Energy Policy 134 (2019) 110957

Contents lists available at ScienceDirect

Energy Policy

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

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

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ARTICLE INFO

Keywords:
China's energy reform
Electricity deregulation
Coal industry
Power industry

JEL classification:
Q41
Q43
Q48
L94
L98

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 electricity price deregulation at the industry level. We first construct two-stage dynamic game models to portrait the interaction between the coal and coal-fired power industries. Using the models, we compare analytically the equilibriums with and without electricity price regulation concerning electricity price, electricity generation, coal price and coal production. The theoretical analyses find three regulated electricity price intervals that differentiate the reform impacts. Afterward, we collect empirical data to estimate the model parameters. The influences on the two industries in terms of market outcome and industrial profitability are simulated. Our results suggest that the current regulated electricity price falls within the medium interval, which means deregulation will result in higher electricity price but lower coal price, less coal production and less electricity generation. The robustness analyses show that our results hold with respect to the electricity generation efficiency and price sensitivity of electricity demand.

1. Introduction

The electricity price in China is strictly regulated, which reduces the price fluctuations and guarantees the stable revenue for power supplier (Chen, 2014). The regulated price mechanism had successfully guided investments in power infrastructures to satisfy the increasing electricity demand along with the fast economy growth during the past decades (Feng et al., 2018; Lin et al., 2018a). For example, the electricity generation in China increased from 267 TWh in 1978 to 6,495 TWh in 2017 (NBS, 2018). The regulated price mechanism, however, has also attracted much criticism because the price distortion harms its capability to optimize resource allocation in the energy industry, which thus brings deadweight loss to the economy (Joskow, 2007; Chen et al., 2015; Sun, 2015).

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 facilitate the implementation of the reform. One of the core tasks of the reform is to deregulate electricity price. Since then, 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 move 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 local governments sometimes apply their administrative power, e.g., providing guidance in the traded volume and price, to influence market outcome. When the energy industries are very important to support regional economy 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. However, the local governments seem to be trapped in a dilemma which holds them in a conservative position

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https://doi.org/10.1016/j.enpol.2019.110957
Received 15 March 2019; Received in revised form 20 July 2019; Accepted 24 August 2019
Available online 06 September 2019
0301-4215/

towards electricity price deregulation. On the one hand, when the economy booms with strong electricity demand growth (e.g., before 2012), they worry that price deregulation will raise the electricity prices and add cost pressure to local business. On the other hand, under economy slowdown with weak electricity demand growth (e.g., after 2014), the local governments are reluctant to pushing deregulation forward because that may cause power plants losing money.

In contrast to the power industry reform in the other countries, the most significant feature of China's reform is that it is applied to the largest unified electricity market with heavy coal dependence (Lin et al., 2018b). For example, the coal-fired power generation accounts for 71.8 percent of the total power generation in 2017 (NBS, 2018), even though it has been continually limited by China for the sake of protecting the environment. 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 the coal and coal-fired power industries. Therefore, lessons learned from the experience of other countries, if not useless, need to be interpreted based on supplemented investigation built on China's specific circumstances. To deepen the understanding of the electricity price deregulation in China, our paper tries to study its effect from the perspective of industries. Therefore, we choose the coal and coal-fired power industries as the objects of study.

To analyze the rational responses of the coal and coal-fired power generation industries to electricity price deregulation, our study uses the game theory which has been prevalent in industry chains investigations (Hu et al., 2019). We will focus on a simple and short industry chain consisting of an upstream coal industry and a downstream coal-fired power industry. The coal industry produces and sells coal to the power industry which generates and sells electricity through the grid network. We build two-stage dynamic game models to characterize how the coal industry and the power industry make strategic decisions at different times. By virtual of the game models, we compare analytically the equilibrium outcomes with and without electricity regulation, and examine the changes in electricity price, electricity generation, coal price and coal production (we assume market clearing for coal in this study and thus its production equals consumption). Afterward, empirical data are collected and applied to estimate the parameters of the game models, based on which the influence of electricity price deregulation on the two industries is simulated quantitatively. Finally, to check the robustness of our theoretical results, we make the sensitivity analysis with respect to the electricity generation efficiency and price sensitivity 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 analytically in this section. Section 4 provides numerical simulation and sensitivity analysis using empirical data of the coal and electricity industries. Finally, Section 5 concludes the study.

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 until then 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 relative monopoly. They claimed that the public welfare would be hurt if the relative monopoly remains unchanged.

From the perspective of coal-fired power industry, many studies pointed out the problems induced by the regulation and suggested further market-oriented reform. Wang (2007) examined the pricing policies and the transaction relationship between the coal and power industries in China, concluding 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 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 reduced the social welfare losses from 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 for the investigated power plants.

