Have market-oriented reforms improved the electricity generation efficiency of China's thermal power industry? An empirical analysis

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ABSTRACT

In 2003, China implemented market-oriented reforms to its electric power industry, aimed at improving the generation efficiency of its thermal power plants. In this paper, we use the polynomial functions, PLS (partial least squares) algorithm, and generation efficiency data from 1993 to 2012 to evaluate the effect of these reforms. Empirical analysis shows that the reforms caused a sudden down shift of 0.142 kW h per kg SCE (standard coal equivalent) to the "natural" generation efficiency curve of the thermal power industry, resulting in 555.8 million tons of SCE of wasted fossil energy during 2003–2012. This was mainly due to the non-implementation of electricity price bidding. To improve the generation efficiency of the thermal power plants, market competition should be further introduced into China's electric power industry as a matter of urgency. The major policy adjustment directions include: a) Electricity price bidding should be promoted by sub-region according to the unified trading rules designed by the central government; b) Over-the-counter transaction should be permitted; as well as c) Dynamic incentive mechanisms for renewable energy development should be established.

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1. Introduction

At the beginning of 2003, China implemented a programme of market-oriented reforms to the electricity industry, aimed primarily at improving the generation efficiency of thermal power plants, fueled by coal, diesel and oil [1]. On Mar. 15, 2015, the publication, by the Central Committee of the Chinese Communist Party and the State Council, of a report entitled "Further strengthening the institutional reform of electric power industry" [2], heralded a second round of market-oriented reforms to the electricity industry. The purpose of this paper is to evaluate the effect of the first round of reforms in 2003, in order to guide the current reforms.

For most developing countries, adequate electricity supply is a key basis for economic development, as demonstrated by Solarin and Shahbaz [3], Hamdi et al. [4], and Wolde-Rufael [5]. Guided by this principle, the Chinese government has attached great importance to the development of its electric power industry. When the People's Republic was founded in 1949, the electric power industry previously controlled by the old governments, private and foreign owners was nationalized. From this point forward, all electricity system assets (including generation, transmission and distribution) were state-owned, with central governments the sole investors in electricity system assets [6]. Management was "vertically integrated" [7], with the planning, investment and operation of the electricity system enterprises managed together by administrational orders [8].

This planned, "vertically integrated" electricity system was suitable for China's socio-economic environment at that time, and had at least two other advantages. Firstly, it supported the unified planning of the country's electric power system, which was weak in the early stages of the People's Republic, following years of war and economic hardship. In 1949, the installed electricity generation capacity was just 1.85 GW and mainly concentrated in several large and medium-sized cities; the amount of electricity generated was only 4.3 billion kW h, 21st and 25th in the world, respectively [9,10]. There were several independent transmission networks, as opposed to a national scale grid covering the whole country. All electric power equipments were imported from different countries and adopted different technical standards. To develop an integrated, national electricity system, a unified development plan

formulated and implemented by the central government was essential. Secondly, from a financial perspective, it was perhaps the only feasible mode at that time to rapidly develop the electric power industry. For political reasons, foreign investment was not allowed in any industrial sectors. Moreover, existing private enterprises had been transformed to public-private form in 1956, and then to state owned or collective forms in 1966 and lacked the financial resources to invest in the electric power industry. Thus the financial support allocated directed by the central government was the only feasible way for the electric power industry to obtain investment. This planned management of the electricity system successfully supported the rapid development of China's electric power industry. In 1985, the installed electricity generation capacity had reached 87.05 GW (47 times of that in 1949) and the power generated was 410.7 billion kW h (96. times of that in 1949) [9]. The annual growth rates were as high as 11.29% and 13.50%, respectively. But, as the socioeconomic environment changed, two disadvantages of this mode were gradually exposed.

First of all, to meet a rapid growth in electricity demand, the investment required in the electric power industry increased quickly. Because of the limited fiscal revenue, the central government, as the only investor, found it was more and more difficult to offer the required investment, especially in the years after China transitioned from a planned economy to a market one and in light of the policy of opening-up to the outside world in 1979. Widespread electricity shortages frequently occurred as a consequence of the lack of investment [11]. Fortunately, changes in the political and economic environment offered the opportunity to solve this problem. At this time, political ideology was no longer opposed to foreign investment, and many of the local governments and domestic private sector companies were financially strong. As a result, from 1985, they were allowed to invest in the power generation sector, although not in the transmission and distribution sectors [11]. This policy strongly supported the construction of power plants, and thus increased power supply. From 1986 to 1995, capacity increased by 13.40 million kW, year on year, with an increase of 9.62%, much higher than the increases of 4.43 million kW and 7.05% seen annually from 1976 to 1985 [12]. The problem of electricity shortages was mitigated rapidly [8,13].

