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Summary

The regulated price mechanism in China's power industry has attracted much criticism because of its incapability to optimize the allocation of resources. To build an "open, orderly, competitive and complete" power market system, the Chinese government launched an unprecedented marketization reform in 2015 to deregulate the electricity price. This paper examines the impact of the electricity price deregulation in the industry level. We first construct two-stage dynamic game models by taking the coal and coal-fired power industries as the players. Using the models, we compare analytically the equilibriums with and without electricity regulation, and examine the changes in electricity price, electricity generation, coal price and coal traded quantity. The theoretical analyses show that there are three intervals of the regulated electricity sales prices which influence the impact of electricity price deregulation. Next, we collect empirical data to estimate the parameters in the game models, and simulate the influence of electricity deregulation on the two industries in terms of market outcome and industrial profitability. Our results suggest that the actual regulated electricity price falls within the medium interval of the theoretical results, which means the price deregulation will result in higher electricity sales price but lower coal price, less coal traded amount and less electricity generation amount. The robustness analysis shows that our results hold with respect to the electricity generation efficiency and price elasticity of electricity demand.

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The impact of China's electricity deregulation on coal and power industries: Two-stage game modeling approach

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Abstract:

The regulated price mechanism in China's power industry has attracted much criticism because of its incapability to optimize the allocation of resources. To build an "open, orderly, competitive and complete" power market system, the Chinese government launched an unprecedented marketization reform in 2015 to deregulate the electricity price. This paper examines the impact of the electricity price deregulation in the industry level. We first construct two-stage dynamic game models by taking the coal and coal-fired power industries as the players. Using the models, we compare analytically the equilibriums with and without electricity regulation, and examine the changes in electricity price, electricity generation, coal price and coal traded quantity. The theoretical analyses show that there are three intervals of the regulated electricity sales prices which influence the impact of electricity price deregulation. Next, we collect empirical data to estimate the parameters in the game models, and simulate the influence of electricity deregulation on the two industries in terms of market outcome and industrial profitability. Our results suggest that the actual regulated electricity price falls within the medium interval of the theoretical results, which means the price deregulation will result in higher electricity sales price but lower coal price, less coal traded amount and less electricity generation amount. The robustness analysis shows that our results hold with respect to the electricity generation efficiency and price elasticity of electricity demand.

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1. Introduction

The electricity price in China is heavily regulated, which reduces the price fluctuations and guarantees the revenue for power supplier. The regulated price mechanism had successfully guided investments in new power infrastructures to satisfy the increasing electricity demand along with the fast economy growth during the past decades. For example, the electricity generation volume in China increased from 267 TWh in 1978 to 6,495 TWh in 2017 (NBS, 2018). However, the regulated price mechanism has also attracted much criticism because the price distortion harms its capability to optimize resource allocation in the power industry, which thus brings deadweight loss to the economy (Joskow, 2007).

Recognizing the negative consequences of the regulated price mechanism, the central government of China has launched an unprecedented marketization reform on its power industry since the release of the so-called "No. 9 Document" (NDRC, 2015) in March 2015, to build an "open, orderly, competitive and complete" power market system. A series of supplementary documents have also been put forward to guide the implementation of the reform. One of the core tasks of the reform is to deregulate electricity price. Over the past two years, the electricity reform has been promoted solidly by the central government, which aims to completely deregulate the industrial electricity price in 2018 and to form the commercial electricity price in 2020 (NEA, 2016).

Compared with the ambitious target of the central government, however, the local government seems to be less positive about the reform and thus the processes have been promoted slowly. So far the price deregulation is mainly executed in the pilot "large users direct supply" market, which consumed about 7.75 percent of the electricity in 2015 (NEA, 2017). Even for that pilot market, the price is not completely marketized because some local governments use their power to influence the market outcome, e.g., providing guidance in the traded volume and price. One of the reasons that local governments are so conservative about the reform is that they lack knowledge about how the reform will affect the local economy, especially under the situation of nationwide economy slowdown. More specifically, when the coal and power industries are very important to support the economy in many regions in terms of tax revenues, job creations, and economic growth, as would be expected, local policy makers tend to be more cautious about the reform before clearly understanding how local coal and electricity producers will react to the deregulation of price mechanism.

Although the coal-fired power generation has been continually limited by China for the sake of protecting the environment and upgrading the energy structure, it still plays an important role in China's electricity market, accounting for 71.8 percent of the total power generation in 2017 (NBS, 2018). Considering the coal-dominated energy structure in the foreseeable future (Lin et al., 2012), the deregulation of electricity price will inevitably exert a huge impact on related industries, especially the coal and coal-fired power industries.

The influence of electricity price deregulation depends on the supply-demand relationships of the related markets. For example, if the currently regulated electricity sales price is at a very low level, which implies a shortage in the electricity market, the price deregulation will raise the electricity sales price to a higher level than the previous regulatory price, leading to an increase in the profit of the power industry. On the contrary, if the currently regulated electricity sales price is

so high that oversupply exists in the electricity market, which is a totally different case. Therefore, it is necessary to distinguish the scenarios with low and high electricity sales price, to reflect the different supply-demand relationships in the regulated markets.