In addition to the aforementioned studies which were conducted mainly based on computable general equilibrium (CGE) model, input-output (IO) model or econometric methodologies, game theory was also frequently 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 that under the benchmark scenario, respectively. Tian et al. (2017) build up game-theoretic models between the power producer and the natural gas supplier to study the impacts of market deregulations on gas power generation.

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 been paid to the electricity reform and its impacts on both the coal and power industries.

To sum up, there is still insufficient research on the influence of electricity price deregulation from the perspective of industries. To fill this research gap, our paper builds up game theoretical models between coal and power industries. The coal and power industries' strategic behaviors and best responses, such as pricing and quantity decisions, are examined. To reflect the shortage and oversupply in the regulated electricity markets, we characterize different scenarios to examine the impact of reform on the two industries. An empirical analysis is also provided based on theoretical results.

3. Game model in coal and electricity industry chain

3.1. Model settings

The electricity and coal markets in China are so complex that simplifying the economic connections helps us concentrate on the main research question, i.e., to examine the impact of electricity price deregulation on the coal and power industries. Therefore, we focus on the essential competitive and cooperative relationships between the two industries. Similar to Liu et al. (2017), the competitions on the enterprises level in the coal and power industries will not be included in this study. On this basis, our paper establishes industry-level game model: the coal industry produces and sells coal to the coal-fired power industry which generates electricity and sells it to end users in the market.

In this paper, we consider the coal market as a buyer's market and assume that the coal-fired power industry is the price maker. The long-lasting coal shortage situation in China ended in 2009 and the country has since had oversupply in its coal market (NBS, 2017). According to the 2018 premier's report on the work of the government, easing overcapacity and closing down outdated coal production facilities are 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, 2017). This new pricing mechanism has exhibited a rising pricing power of coal-fired electricity industry.

The dynamic game model includes two stages. In the first stage, the coal-fired power industry decides the coal price p_1 and the electricity generation q_2. If electricity price is regulated, the price is considered as public information to all players throughout the whole gaming period. Thus, electricity price will be an exogenous variable in the electricity regulation model. 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 decides the coal output q_1, with the price as known information. Coal purchase agreement will be signed between the coal and coal-fired power industries after both stages.

According to Yang (2008) and Liu et al. (2017), we assume the mining cost of coal (denoted as C_c) and the electricity generation cost (denoted as C_e) are quadratic functions of the coal supply in the market (denoted as q_1) and electricity generation (denoted as q_2), respectively. Therefore, we have $C_c = a_1 q_1^2 + b_1 q_1 + c_1$ and $C_e = a_2 q_2^2 + b_2 q_2 + c_2$, where c_1 and c_2 are the fixed costs, and a_1, b_1, a_2 and b_2 are parameters related to the variable cost. To simplify the model, we assume that one unit of coal can generate t unit of electricity, which means $q_2 = tq_1$. Here t is the parameter to reflect power generation efficiency.

Electricity has become an indispensable necessity that powers our society. Electricity is a typical normal commodity, which means that an increase of the electricity price will reduce its market demand. In this study, we assume that the market demand q is a linear function of the electricity price (retail price) p_2, which gives. Here Q is the market base 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 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 the same 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:

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

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

$$\pi_e = (p_2 - c_t) Min[Q - kp_2, q_2] - p_1 q_1 - (a_2 q_2^2 + b_2 q_2 + c_2) \quad (2)$$

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 pricep_1, the coal industry decides the supply amount q_1 to maximize its profit (calculated by Eq. (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 $q_1 = (p_1 - b_1)/(2a_1)$.

In the second stage, the coal-fired power industry decides the electricity generationq_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 reduce the planned electricity generation or provide a higher coal price to get sufficient 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 $q_1 = (p_1 - b_1)/(2a_1)$, the electricity generation is $q_2 = t(p_1 - b_1)/(2a_1)$.

The aim of the coal-fired power industry is to maximize its profit (calculated by Eq. (2)) by adjusting the coal price p_1. In the situation that electricity price is regulated by the government, two scenarios will be analyzed. Scenario S_1 has a low electricity price and Scenario S_2 has a high electricity price. The definitions of low and high prices will be explained below. These two scenarios reflect the shortage and oversupply in the regulated electricity market, and may occur in different periods when applying to the practice (Zhang et al., 2014). If the currently regulated electricity price is at a very low level, the potential demand will be high, which may exceed the generation quantity that the power industry chooses. If the regulated electricity price is set to be quite high, the potential demand will be restrained, which leads to a suppressed generation lower than the level the power industry originally would generate.