Another disadvantage was the generation inefficiency exacerbated by the vertically integrated management system, where there was no market competition. Because of the abundance of coal resource and historical overdevelopment of the coal-fired power plants, electricity generated by fossil energies accounted for the single largest part of the country's total; this share has never been less than 75% [14]. On the contrary, except for the hydropower, renewable energy sources which have great potential of development [15–17] have not been attached sufficient importance. Their generation share was lower than the global average for a long time [14]. In 2002, the year before the market-oriented reforms were initiated, 1327 billion kW h of electricity was generated by China's thermal power plants, accounting for 80.10% of the country's total [14]. However, the generation efficiency of China's thermal power plants, a measure of the amount of electricity generated per unit of fossil fuel consumed, was not high. In 2002, as an average, the generation efficiency of China's thermal power plants was only equal to 98.96%, 94.00%, 88.25%, 87.99%, 80.68% of that of Australia, US, UK, Russia, and Italy, respectively [18]. Considering the large amount of electricity generated by the thermal power plants, this inefficiency caused an enormous waste of resources, increased generation cost, and environmental pollution. Whilst this is partly because of the outdated power generation equipment, the influence of the non-competitive management system should also not be ignored.

To improve generation efficiency of the thermal power plants by introducing market competition, China implemented a first round of market-oriented reforms to the electricity industry at the beginning of 2003. The "vertically integrated" management system was dismantled in order to ensure that all generating plants had equal access to the transmission grid. The state-owned generation assets were allocated to five large generation corporations with similar competitive strengths. With the generation and transmission sectors vertically separated, the grid companies kept only a few peaking generation plants [13].

In recent years, a number of researchers have sought to understand how the market-oriented reforms of 2003 impacted on the generation efficiency of China's thermal power industry. Mou has analyzed the efficiency change of China's coal-fired power plants using the Data Envelopment Analysis—Slack Based Measure method [19], however due to the method adopted, this research only measures the relative change of the efficiency rather than the absolute change in efficiency and therefore the quantitative impact of the reforms. Zhao and Ma used data from 34 large thermal power plants for the period of 1997−2010 to test the impact of the reforms on the operational efficiency of these plants, and showed that the 'unbundling' reform boosted the relative productivity of these power plants [1]. However, their survey only considered a relatively small, special samples, whereas the aim of the reforms is to improve the generation efficiency of the whole industry, not just the large thermal power plants which existed prior to 2003. Du et al. have investigated the productivity and efficiency changes of China's generation plants during 1995−2004 [13]. Whilst they found a significant productivity improvement in fuel usage, the fuel usage efficiency would be expected to improve, gradually, without the reforms as a result of technology innovation [20] and improved management [21], and therefore the identified efficiency improvement cannot be attributable to the market-oriented reforms.

Taking a different approach, this paper measures the quantitative impact of the market-oriented reforms of 2003 on the electricity generation efficiency of the whole Chinese thermal power industry, and makes policy suggestions for the second round of reforms based on the empirical analysis. Specifically, polynomial equations which can uniformly fit any efficiency trends are used to fit the "natural" development trend of the generation efficiency of China's thermal power industry. Furthermore, to obtain the steady structures of the polynomial equations with small samples, the partial least squares (PLS) algorithm is adopted to estimate the equation parameters. The quantitative impact of the market-oriented reforms in 2003 is measured by investigating the curve changes of the fitting equation.

The rest of this paper is organized as follows: Section 2 introduces the main methods and the relative efficiency data used within the analysis. Section 3 describes the modeling results which are discussed in Section 4. Section 5 concludes the paper and explores the policy implications of this work for future reforms.

2. Methods and data

2.1. Polynomial fitting equation

Regardless of the stochastic impacts, the generation efficiency of the thermal power industry over time could be demonstrated by a smooth curve, which rises because of updating of generation equipment, the improvement of the management level and other factors. Unfortunately, the specific form of its fitting equation is

unknown and as a result, a general equation is needed.

The polynomial equation is written as follows.

$$GE_t = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + \cdots + b_p t^p \tag{1}$$

where *GE* is the generation efficiency; *t* refers to time; $b_0 - b_p$ are parameters.

By adjusting the parameters, Eq. (1) can theoretically fit any generation efficiency curves [22].

2.2. Multicollinearity test

Multicollinearity is a phenomenon in which two or more independent variables in a multiple regression model are highly correlated, meaning that one can be linearly predicted from the others with a non-trivial degree of accuracy. Multicollinearity is one of the most serious and frequently encountered problems in multiple linear regression. Due to the presence of multicollinearity, the variance of the ordinary least squares (OLS) estimator gets inflated and consequently, the OLS estimator becomes unstable and gives misleading results [23]. When a variable is seen in a model more than once as in polynomial models, or if inter-correlated variables are included in the same model, strong multicollinearity structures may well be formed [24]. Considering the equation structure of Eq. (1), the multicollinearity phenomenon may well exist and the OLS algorithm cannot be used to estimate the parameters of it. The strict testing method is as follows.