To analyze the rational responses of the coal and coal-fired power generation industries to electricity price deregulation, this study constructs game models to connect the two industries. In the industry chain, the upstream coal production industry produces and sells coal to the coal-fired power industry, and then the downstream power industry generates and sells electricity through the grid network. This study builds up two-stage dynamic game models to characterize how the coal production industry and the coal-fired power industry make strategic decisions at different times, using coal trading price and traded quantity to indicate the game-theoretic interaction between the two industries. By virtual of the game models, we compare the equilibrium outcomes with and without electricity regulation, and examine the changes in electricity price, electricity generation, coal price and coal traded quantity. Next, empirical data are collected and applied to estimate the parameters in the game models, based on which the influence of electricity deregulation on the two industries in terms of trading price, traded quantity and industrial profitability are simulated. Finally, we examine the robustness of the results with respect to the electricity generation efficiency and price elasticity of electricity demand.

The remaining parts of this paper are organized as follows. Section 2 provides a review of literature. Section 3 builds game models in the coal and electricity industry chain. Equilibrium outcomes of electricity regulation model and electricity deregulation model are compared in this section. Section 4 provides numerical simulation and sensitivity analysis using the empirical data in coal and electricity industries. Finally, Section 5 concludes the study by providing policy recommendations.

2. Literature review

As the world's biggest energy consumer (BP, 2016), China's power industry development and the associated market-oriented reforms have always been important research topics for energy analysts. Zhang and Heller (2004) examined the interaction of the political, legal and economic factors that affect China's restructuring in the electricity systems, and reviewed the history, fuel structure and transmission in the power industry. Ngan (2010) reviewed the three main stages of China's electricity reforms, including power investment financing, the separation between government and power enterprises and the division between power generation firms and power grids, and pointed out the necessity of further regulatory change. Wang and Chen (2012) indicated that China's power industry had transformed from absolute monopoly to then relative monopoly. If the relative monopoly remains unchanged, the public welfare would be hurt.

From the perspective of coal-fired power industry, many studies pointed out the problems existed in the regulation and the urgent need to further market-oriented reform. Wang (2007) examined the pricing policies and the transaction relationship between the coal and power industries in China and found that a stable, reasonable and transaction cost-saving relationship between these two industries is hard to establish due to the excessive intervention of government. By using the Data Envelopment Analysis-Slack Based Measure (DEA-SBM) method, Mou (2014) studied the efficiency of China's coal-fired power plants and showed that the coal-electricity efficiency disparity across provinces is obvious and long-lasting. By conducting a nationwide

survey on the economics of coal power, Zhao et al. (2017) concluded that the recent boom of coal-fired power investment is absurd in many perspectives, which is largely the aftermath of the uncompleted market reform in the power sector.

The achievements of the market-oriented reform in the power industry have also been documented in a series of studies. Zhao et al. (2012) pointed out that the governance reforms successfully ended the significant social welfare losses due to the severe power shortages of the previous three decades by introducing competition and encouraging technological progress. Zhao and Ma (2013) focused on the unbundling reform on the integrated electricity utility and explored the impacts on the operational efficiency for 34 large power plants during 1997–2010. Results showed that the reform had boosted productivity of China's large utility power plants. Besides the unbundling reform, Ma and Zhao (2015) further showed that technology mandates contributed to at least half of the observed efficiency improvement. In Chan et al. (2017), the empirical study from 1991 to 2005 showed that the restructuring of electricity market had brought nearly 15 percent savings in operating expenses and up to 7.5 percent emissions reduction among the investigated power plants.

The above research was conducted based mainly on computable general equilibrium (CGE) model, input-output (IO) model or other empirical methodologies. Game theory, another potential method, has also been used to study the market-oriented reform of the power industry. For example, Kemfert et al. (2002) constructed game models between electricity firms to examine the economic effects of the liberalization of the German electricity market, and characterized the differences between oligopolistic market and complete competitive market. Lise et al. (2006) extended Kemfert' model to study the electricity market liberalization of eight Northwestern European countries, and found that a reduction in the market power of large producers may be beneficial for both consumers and the environment. Using Lise's model, Kamiński (2011) studied the liberalization of Polish's power industry under five scenarios and eight cases. Results showed that under the competitive scenario the average electricity price would be approximately 14.7 percent lower and the production would be 6.7 percent higher than the benchmark scenario.

There are also attempts to extend the research scope from solely the electricity market to its upstream segments, especially the coal industry. For example, some studies examined the vertical cooperation between the coal and power producers (Yu, 2006; Wu, 2008; Yang, 2008; Zhao and Qi, 2007, 2008; Zhang, 2015), while others analyzed their price and output strategies (Shafie-khah et al., 2013; Srinivasan et al., 2016; Zhang and Zhang, 2013). Nevertheless, less attention has paid to the electricity reform and its impacts on both the coal and power industries.