3.2.1. Scenario S_1 with low regulated electricity price

In this scenario, the regulated electricity price is so low that electricity demand is larger than the electricity generation chosen by the power industry. On this basis, the market demand will not be fully satisfied. Define $\overline{p_2}$ as the regulated electricity price in this situation. We have $Q - kp_2 > q_2$, which is equivalent to the condition $p_2 < \overline{p_2}$. We will provide the detailed expression of $\overline{p_2}$ later.

The profit function of the power industry is converted as follows.

$$\text{Max} \quad \pi_e = (p_2 - c_t) q_2 - p_1 q_1 - (a_2 q_2^2 + b_2 q_2 + c_2) \quad (3)$$

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 $p_1^* = \frac{a_2 b_1 t^2 + a_1(b_1 + (p_2 - c_t - b_2)t)}{2a_1 + a_2 t^2}$.

In the equilibrium, the coal supply amount is $q_1^* = \frac{(p_2 - c_t)t - b_1 - b_2 t}{4a_1 + 2a_2 t^2}$, and the electricity generation is $q_2^* = \frac{((p_2 - c_t)t - b_1 - b_2 t)t}{4a_1 + 2a_2 t^2}$. The profit of the coal industry is $\pi_c^* = \frac{a_1(b_1^2 + 2b_1(b_2 - (p_2 - c_t))t + (b_2^2 - 16a_2c_1 - 2b_2(p_2 - c_t) + (p_2 - c_t)^2)t^2) - 16a_1^2 c_1 - 4a_2^2 c_1 t^4}{4(2a_1 + a_2 t^2)^2}$, and the profit of the coal-fired power industry is $\pi_e^* = \frac{b_1^2 - 8a_1c_2 + 2b_1(b_2 - (p_2 - c_t))t + (b_2^2 - 4a_2c_2 - 2b_2(p_2 - c_t) + (p_2 - c_t)^2)t^2}{8a_1 + 4a_2 t^2}$.

It is clear that the equilibrium outcomes are functions of the regulated electricity price. In this scenario S_1 with a low electricity price, $Q - kp_2 > q_2^* = \frac{((p_2 - c_t)t - b_1 - b_2 t)t}{4a_1 + 2a_2 t^2}$. With the generation q_2^*, the power industry actually expects a higher 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 $Q - kp_2 = q_2^* = \frac{((p_2 - c_t)t - b_1 - b_2 t)t}{4a_1 + 2a_2 t^2}$, we obtain the price threshold$\overline{p_2} = \frac{4a_1 Q + t(b_1 + (b_2 + c_t + 2a_2 Q)t)}{4a_1 k + (1 + 2a_2 k)t^2}$. 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 high regulated electricity price

In this scenario, the electricity 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 $p_2 > \overline{p_2}$.

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 obtain 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 is $q_2^* = Q - kp_2$. The profit of the coal industry is $\pi_c^* = \frac{a_1(Q - kp_2)\hat{}2 - c_1t^2}{t^2}$, 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 depends on the regulated electricity price.

3.3. Electricity deregulation model

We use backwards induction to solve the equilibrium of the two-stage dynamic game model. In the second stage, the coal industry decides the coal supply amount q_1 to maximize its profit (Eq. (1)). 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 $q_2 = \frac{p_1 - b_1}{2a_1}t$.

In the first stage, the coal-fired power industry decides the coal price and electricity price, to maximize its profit (Eq. (2)). 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 price is exogenous in the regulation model but endogenous in the deregulation model. In the deregulation model, if the electricity price p_2 at a given point of time is so low that the market demand is higher than the generation, which means $Q - kp_2 > q_2$ (the final sales amount is q_2), then the power industry has incentive to increase the electricity 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.

$$\text{Max} \quad \pi_e = (p_2 - c_t)(Q - kp_2) - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) \tag{3a}$$

Subject to. $q_2 - (Q - kp_2) \ge 0$

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

$$L = (p_2 - c_t)(Q - kp_2) - p_1q_1 - (a_2q_2^2 + b_2q_2 + c_2) + \lambda(q_2 - Q + kp_2) \tag{4}$$

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. (4), we take derivation with respect to p_1 and p_2. The Karush–Kuhn–Tucker (KKT) optimization conditions are as follows.

$$\frac{\partial L}{\partial p_1} = \frac{a_2(b_1 - p_1)t^2 + a_1(b_1 - 2p_1 - b_2t + t\lambda)}{2a_1^2} = 0 \tag{5}$$

$$\frac{\partial L}{\partial p_2} = Q + k(-2p_2 + \lambda) + c_tk = 0 \tag{6}$$

$$\lambda(q_2 - Q + kp_2) = 0 \tag{7}$$

$$\lambda \ge 0 \tag{8}$$

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

Case 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.

