiliary mechanisms. To reduce carbon emissions quickly and effectively, auxiliary measures must be taken to help solve potential problems in the market. The carbon pricing proposed in this study is one feasible method, which can be realized by a carbon market or carbon tax. By internalizing environmental costs, carbon pricing could improve the cost advantage of high-efficiency units, help renewable energy participate in production without subsidies, and limit the emissions of energy-intensive industries to achieve the emission reduction potential of reform.

The third is to relieve cost pressure by establishing a regional market and integrating the design of environmental regulations. The relatively high CO_2 prices indicate that, under existing conditions, the pressure of emission reduction through power sector reform is still significant. A regional market could help alleviate the cost pressure. The distribution of energy resources in China is not equal among provinces. The integration of the provincial electricity market could optimize the allocation of resources and promote substitution between high- and low-efficiency units, thus reducing the required carbon price. China is currently promoting the construction of integrated electricity markets, with it having set the goal of establishing a national integrated electricity market system by

2030 (NDRC, 2022). In addition, the integration of environmental regulations can reduce carbon prices. Carbon pricing is one of several strategies for regulating emissions. If other environmental regulations are added to restrict low-efficiency generators, the carbon pricing burden can be shared.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

Acknowledgements

Financial supports from the National Natural Science Foundation of China (20211GZ0113, 71703163, 72141308), the National Social Science Foundation of China (2020010306), the Research Funds of Renmin University of China (22XNLG12, 17XNS001, 11XNL004), the Teaching and Research Funds of Renmin University of China (KCSZ202212), Major Innovation & Planning Interdisciplinary Platform for the "Double-First Class" Initiative, Renmin University of China are gratefully acknowledged.

Appendix A. Appendix

Table A1 Summary statistics of coal-fired generators.

Type	Observations	Total generation (billion kWh)	Total carbon emissions (billion tons)	Average emission factor (gCO_2/kWh)	Average heat rate (gceCoal/kWh)
High-efficiency	1480	3422.4	3.17	946	276.9
Low-efficiency	1457	1102.3	1.25	1141	339.3