To fill the research gap, our paper focuses on the impacts of electricity deregulation reform on the coal-electricity industry chain. The coal and power industries' strategic behaviors and best responses, such as pricing and quantity decisions, are examined. Specifically, under the two situations of low and high regulatory electricity prices, we first construct two-stage dynamic game models connecting the coal industry and the coal-fired power industry, and analyze the best responses of the two game players. By applying empirical data to the equilibrium outcomes, we then examine the influence of electricity deregulation on the two industries in terms of trading price, traded volume, and industrial profitability.

3. Game model in coal and electricity industry chain

3.1 Model settings

The electricity and coal markets in China are so complex that analysts usually have to simplify or idealize the economic connections to concentrate on the main research questions. The objective of this study is to examine the impact of electricity deregulation on the coal and power industries. Therefore, we only examine the essential competitive and cooperative relationships at the industry level, without missing important market factors. On this basis, our paper establishes industry-level game model: the coal production industry produces and sells coal to the coal-fired power industry, which generates electricity and sells it to end users through the grid companies.

The long-lasting coal shortage situation in China ended in 2009 and the country has since had oversupply in its coal market (Liu et al., 2017; NBS, 2016). According to the 2018 premier's report on the work of the government, easing overcapacity and closing down outdated coal production facilities are still tasks with priorities (Xinhua, 2018). In addition, the China Electricity Coal Index (CECI), which aims to objectively reflect coal procurement costs from the power generation-side, has been adopted into the pricing mechanism for mid- and long-term coal supply contract since 2018 (Xinhua, 2017). The new pricing mechanism exhibits a rising pricing power of coal-fired electricity industry. In this background, we consider the utility coal market as a buyer's market and assume that the coal-fired power industry is the price maker. The dynamic game model includes two stages. In the first stage, the coal-fired power industry (which is assumed to be a coalition of all coal-fired power plants) decides the utility coal price p_1 and the electricity generation amount q_2. If electricity price is regulated, the price is considered as public information to all players throughout the whole gaming period. If electricity price has been deregulated, a uniform price will be determined by the coal-fired power generators in this stage. In the second stage, the coal industry (which is also assumed to be a coalition of all the utility coal producers) decides the utility coal output q_1, with the utility coal price as known information. Utility coal purchase agreement will be signed between the coal and coal-fired power industries after both stages.

For the utility coal producers, assume that the supply of coal in the market is q_1, and the mining cost is $C_c = a_1 q_1^2 + b_1 q_1 + c_1$, where c_1 is the fixed cost, and a_1 and b_1 are parameters related to the variable cost. For the coal-fired power industry, we assume that the electricity generation amount is q_2 and the cost of electricity generation is $C_e = a_2 q_2^2 + b_2 q_2 + c_2$, in which c_2 is the fixed cost, and a_2 and b_2 are parameters related to the variable cost. To simplify the model, we assume that one ton of standard coal can generate t times ten thousand kilowatt hours of electricity, which is $q_2 = t q_1$. Here t is the parameter to reflect power generation efficiency.

Electricity has become an indispensable necessity that powers our society. However, as a typical normal commodity, the higher the electricity price, the lower its market demand will be. In this study, we assume that the market demand q is a linear function of the electricity sales price (retail price) p_2, which gives $q = Q - k p_2$. Here Q is the demand when electricity is free of charge and k is the price sensitivity. It is important to note that there is a gap between the electricity sales price paid by users and that received by the power generators (i.e., the on-grid electricity price), which consists mainly of the transmission and distribution fee and taxes. Assume that the gap is uniform for each unit of electricity used, which is denoted as c_t, then the on-gird electricity price is $p_2 - c_t$.

Based on the above model settings, the profit function of the coal industry is:

$$\pi_c = p_1 q_1 - (a_1 q_1^2 + b_1 q_1 + c_1) \tag{1}$$

The profit function of the coal-fired power industry is:

$$\pi_e = (p_2 - c_t)Min[Q - kp_2, q_2] - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) \quad (2)$$

3.2 Electricity regulation model

We proceed backwards to derive the equilibrium of the two-stage dynamic game model. In the second stage, given the coal price p_1, the coal industry decides on the supply amount q_1 to maximize its profit.

$$\text{Max} \quad \pi_c = p_1q_1 - (a_1q_1^2 + b_1q_1 + c_1)$$

We first take derivation with respect to q_1. According to the first order condition, the best response function of the coal-fired power industry is $q_1 = \frac{p_1 - b_1}{2a_1}$.

In the second stage, the coal-fired power industry decides on the electricity generation amount q_2. If q_2 is lower than tq_1, then the coal-fired power industry has incentive to provide a lower price quotation of coal, which allows the coal-fired power industry to purchase sufficient coal with lower cost. Otherwise, if q_2 is higher than tq_1, the coal-fired power industry will tend to reduce the planned electricity generation amount or provide a higher coal price to get sufficient coal supply. Therefore, in the equilibrium q_2 will be equal to the amount of the electricity generated by the coal supply q_1, i.e., $q_2 = tq_1$. Thus, based on the best response of the coal-fired power industry $q_1 = \frac{p_1 - b_1}{2a_1}$, the electricity generation amount is $q_2 = \frac{p_1 - b_1}{2a_1}t$.