Case 2): $q_2 - Q + kp_2 > 0$ and $\lambda = 0$. The equilibrium outcomes are $p_1^* = \frac{a_1b_1 - a_1b_2t + a_2b_1t^2}{2a_1 + a_2t^2}$ and $p_2^* = \frac{Q + c_tk}{2k}$. $q_2^* - Q + kp_2^* = -\frac{2a_1(Q - c_tk) + t(b_1 + (b_2 - a_2c_tk + a_2Q)t)}{4a_1 + 2a_2t^2} < 0$, which does not satisfy the non-negativity condition of the optimization. Therefore, this case does not hold.

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 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 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 $\pi_c^* = \frac{(a_1(b_1^2 - 16a_1c_1)k^2 + 2a_1b_1k(b_2k + c_tk - Q)t + a_1(-16c_1k(1 + a_2k) + (-b_2k - c_tk + Q)^2)t^2 - 4c_1(1 + a_2k)^2t^4)}{4(2a_1k + (1 + a_2k)t^2)^2}$, and the profit of the coal-fired power industry is $\pi_e^* = \frac{b_1^2k^2 - 8a_1c_2k^2 + 2b_1k(b_2k + c_tk - Q)t + (-4c_2k(1 + a_2k) + (-b_2k - c_tk + Q)^2)t^2}{4k(2a_1k + (1 + a_2k)t^2)}$.

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, the regulated electricity price p_2 is lower than the threshold $\overline{p_2}$, a level with the market supply and demand to be matched. After the deregulation, we have*:

(1) *The electricity price will increase to a level higher than $\overline{p_2}$.*
(2) *The coal price, the coal production and the electricity generation will increase if $p_2 \in (0, \check{p}_2)$ and decrease if $p_2 \in (\check{p}_2, \overline{p_2})$. Here $\check{p}_2 = \frac{2a_1Q + t(b_1 + (b_2 + c_t + a_2Q)t)}{2a_1k + (1 + a_2k)t^2}$.*

According to Proposition 1, in Scenario S_1, after eliminating the regulation, the electricity price will go up. The coal price and the traded amount may either increase or decrease, depending on the previously regulated electricity price. When the regulated price is sufficiently low, the electricity industry is willing to generate more to meet the potential market demand. Therefore, the electricity generation will go up. The coal price will also rise to stimulate the coal industry to increase its supply. When the regulated price is sufficiently high, however, the actual generation has almost met the potential market demand under the electricity regulation. After the reform, the increase in the electricity price will cause a decrease in electricity usage, so the coal production and the electricity generation will drop, which is accompanied by a decrease in the coal price.

Proposition 2. *Under Scenario S_2, the regulated electricity price p_2 is higher than the threshold $\overline{p_2}$. After the deregulation, we have*:

(1) *The electricity price will increase if $p_2 \in (\overline{p_2}, \hat{p}_2)$, and decrease if $p_2 > \hat{p}_2$.*
(2) *The coal price, the coal production and the electricity generation will decrease if $p_2 \in (\overline{p_2}, \hat{p}_2)$, and increase if $p_2 > \hat{p}_2$. Here $\hat{p}_2 = \frac{4a_1kQ + t(b_1k + (b_2k + c_tk + Q + 2a_2kQ)t)}{2k(2a_1k + (1 + a_2k)t^2)}$.*

According to Proposition 2, in the scenario S_2 with a high electricity price, the change of electricity price depends on 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 price which determine the impact of electricity price deregulation.

Proposition 3.

(1) *The low interval is* $p_2 < \check{p}_2$.

If the regulated electricity price is very low, then after the reform the electricity price will rise, the coal price will rise, and the coal production and the electricity generation will increase.

(2) *The medium interval is* $\check{p}_2 < p_2 < \hat{p}_2$.

If the regulated electricity price is at the medium level, then after the deregulation the electricity price will increase, the coal price will drop down, and the electricity generation and coal production will decrease.

(3) *The high interval is* $p_2 > \hat{p}_2$.

If the regulated electricity price is high, then after the reform the electricity price will decrease, the coal price will rise, and the coal production and the electricity generation will increase.

4. Numerical simulation and sensitivity analysis

Based on the above analysis, we further study the empirical impact of China's electricity price deregulation on the coal and coal-fired power industries through numerical simulation. First, we collect the industrial data to estimate the model parameters which are then applied to the equilibrium outcomes of game models. Next, we examine which interval (among the three mentioned in Proposition 3) China's current regulated electricity price lies in and show the influence of electricity deregulation on the two industries quantitatively. Last, to check the robustness of our results, sensitivity analysis of equilibrium outcomes with respect to the electricity generation efficiency and the price sensitivity of electricity demand is provided.