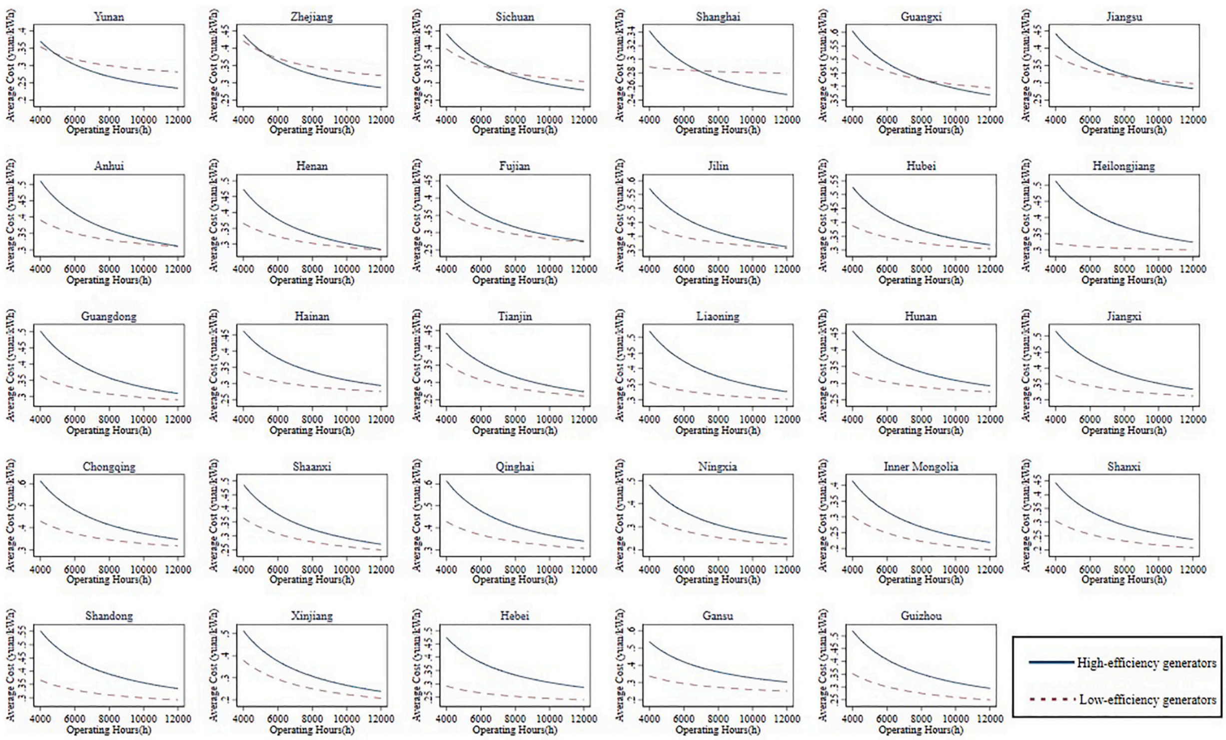

Fig. A1 Cost difference between high- and low-efficiency generators in different provinces. Fig. A1 discusses the scenario of all low-efficiency generators being replaced by high-efficiency generators; Beijing and Tibet are excluded because of data availability.

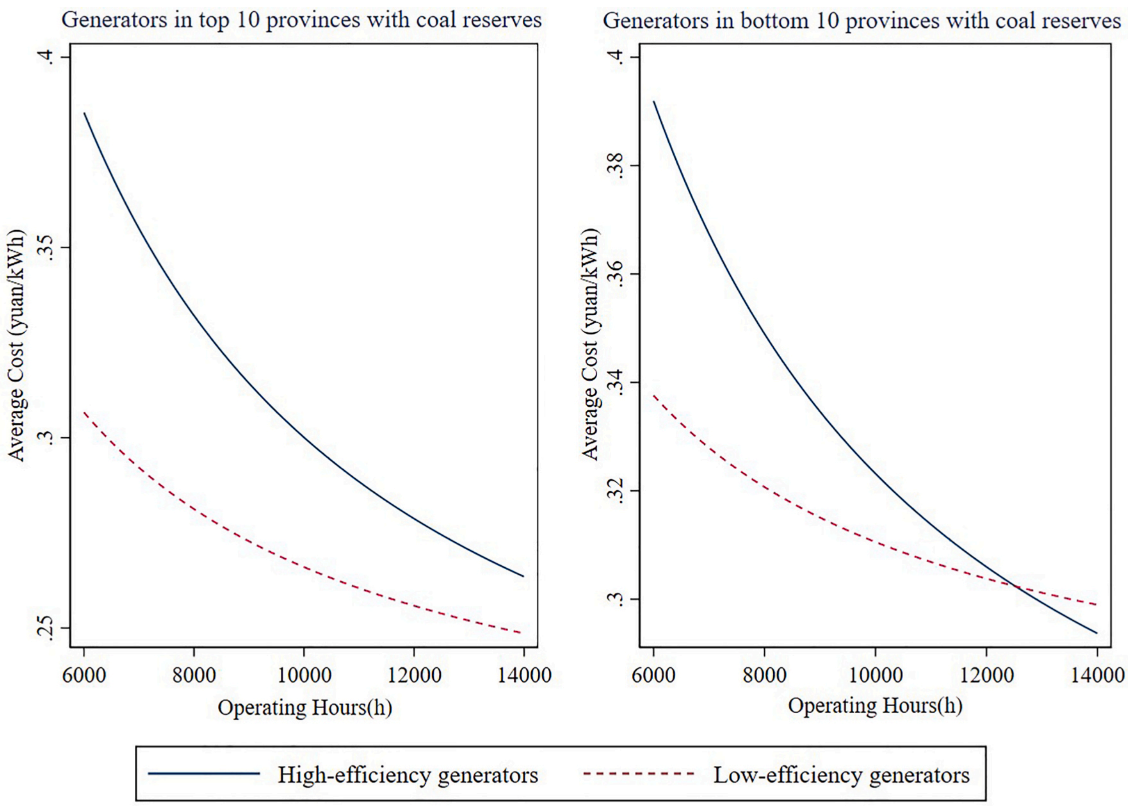

Fig. A2 Cost difference between high- and low-efficiency generators in provinces with different levels of coal reserves. According to the order of coal reserves in 2019, Fig. A2 depicts the high- and low-efficiency generator cost curves of the top 10 and bottom 10 provinces. The critical hour level in provinces with lower coal reserves is lower than that in provinces with higher coal reserves.

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