The aim of the coal-fired power industry is to maximize its profit by adjusting the coal price p_1.

$$\text{Max} \quad \pi_e = (p_2 - c_t)Min[Q - kp_2, q_2] - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2)$$

In the situation of electricity regulation, the electricity sales price is regulated by the government. In this study, two scenarios will be analyzed: Scenario S_1 with a low electricity sales price; and Scenario S_2 with a high electricity sales price.

3.2.1 Scenario S_1 with a low electricity sales price

In this scenario, the regulated electricity sales price is so low that electricity demand is larger than the electricity generation amount chosen by the power industry. On this basis, we have $Q - kp_2 > q_2$ and part of the market demand will not be satisfied. The profit function of the power industry is converted as follows.

$$\text{Max} \quad \pi_e = (p_2 - c_t)q_2 - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) \quad (3)$$

Substituting $q_1 = \frac{p_1 - b_1}{2a_1}$ and $q_2 = \frac{p_1 - b_1}{2a_1}t$ into Eq. (3), we take derivation with respect to p_1.

According to the first order condition, we get the optimal coal price $p_1^* = \frac{a_2b_1t^2 + a_1(b_1 + (p_2 - c_t - b_2)t)}{2a_1 + a_2t^2}$.

In the equilibrium, the coal supply amount is $q_1^* = \frac{(p_2 - c_t)t - b_1 - b_2t}{4a_1 + 2a_2t^2}$, and the electricity generation amount is $q_2^* = \frac{((p_2 - c_t)t - b_1 - b_2t)t}{4a_1 + 2a_2t^2}$. The profit of the coal industry is $\pi_c^* = \frac{a_1(b_1^2 + 2b_1(b_2 - (p_2 - c_t))t + (b_2^2 - 16a_2c_1 - 2b_2(p_2 - c_t) + (p_2 - c_t)^2)t^2) - 16a_1^2c_1 - 4a_2^2c_1t^4}{4(2a_1 + a_2t^2)^2}$, and the profit of

the coal-fired power industry is $\pi_e^* = \frac{b_1^2 - 8a_1c_2 + 2b_1(b_2-(p_2-c_t))t + (b_2^2 - 4a_2c_2 - 2b_2(p_2-c_t)+(p_2-c_t)^2)t^2}{8a_1 + 4a_2t^2}$.

It is clear that the equilibrium outcomes are functions of the regulated electricity sales price. In this scenario S_1 with a low electricity sales price, $Q - kp_2 > q_2^* = \frac{((p_2-c_t)t-b_1-b_2t)t}{4a_1+2a_2t^2}$. With the generation amount q_2^*, the power industry actually expects a higher sales price to reduce the gap between the potential market demand and its supply level. When there is an alternative regulated price to balance the supply and demand, which is $Q - kp_2 = q_2^* = \frac{((p_2-c_t)t-b_1-b_2t)t}{4a_1+2a_2t^2}$, we obtain the price threshold $\overline{p_2} = \frac{4a_1Q+t(b_1+(b_2+c_t+2a_2Q)t)}{4a_1k+(1+2a_2k)t^2}$. In scenario S_1, the regulated sales price of electricity is lower than $\overline{p_2}$, i.e., $p_2 < \overline{p_2}$.

3.2.2 Scenario S_2 with a high electricity sales price

In this scenario, the electricity sales price is so high that some users will conserve the usage of electricity. The coal-fired power industry has to generate the amount equal to the level of market demand, despite that the marginal revenue (on-grid price) is still higher than the marginal production cost. According to the discussion in scenario S_1, the condition for scenario S_2 will be the opposite, which is $p_2 > \overline{p_2}$.

On this basis, we have $Q - kp_2 = q_2$ and the profit function of the power industry is converted as $\pi_e = (p_2 - c_t)(Q - kp_2) - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2)$.

Substituting $q_1 = \frac{p_1-b_1}{2a_1}$ and $q_2 = \frac{p_1-b_1}{2a_1}t$ into the formula $Q - kp_2 = q_2$, we get the optimal coal price $p_1^* = \frac{-2a_1kp_2+2a_1Q+b_1t}{t}$.

In the equilibrium, the coal supply amount is $q_1^* = \frac{Q-kp_2}{t}$, and the electricity generation amount is $q_2^* = Q - kp_2$. The profit of the coal industry is $\pi_c^* = \frac{a_1(Q-kp_2)^2 - c_1t^2}{t^2}$, and the profit of the coal-fired power industry is $\pi_e^* = \frac{-2a_1(Q-kp_2)^2 + t(-c_2t+(kp_2-Q)(b_1+(b_2+c_t-(1+a_2k)p_2+a_2Q)t))}{t^2}$.

In scenario S_2, the optimal electricity generation amount is determined by the regulated electricity sales price.

3.3 Electricity deregulation model

The response of the utility coal industry to the coal price p_1 is the same as that in the electricity regulation model, which means that the coal supply amount q_1 will be decided to maximize the coal industry's profit.

$$\text{Max} \quad \pi_c = p_1q_1 - (a_1q_1^2 + b_1q_1 + c_1)$$

Therefore, the best-response quantities of the coal industry and the coal-fired power industry are the same as those in the electricity regulation model as $q_1 = \frac{p_1-b_1}{2a_1}$ and $q_2 = \frac{p_1-b_1}{2a_1}t$.