The parameters in 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 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 $a_1 = 0.00045671$, $b_1 = 207.33$, $c_1 = 0$, $a_2 = 0$, $b_2 = 369$, $c_2 = 25014369$, $c_t = 2902.3$, $t = 0.3205$, $Q = 83808$, $k = 3.8424$ (see Appendix A for more detailed explanation).

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

Currently, the regulated electricity price is 6612 (RMB/ten thousand kWh), which is higher than $\check{p}_2 = 4509.4$ and lower than $\hat{p}_2 = 13160.4$. Therefore, the actual regulated electricity price falls within the medium interval of the theoretical results. According to Section 3.4, after the deregulation the electricity price will increase, the coal price will decrease, the coal traded amount and the electricity generation 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.

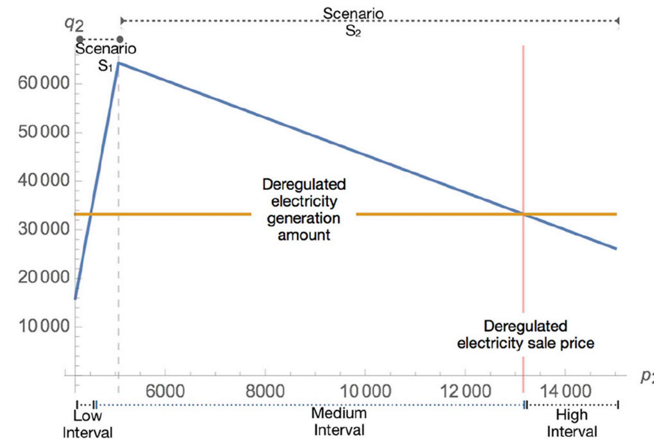

Fig. 1. The electricity generation (unit: one hundred million kWh) at different levels of regulated sales price (unit: RMB/ten thousand kWh).

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. Theoretical results are as follows.

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 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 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 in the coal production, the coal price will be raised in the game between two industries. In the Scenario S_2 with a high electricity price, the electricity generation is equal to the demand at the regulated price. With a certain electricity generation and a higher generation efficiency, the coal consumption will be lower and the coal price will have to be lower too.

As the electricity generation efficiency rises, the coal price and production change differently in the two scenarios. Fig. 2 shows the change of the coal price if the electricity generation efficiency increases by 10% on the basis of that in Fig. 1. Results show the coal price increase in Scenario S_1, and decreases in Scenario S_2.

Table 1
A numerical simulation with the electricity price to be regulated at 6612 (RMB/ten thousand kWh).

	Under regulation	Deregulation
Coal price (RBM/ton)	373.78	302.07
Coal production (Million tons)	182.22	103.71
Electricity price (RMB/kWh)	0.66	1.32
Electricity generation (Billion kWh)	5840	3324
The profit of the coal industry (Billion RMB)	151.65	49.12
The profit of electricity industry (Billion RMB)	1019.79	2723.76

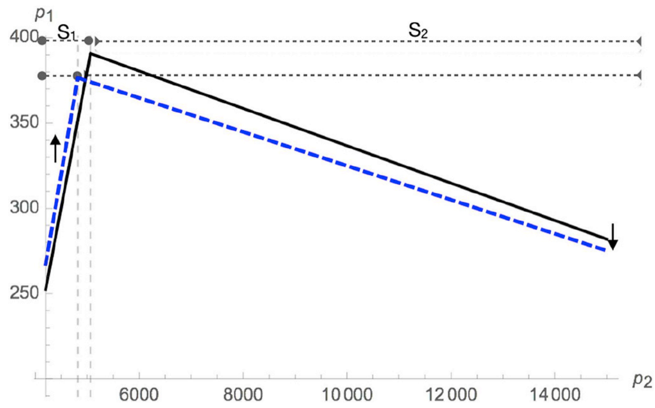

Fig. 2. The change of the coal trading price (unit: RBM/ton) under Scenarios S_1 and S_2 if the electricity generation efficiency increases by 10% (Dashed line here represents the new coal price with an improved generation efficiency).

After relaxing the regulation, as the electricity generation efficiency rises, the generation, which is equal to the market demand, will be higher and the sales price will be lower. Fewer coal will be consumed and the its price will decrease.

As the price sensitivity of electricity demand decreases (a lower k), the electricity demand will go up in the regulated with Scenario S_2 and the deregulated situation. Therefore, the electricity generation will be higher. With a stronger demand of coal, the power industry will offer a higher price to encourage higher supply from the coal industry. In the deregulated situation, the electricity price will rise as well.