The profit function of the coal-fired power industry is

$$\pi_e = (p_2 - c_t)Min[Q - kp_2, q_2] - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) \tag{4}$$

Despite that the profit function appears to be the same in the electricity regulation and deregulation models, there is an important difference between the two models, i.e., the electricity sales price is exogenous in the regulation model but endogenous in the deregulation model. In the deregulation model, if the electricity sales price p_2 at a given point of time is so low that the market demand is higher than the generation amount, which means $Q - kp_2 > q_2$ (the final sales amount is q_2), then the power industry has incentive to increase the electricity sales price and obtain a higher profit. Therefore, $Q - kp_2 > q_2$ will not be a stable equilibrium. On this basis, we have $Q - kp_2 \le q_2$ and the profit function of the power industry is converted as follows.

$$\text{Max} \quad \pi_e = (p_2 - c_t)(Q - kp_2) - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) \tag{5}$$
$$\text{Subject to} \quad q_2 - (Q - kp_2) \ge 0$$

The Lagrangian expression of the power industry's objective function is

$$L = (p_2 - c_t)(Q - kp_2) - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) + \lambda(q_2 - Q + kp_2) \tag{6}$$

Here λ is Lagrange multiplier. Substituting $q_1 = \frac{p_1 - b_1}{2a_1}$ and $q_2 = \frac{p_1 - b_1}{2a_1}t$ into Eq. (6), we take derivation with respect to p_1 and p_2. The Karush–Kuhn–Tucker (KKT) optimization conditions are as follows.

$$\frac{\partial L}{\partial p_1} = \frac{a_2(b_1 - p_1)t^2 + a_1(b_1 - 2p_1 - b_2t + t\lambda)}{2a_1{}^2} = 0 \tag{7}$$

$$\frac{\partial L}{\partial p_2} = Q + k(-2p_2 + \lambda) + c_tk = 0 \tag{8}$$

$$\lambda(q_2 - Q + kp_2) = 0 \tag{9}$$
$$\lambda \ge 0 \tag{10}$$

The above mathematical problem can be solved through discussing two scenarios.

Scenario 1): $q_2 - Q + kp_2 = 0$ and $\lambda > 0$. After calculating the equilibrium outcomes, we obtain $\lambda = \frac{2a_1(Q - c_tk) + t(b_1 + (b_2 - a_2c_tk + a_2Q)t)}{2a_1k + (1 + a_2k)t^2}$, which is positive and satisfies the non-negativity condition of the optimization.

Scenario 2): $q_2 - Q + kp_2 > 0$ and $\lambda = 0$. The equilibrium outcomes are $p_1^* = \frac{a_1b_1 - a_1b_2t + a_2 b_1t^2}{2a_1 + a_2 t^2}$ and $p_2^* = \frac{Q + c_tk}{2k}$. $q_2^* - Q + kp_2^* = -\frac{2a_1(Q - c_tk) + t(b_1 + (b_2 - a_2c_tk + a_2Q)t)}{4a_1 + 2a_2 t^2} < 0$, which does not satisfy the non-negativity condition of the optimization. Therefore, only the first scenario holds.

In the equilibrium, the coal price is $p_1^* = \frac{b_1(1 + a_2k)t^2 + a_1(b_1k + (Q - b_2k - c_tk)t)}{2a_1k + (1 + a_2k)t^2}$ and the electricity sales price is $p_2^* = \frac{4a_1kQ + t(b_1k + (b_2k + c_tk + Q + 2a_2kQ)t)}{2k(2a_1k + (1 + a_2k)t^2)}$. The coal supply amount is $q_1^* = \frac{Qt - b_1k - b_2kt - c_tkt}{4a_1k + 2t^2 + 2a_2kt^2}$, and the electricity generation amount is $q_2^* = \frac{t(Qt - b_1k - b_2kt - c_tkt)}{4a_1k + 2t^2 + 2a_2kt^2}$. The profit of the coal industry is $\pi_c^* = \frac{(a_1(b_1^2 - 16a_1c_1)k^2 + 2a_1b_1k(b_2k + c_tk - Q)t + a_1(-16c_1k(1 + a_2 k) + (-b_2k - c_tk + Q)^2)t^2 - 4c_1(1 + a_2k)^2t^4)}{4(2a_1k + (1 + a_2k)t^2)^2}$, and the profit of the coal-fired power industry is $\pi_e^* = \frac{b_1^2k^2 - 8a_1c_2k^2 + 2b_1k(b_2k + c_tk - Q)t + (-4c_2k(1 + a_2k) + (-b_2k - c_tk + Q)^2)t^2}{4k(2a_1k + (1 + a_2 k)t^2)}$.

3.4 Comparison of equilibrium outcomes

By comparing the equilibrium outcomes of the electricity deregulation and regulation models, we then examine the impact of electricity reform on the coal and power industries.

Proposition 1 **Under scenario S_1 with a low regulated electricity sales price,**

(1) The regulated electricity sales price p_2 is lower than the threshold $\overline{p_2} = \frac{4a_1Q+t(b_1+(b_2+c_t+2a_2Q)t)}{4a_1k+(1+2a_2k)t^2}$, a level with the market supply and demand to be balanced. After the deregulation, the equilibrium sales price will be higher than $\overline{p_2}$.

(2) If the regulated electricity sales price is sufficiently low, which means $p_2 < \overline{\overline{p_2}} = \frac{2a_1Q+t(b_1+(b_2+c_t+a_2Q)t)}{2a_1k+(1+a_2k)t^2}$, then after the deregulation the coal price, the coal traded amount and the electricity generation amount will all increase. If the regulated price satisfies $\overline{\overline{p_2}} < p_2 < \overline{p_2}$, then after the deregulation the coal price, the coal traded amount and the electricity generation amount will all decrease.

According to Proposition 1, after eliminating the regulation, the electricity sales price will go up. The coal price and the traded amount may either increase or decrease, depending on the previously regulated electricity sales price. When the regulated price is sufficiently low, the electricity industry is willing to generate more to meet the potential market demand. Therefore, the coal traded amount and the electricity generation amount will go up. With the power industry as the price maker of coal, the coal industry will provide more with a higher coal price. When the regulated price is sufficiently high, the actual generation amount has almost met the potential market demand under the electricity regulation. After the reform, the increase in the electricity will cause a decrease in electricity usage, so the coal traded amount and the electricity generation amount will drop, which is accompanied by a decrease in the coal price.

Proposition 2 **Under the scenario S_2 with a high electricity sales price,**

(1) If the regulated price is very high, which means that $p_2 > \frac{4a_1kQ+t(b_1k+(b_2k+c_tk+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$, then after the deregulation the electricity sales price will decrease, the electricity generation amount and coal traded amount will increase, and the coal price will go up.

(2) If the regulated price satisfies that $\overline{p_2} < p_2 < \frac{4a_1kQ+t(b_1k+(b_2k+c_tk+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$, then after deregulation the electricity sales price will increase, the electricity generation amount and coal trading amount will decrease, and the coal price will drop down.

According to Proposition 2, the change of electricity sales price is determined by the regulated price level. Under the regulation, the power industry only generates the electricity to meet the market demand with high willingness to pay. Under the deregulation, the power industry will optimize its decisions to maximize its profit in the market environment.

To sum up, we combine the results shown in Proposition 1 and Proposition 2, and obtain the following Proposition 3. There are three intervals of the regulated electricity sales price which influence the impact of electricity price deregulation.

Proposition 3

(1) The low interval is $p_2 < \overline{\overline{p_2}}$.

If the regulated electricity sales price is very low, which means $p_2 < \overline{\overline{p_2}}$, then after the reform the electricity sales price will rise, the coal price will rise, and the coal traded amount and the electricity generation amount will increase.

(2) The medium interval is $\overline{\overline{p_2}} < p_2 < \frac{4a_1kQ+t(b_1k+(b_2k+c_tk+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$.

If the regulated electricity sales price satisfies that $\overline{\overline{p_2}} < p_2 < \frac{4a_1kQ+t(b_1k+(b_2k+c_tk+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$, then after the deregulation the electricity sales price will increase, the coal price will drop down, and the electricity generation amount and coal traded amount will decrease.

(3) The high interval is $p_2 > \frac{4a_1kQ+t(b_1k+(b_2k+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$.

If the regulated electricity sales price satisfies that $p_2 > \frac{4a_1kQ+t(b_1k+(b_2k+Q+2a_2kQ)t)}{2k(2a_1k+(1+a_2k)t^2)}$, then after the reform the electricity sales price will decrease, the coal price will rise, and the coal traded amount and the electricity generation amount will increase.

4 Numerical simulation and sensitivity analysis

Based on the above theoretical analysis, we further study the empirical impact of China electricity price deregulation on the utility coal and coal-fired power industries through numerical simulation.

The parameters of the cost functions of the coal and coal-fired power industries are estimated based on the ordinary least squares (OLS) regression using empirical industrial data. The national average electricity sales price is estimated according to the provincial prices and sales amounts data. The power generation efficiency is calculated based on the average consumption rate of standard coal. Finally, estimations of the parameters can be obtained as $a_1 = 0.00045671$, $b_1 = 207.33$, $c_1 = 0$, $a_2 = 0$, $b_2 = 369$, $c_2 = 25019488$, $c_t = 3214$, $t = 0.3497$, $Q = 84604.12$, $k = 3.72$ (see the Appendix for more detailed explanation).