5. Additional discussion for coal shortage scenario

In reality, coal shortage happens from time to time. Therefore, this section sets up model for the scenario that the coal industry owns the pricing power because of coal shortage. This dynamic game model is divided into two stages. In the first stage, the coal industry decides the coal pricep_1. In the second stage, with the known coal price, the coal-fired power industry decides the electricity generation amount q_2 and electricity price p_2 (in the deregulation model). 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. Then the coal industry and coal-fired power industry will sign a purchase agreement. After electricity generation, transmission and distribution, electricity generated is sold in the market.

5.1. Electricity regulation model

We proceed backwards to derive the equilibrium of the two-stage dynamic game model. In the second stage, given the coal pricep_1, the coal-fired power industry decides the generation amount q_2 to maximize its profit (calculated by Eq. (2)). We first take derivation with respect to q_2 and the best response function of the power industry is $q_2 = \min\left\{Q - kp_2, \frac{(p_2 - c_t - b_2)t - p_1}{2a_2t}\right\}$.

Back to the first stage, the coal industry decides the coal pricep_1 to maximize its profit (calculated by Eq. (1)). With the forecasted power generation, the demand on coal usage is $q_1 = \frac{q_2}{t} = \min\left\{Q - kp_2, \frac{(p_2 - c_t - b_2)t - p_1}{2a_2t}\right\}/t$.

It's easy to check that if$p_1 \in (0, (p_2(1 + 2a_2k) - 2a_2Q - b_2 - c_t)t]$, the optimal coal price will be the upper bound, i. e., $p_1^* = (p_2(1 + 2a_2k) - 2a_2Q - b_2 - c_t)t$. Thus, the coal demand will be $q_1^* = (Q - kp_2)/t$. Otherwise, if $p_1 \in ((p_2(1 + 2a_2k) - 2a_2Q - b_2 - c_t)t, +\infty)$, the optimal coal price will be $p_1^* = \frac{t((a_1 + a_2t^2)(p_2 - b_2 - c_t) + a_2b_1t)}{a_1 + 2a_2t^2}$. Correspondingly, the coal demand will be $q_1^* = \frac{(p_2 - c_t - b_2)t - p_1}{2a_2t^2}$. By combining the above two scenarios, we have the following proposition.

Proposition 5. *Under the electricity regulation model.*

(1) *if the regulated electricity price is higher than* $\overline{\overline{p_2}}$, *then in the equilibrium the coal price is* $p_1^* = (p_2(1 + 2a_2k) - 2a_2Q - b_2 - c_t)t$, *the coal demand is* $q_1^* = (Q - kp_2)/t$, *and the electricity generation amount is* $q_2^* = Q - kp_2$. *Here* $\overline{\overline{p_2}} = \frac{Q(2a_1 + 4a_2t^2) + b_1t + (b_2 + c_t)t^2}{2a_1k + (1 + 4a_2k)t^2}$.
(2) *if the regulated electricity price is lower than* $\overline{\overline{p_2}}$, *then in the equilibrium the coal price is* $p_1^* = \frac{t((a_1 + a_2t^2)(p_2 - b_2 - c_t) + a_2b_1t)}{a_1 + 2a_2t^2}$, *the coal demand is* $q_1^* = \frac{(p_2 - c_t - b_2)t - p_1}{2a_2t^2}$, *and the electricity generation amount is* $q_2^* = \frac{(p_2 - c_t - b_2)t - p_1}{2a_2t}$.

5.2. Electricity deregulation model

We use backwards induction to solve the equilibrium of the two-stage dynamic game model. In the second stage, given the coal pricep_1, the coal-fired power industry decides the electricity price p_2 to maximize its profit (calculated by Eq. (2)). Obviously, the power generation amount $q_2$will equal the market demand $Q - kp_2$. Thus, the corresponding coal usage will be $(Q - kp_2)/t$. We first take derivation with respect to p_2 and the best response function of the power industry is $p_2 = \frac{Qt(1 + 2a_2k) + (b_2 + c_t)kt + p_1k}{2kt(1 + a_2k)}$.

Back to the first stage, the coal industry decides the coal pricep_1 to maximize its profit (calculated by Eq. (1)). With the forecasted electricity price p_2, the demand on coal usage is $q_1 = \frac{Q - kp_2}{t} = \frac{Qt - (b_2 + c_t)kt - p_1k}{2(1 + a_2k)t^2}$. By taking derivation with respect to p_1, we obtain the following equilibrium.