Figure 1 shows the electricity generation amount under different levels of regulated sales price. In Scenario S_1 with a low electricity sales price, as the regulated sales price rises, the deregulated electricity generation amount is initially higher and then lower than the regulated level. In Scenario S_2 with a high electricity sales price, as the regulated sales price goes up, the deregulated electricity generation amount is initially lower and then higher than the regulated level. Figure 1 also show the three intervals of the regulated electricity sales price obtained in the Proposition 3. For the low interval, after the reform the electricity sales price will rise, and the electricity generation amount will increase. For the medium interval, after the reform the electricity sales price will rise, and the electricity generation amount will decrease. For the high interval, after the reform the electricity sales price will decrease, and the electricity generation amount will increase.
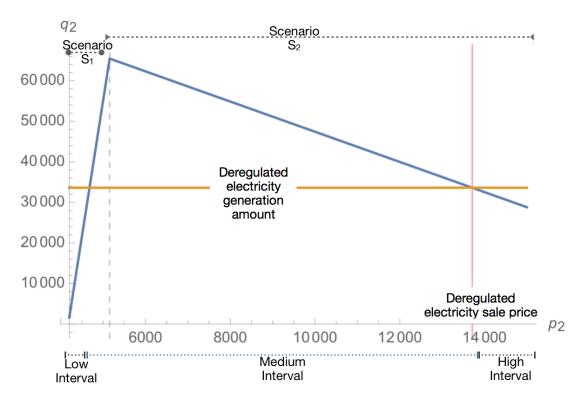
Figure 1. The electricity generation amount at different levels of regulated sales price

For example, assume that the regulated electricity sales price is 5000 (RMB/ten thousand kWh), which is higher than $\overline{\overline{p_2}} = 4677.84$. Therefore, according to Section 3.4, after the deregulation the electricity sales price will increase, the coal price will decrease, the coal traded amount and the electricity generation amount will decrease. Our numerical simulation outcomes shown in Table 1 confirm the above results. In addition, the results also show that the deregulation will reduce the profit of the coal industry but increase that of the electricity industry. But the extra gain of the electricity industry exceeds the loss that the coal industry would bear, which results in a net benefit to the whole industry chain.

Table 1. An example of numerical simulation with the electricity sales price to be regulated at 5000 (RMB / ten thousand kWh)

	Under regulation	Deregulation
Coal price (RBM/ton)	351.42	295.10
Coal traded amount (Million tons)	1578	961
Electricity sales price (RMB/kWh)	0.50	1.37
Electricity generation amount (Billion kWh)	5517	3360
The profit of the coal industry (Billion RMB)	113.66	42.17
The profit of electricity industry (Billion RMB)	-22.87	2869.21

Based on the parameters in the numerical simulation, we next examine the static analysis of equilibrium outcomes with respect to the electricity generation efficiency and the price sensitivity of electricity demand.

Proposition 4

(1) In the situation of electricity regulation with Scenario S_1, $\frac{\partial p_1^*}{\partial t} > 0$, $\frac{\partial q_1^*}{\partial t} > 0$ and $\frac{\partial q_2^*}{\partial t} > 0$.

(2) In the situation of electricity regulation with Scenario S_2, $\frac{\partial p_1^*}{\partial t} < 0$, $\frac{\partial q_1^*}{\partial t} < 0$, $\frac{\partial q_2^*}{\partial t} = 0$, and

$\frac{\partial p_1^*}{\partial k} < 0, \frac{\partial q_1^*}{\partial k} < 0$.

(3) In the situation of electricity deregulation, $\frac{\partial p_1^*}{\partial t} < 0$, $\frac{\partial q_1^*}{\partial t} < 0$, $\frac{\partial p_2^*}{\partial t} < 0$ and $\frac{\partial q_2^*}{\partial t} > 0$;

$\frac{\partial p_1^*}{\partial k} < 0, \frac{\partial q_1^*}{\partial k} < 0, \frac{\partial p_2^*}{\partial k} < 0$ and $\frac{\partial q_2^*}{\partial k} < 0$.

According to Proposition 4, in Scenario S_1 with a low electricity sales price, as the electricity generation efficiency rises (a higher t), the coal price will go up, both the coal traded amount and the electricity generation amount will increase. This is because in this scenario the potential market demand is large and there is a considerable room for the power industry to generate more. With a higher generation efficiency, the generation cost of unit electricity will be lower. The power industry redoes its cost-benefit analysis and expects to purchase more coal. With a stronger demand from the downstream, the coal industry will raise the coal price. In the Scenario S_2 with a high electricity sales price, the electricity generation amount is equal to the demand at the regulated sales price. With a certain electricity generation amount and a higher generation efficiency, the coal usage amount will be lower and the coal trading price will have to be lower too.

As the electricity generation efficiency rises, the coal price and traded amount change differently in the two scenarios. Figure 2 shows the change of the coal trading price if the electricity generation efficiency increases by 10% on the basis of that in Figure 1. In the Scenario S_1, the coal price increase in the Scenario S_1, and decreases in the Scenario S_2.
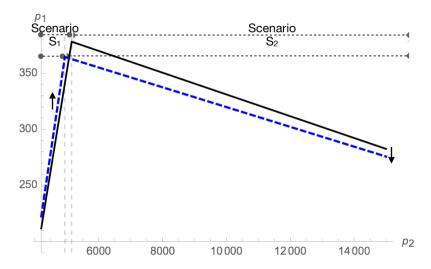

Figure 2. The change of the coal trading price under Scenarios S_1 and S_2 if the electricity generation efficiency increases by 10%

After relaxing the regulation, as the electricity generation efficiency rises, the generation amount, which is equal to market demand, will be higher and the sales price will be lower. Few coal will be used and then the coal trading price is decreased.