Proposition 6. *Under the electricity deregulation model, there exists only one equilibrium. The coal price is* $p_1^* = \frac{(a_1k + (1 + a_2k)t^2)(Qt - (b_2 + c_t)kt) + b_1k(1 + a_2k)t^2}{k(a_1k + 2(1 + a_2k)t^2)}$, *the electricity price is* $p_2^* = \frac{(2a_1k + 3t^2 + 4a_2kt^2)Q + (b_2 + c_t)kt^2 + b_1kt}{2k(a_1k + 2(1 + a_2k)t^2)}$, *the coal demand is* $q_1^* = \frac{Qt - (b_2 + c_t)kt - b_1k}{2a_1k + 4(1 + a_2k)t^2}$ *and the power generation is* $q_2^* = t\frac{Qt - (b_2 + c_t)kt - b_1k}{2a_1k + 4(1 + a_2k)t^2}$.

By comparing the results in Proposition 5 and Proposition 6, we next examine the changes brought by the electricity deregulation, as the following Proposition 7 shown.

Proposition 7. *Assume the regulated electricity price to be* p_2, *after the deregulation, we have*:

(1) *The electricity price will increase if* $p_2 < p_2^*$, *and decrease if* $p_2 > p_2^*$. *Here* p_2^**is the equilibrium price under the deregulated model and* $p_2^* > \overline{\overline{p_2}}$.
(2) *The coal price increases if* $p_2 < \widetilde{p_2}$, *and decrease if* $p_2 > \widetilde{p_2}$.
(3) *The coal production and the electricity generation will increase if* $p_2 < p_2'$, *decrease if* $p_2 \in (p_2', p_2'')$ *and increase if* $p_2 > p_2''$ *(see the* Appendix B *for the details of* $\widetilde{p_2}$, p_2' *and* p_2''*).*

In comparison to Proposition 3, we find that the basic results still hold. After deregulation, the electricity price will increase if the regulated electricity price is low, and decrease if the regulated electricity price is high. As to the changes in the electricity generation and coal production, there still exist three intervals in terms of the regulated electricity price. That's to say, as the regulated electricity price rises, the coal production and the electricity generation will first increase, then decrease and finally increase again. Slightly different from Proposition 3, there are only two intervals for the change of the coal price. This is because that if the regulated electricity price is too high, stimulating more coal usage and more power generation is the best strategy after the deregulation. Therefore, the coal industry will reduce the coal trading price, rather than raise it. Thus, after deregulation, the coal price will increase if the regulated electricity price is low, and decrease if the regulated electricity price is high.

6. Concluding remarks

As a heritage of the planned economy system, the electricity tariff in China is heavily regulated. The regulated price mechanism attracts much criticism because of its incapability to optimize the allocation of resources in the power industry. Recognizing the negative effect of the current price mechanism, China has launched an unprecedented marketization reform on its power industry to deregulate the electricity price. This study 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 industry and the downstream power generation industry not only cooperate but also game with each other. The interaction between the two industries will be reflected on the coal price and its production. 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 electricity price, electricity generation, coal price and coal production after deregulation. Two scenarios are characterized to reflect the shortage and oversupply in the regulated electricity markets. Afterward, empirical data are collected to estimate the parameters in the game model and simulate 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 there are three intervals of the regulated electricity prices which determine the impact of electricity price deregulation. According to the collected industrial data, the actual regulated electricity price falls within the medium interval of the theoretical results. The price deregulation will result in higher electricity price, lower coal price, less coal production and less electricity generation. Empirical analyses of our study show that the deregulation will reduce the profit of the coal industry but increase that of the electricity industry. The extra gain of the electricity industry exceeds the loss of the coal industry, leading to a net benefit to the whole industry chain. Since industry structures vary significantly from place to place, the gain and loss may be 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 industry chain better off.

It is obvious that budget balance plays a vital role in the design and implementation of the financial instruments to redistribute welfare between industries and regions. Fortunately, the industrial ownership and the fiscal system in the Chinese circumstance both support the reform. On the one hand, when subsidy is easy to implement to compensate the industry that burdens loss from a reform, it is less likely for the government to raise income from the industry that gains additional profit in most countries (because of tax law, lobbying power, etc.). However, in our case the gaining industry, i.e., the power industry consisting of grid and power generation companies, is mainly state-owned, which means that its profit will eventually become government revenue and thus can be used to finance the subsidy. On the other hand, the regional welfare redistribution is of importance because most of the coal production companies base in the less developed Northern and Western provinces of China. On the contrary, a large fraction of the power industry locates in the more developed coastal Southern and Eastern provinces. The fiscal decentralization of central and regional governments in China shows its merit, or flexibility, in this case because inter-province transfer payment becomes more political feasible. To summarize, the economic and political characteristics of China are in favor of the welfare redistribution policies and thus support the reform.

Acknowledgements

The authors thank four anonymous referees and Jinjun Xue for their valuable comments on this study. This study has been supported by the National Natural Science Foundation of China (Grants Nos. 71602186 and 71373055), the Natural Science Foundation of Beijing (No. 9192012), Humanities and Social Sciences Youth Foundation of the Ministry of Education of China (Grant No. 15YJC630075), and the Science Foundation of China University of Petroleum, Beijing (No. 2462017BJB08).

Appendix A

The parameters of the cost functions of the coal and coal-fired power industries are estimated based on the 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 are used in our numerical simulation. Data and calculation procedures are provided below.

There are 15 listed companies reported their utility coal sale information in 2016, which contributed to 37.35 percent of the country's coal consumption with an average price of 310 RMB/ton (Table A1). Since there are a great number of coal traders in China, the coal trade activities are considered to have sufficient competiveness. In this case, the coal price can be a good proxy of the supply cost (per unit of output) of a company in terms of opportunity cost.

Table A1
Utility coal sale statistics for 2016 of China's listed companies.

Stock code of company	Sale volume (thousand tons)	Sale revenue (million RMB)	Price (RMB/ton)
600123	48	6	129
600714	294	46	157
601225	124,409	31,754	255
600403	9,553	2,463	258
601699	23,849	6,270	263
600397	2,329	640	275
601666	12,317	3,721	302
600395	3,723	1,150	309
601088	394,700	125,189	317
900948	63,804	20,619	323
601898	70,950	23,381	330
600188	14,782	5,039	341
601918	14,047	4,953	353

(*continued on next page*)

Table A1 (*continued*)

Stock code of company	Sale volume (thousand tons)	Sale revenue (million RMB)	Price (RMB/ton)
601001	19,380	7,066	365
600508	6,792	3,772	555

To simplify our calculation, the following assumptions are adopted. (1) All the 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 of the coal producers consists of only variable cost. (4) The short-run supply curve of coal (which is also the curve between coal output and variable cost) is linear. Based on the above assumptions, the supply curve of coal is obtained by applying the OLS regression using the above 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 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 1.05 TW in 2016. In this study, we introduce the concept of standard power plant, which means the average unit capacity of 600 MW 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), the average coal consumption efficiency for all coal-fired power plants with installed capacity over 6 MW is 312 g standard coal/kWh, which makes t equal to 320.5 kWh/ton standard coal.

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. According to China's National Energy Administration (http://zfxxgk.nea.gov.cn/auto92/201712/P020171228590567105234.pdf), the average electricity tariff paid by consumer (p_2) and that received by generator ($p_2 - c_t$) are 0.6612 RMB/kWh and 0.3710 RMB/kWh, respectively, which makes the gap between to two (c_t) as 0.2902 RMB/kWh. The demand curve of electricity for the Chinese society can also be calculated based on the above data as $Q = -3.8424p_2 + 83808$.

It is worth noting that the above parameter estimation procedure based on many assumptions is far from an ideal simulation of the actual situation. However, since the purpose of the empirical examination is not to provide precise quantitative results, using the best available data and some simplifications are deemed to be reasonable for this study.

Appendix B

Additional proof of Proposition 7

(2) If the regulated electricity price p_2 is higher than $\overline{\overline{p_2}}$, the change of coal price after deregulation is negatively correlated with p_2. Specifically, the coal price increases if $p_2 < p_{2\_1}$ and decreases otherwise. Similarly, if the regulated electricity price p_2 is lower than $\overline{\overline{p_2}}$, the change of coal price after deregulation is negatively correlated with p_2. Specifically, the coal price increases if $p_2 < p_{2\_2}$ and decreases otherwise.

Note that either both p_{2_1} and p_{2_2} are bigger than $\overline{\overline{p_2}}$, or both are smaller than $\overline{\overline{p_2}}$. Therefore, there are only two intervals in terms of the regulated electricity price. $\widetilde{\overline{p_2}}$ equals p_{2_1} if $p_{2\_1} < \overline{\overline{p_2}}$, and p_{2_2} otherwise.

(3) If the regulated electricity price p_2 is higher than $\overline{\overline{p_2}}$, the changes of coal production and the electricity generation after deregulation are negatively correlated with p_2. Specifically, they increase if $p_2 < p_{2\_3}$ and decreases otherwise. In contrast, if the regulated electricity price p_2 is lower than $\overline{\overline{p_2}}$, the changes of coal production and the electricity generation after deregulation are positively correlated with p_2. Specifically, they decrease if $p_2 < p_{2\_4}$ and increase otherwise.

Note that $p_{2\_4} > \overline{\overline{p_2}}$, therefore, there always exist three intervals in terms of the regulated electricity price. p_2' equals $\min\{p_{2_3}, \overline{\overline{p_2}}\}$, and p_2'' equals p_{2_4}.

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