As the price sensitivity of electricity demand decreases (a lower k), the electricity demand will go up in the regulated situation with Scenario S_2 and the deregulated situation. Therefore, the electricity generation amount will be higher. With a stronger demand in the downstream, the coal industry will charge a higher trading price. In the deregulated situation, the electricity sales price will be raised too.

5. Conclusions

As a heritage of the planned economy system, the electricity tariff in China has been heavily regulated. The regulated price mechanism attracts much criticism, because of its incapability to optimize the allocation of resources in the power industry, which leads to deadweight loss to the economy. Recognizing the negative effect of the current price mechanism, China has launched an unprecedented marketization reform on its power industry to deregulate the electricity sales price. Our paper aims to assess the impact of the electricity price reform in the industry level.

As the integral parts of coal-electricity industry chain, the upstream coal production industry and the downstream power industry not only cooperate but also game with each other, which is reflected on the coal trading price and traded quantity. Based on that, our study constructs two-stage dynamic game models between the two industries and analyzes how they will react to the deregulation of price mechanism. Using the game models, we compare the equilibriums with and without electricity regulation, and examine the changes in the electricity sales price, generation amount, the coal trading price and coal traded volume after deregulation. Our theoretical analyses suggest that the impact of electricity price deregulation depends on whether the regulated price is in a high or low level. Next, empirical data are collected to estimate the parameters in the game model and simulate numerically the influence of electricity deregulation on industries in terms of trading price, traded volume, and industrial profitability. Finally, we perform the static analysis of equilibrium with respect to the electricity generation efficiency and the price sensitivity of electricity demand.

Our theoretical results suggest that the actual regulated electricity price falls within the medium interval of the theoretical results, which means that the price deregulation will result in higher electricity sales price, lower coal price, less coal trade and less electricity generation. Based on the current electricity price level, empirical analyses of our study show that the deregulation will reduce the profit of the coal industry but increase that of the electricity industry. But the extra gain of the electricity industry exceeds the loss of the coal industry, leading to a net benefit to the whole industry chain. However, since industry structure varies significantly from place to place, the gain and loss are distributed unevenly among different provinces. Nevertheless, our results imply that, with appropriate mechanism design to redistribute the impact between the coal and electricity industry and between different regions, the price deregulation reform has potential to make the whole society better off.

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Appendix

The parameters of the cost functions of the coal and coal-fired power industries are estimated based on the ordinary least squares (OLS) regression using empirical industrial data collected from the companies listed on China's stock market. We assume that the regression results on the data of these companies can represent the industry averages, which will be used in our numerical simulation. Functions are obtained as follows.

There are 15 listed companies (stock codes: 000968, 600123, 600188, 600395, 600397, 600403, 600508, 600714, 601001, 601088, 601225, 601666, 601699, 601898 and 900948) reported their utility coal output and cost in 2016, which contributed to 37.35 percent of the country's utility coal consumption.

To simplify calculation, the following assumptions are made: (1) all the utility coal consumed by coal-fired power plants is domestically produced; (2) the cost distribution of the listed companies is representative of the whole utility production industry; (3) the cost reported by the utility coal producers is variable cost; (4) the short-run supply curve of coal (which is also the curve between coal output and variable cost) is linear. Therefore, the supply curve of coal can be obtained by applying the OLS regression using the variable cost and output data as $P = 0.00091343Q + 207.33$ with $R^2 = 0.6067$, where the units of Q and P are ten thousand tons and ten thousand RMB. Thereafter, the overall cost function of the utility cost industry can be obtained by integrating the supply curve to $C = 207.33Q + 0.00045671Q^2$.

China has more than one thousand coal-fired power plants with an overall installed capacity of 1.05TW in 2016. In this study, we introduce the concept of standard power plant, which means the average unit capacity of 600MW coal-fired power plant as the dominant type of newly constructed plants in China. We treat the coal-fired power generation industry as an integration of 1756 standard power plants in order to simplify the calculation. The cost function of each of the standard power plant can be calculated based on the parameters from Zhao et al. (2017) and the overall cost function of the industry can be obtained as the sum of the cost functions of all the 1756 plants, which is $C = 369q_2 + 25014369$.

According to China's National Energy Administration (2017, http://www.nea.gov.cn/2017-01/16/c_135986964.htm), t is 312 gsc/kWh for all coal-fired power plants with installed capacity over 6MW.

The demand curve of electricity for the whole society is assumed to be linear. In 2016, the residential and non-residential electricity consumption for China are 805.4 GWh and 5114.4 GWh. Kamerschen and porter (2004) estimate the price demand elasticities of residential and industrial users as -0.9325 and -0.3499, respectively. By assuming that all non-residential users have the same price demand elasticity as industrial users, the overall price demand elasticity can be calculated as -0.4292. The average electricity tariff in 2015 is 0.6826 RMB/kWh according to China's National Energy Administration (2016, http://zfxxgk.nea.gov.cn/auto92/201611/t20161101_2312.htm). When no updated information is available, this tariff is applied in our calculation to represent the average electricity tariff in 2016. Therefore, the demand curve of electricity for the Chinese society can be calculated as $Q = -3.7221p_2 + 84604$.

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