Multicollinearity can be tested by measuring the explanation power of each dependent variable by others. Specifically, for the *j*th independent variable, other independent variables are used to construct the linear regression equation and the explanation power can be measured by the following *F* statistic.

$$F_j = \frac{R_j^2 / (p-1)}{\left(1 - R_j^2\right) / (n-p)} \tag{2}$$

where R_j is the determination coefficient of the constructed equation; *p* is the number of independent variables of Eq. (1).

If the *F* statistic of any independent variable is larger than the threshold, the multicollinearity is deemed to be in existence.

2.3. PLS algorithm

Considering the equation structure of Eq. (1), the multicollinearity phenomenon may well exist and then the ordinary least squares (OLS) algorithm cannot be used to estimate it's parameters. Enlarging the sample size may mitigate the extent of multicollinearity, but because the electricity industry market-oriented reforms were pursued at the beginning of 2003, it is impossible to add to the sample number. The PLS parameter estimation algorithm, which is based on factor analysis fundamentals, is applied where there are many variables but not enough samples or observations, especially when the multicollinearity phenomenon obviously exists and under these conditions, the PLS algorithm has the ability to obtain stable regression parameters [25,26]. The mathematical construction of PLS is that the correlation between the independent and the dependent variables has to be devised by taking into consideration the contribution from all other independent variables. More specifically, PLS reduces the dimension of the independent variable samples by extracting components that are correlated with the dependent variable observations while capturing a large amount of the variations in the independent variable samples; as demonstrated by Wang et al. [27], as well as Meng and Niu [28]. With the extraction of one component after

another, the importance of information contained in the extracted component decreases gradually. In particular, when the useful information has been totally involved in the extracted components, the following components will introduce the stochastic information into the final estimated equation. In this case, the generalization ability of the estimated equation will decrease, although the fitting results will be more perfect. To keep the generalization ability of the PLS regression equation, the goal of optimizing the parameters is not minimizing the sum of squared residuals of fitting, but controlling it to a certain level by using the Q_h^2 criterion [28], especially for the limited observations.

2.4. Chow test

The Chow test, which is proposed by Gregory Chow, is a statistical and econometric test of whether the coefficients in two linear regressions on different data sets are equal [29].

To calculate the Chow statistic, all samples should be divided into two groups. Besides the equation estimated by all samples, equations estimated by each group of samples should also be obtained. Once these have been done, the following *F* statistic can be computed.

$$F = \frac{[SSR - (SSR_1 + SSR_2)]/(p+1)}{(SSR_1 + SSR_2)/(n_1 + n_2 - 2p - 2)} \tag{3}$$

where *SSR*, SSR_1 and SSR_2 are the sum of squared residuals from equations estimated by all samples, the first group of samples, and the second group of samples, respectively; n_1 and n_2 are the numbers of samples of the first and the second group of samples, respectively; *p* is the number of independent variables.

Similar to Eq. (2), if the *F* statistic is larger than the threshold, the coefficients in two linear regressions are considered to be different.

2.5. Data selection

Calculating the generation efficiency values, requires time series data of the electricity generated and fossil energies consumed by China's thermal power industry. Annual electricity generation data from China's thermal power industry were selected from the *China Statistical Yearbook* (*1995–2014*) [14]. Data for the amounts of fossil energies consumed including coal, crude oil, fuel oil and diesel, were obtained from the *China Energy Statistical Yearbook* (*1994–2013*) [30]. As the most recent available data were from 2012, in order to balance the sample size before and after the market-oriented reforms, the time span covered by the samples was from 1993 to 2012. All selected data are listed in Table 1.

When calculating the generation efficiency, the fossil energies consumed must be converted to standard coal equivalent (SCE) and summed. The conversion factors were selected from "General Principles for Calculation of Total Production Energy Consumption" (GB/T 2589–2008) [31], as listed in Table 2.

Using the electricity generation data listed in Table 1 and the sum of the fossil fuels consumed in SCE, the generation efficiency values of China's thermal power industry were obtained (Table 3).

3. Results

To evaluate the multicollinearity extent, the *F* statistics calculated by Eq. (2) for 2-variable form of Eq. (1) were calculated. They were 300.68 and 300.68 (For 2-dependent variable form of Eq. (1), the *F* statistics for each independent variable are equal), much bigger than 10.22, the threshold with a confidence of 99.5% [32]. Similarly, the *F* statistics for 3-dependent variable form were calculated. They were also much larger than the threshold.

Table 1
Annual electricity generation and fossil energy consumptions from China's thermal power industry.

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Electricity	683.9	745.9	804.3	877.7	924.1	944.1	1020.5	1114.2	1183.4	1338.1
Coal	368.31	400.53	444.40	488.07	489.80	494.89	524.58	558.11	597.98	686.00
Crude oil	0.946	0.648	0.616	0.682	0.643	0.744	0.802	0.85	0.816	0.783
Fuel oil	12.034	8.927	10.715	8.888	8.392	9.938	9.063	8.142	8.385	9.127
Diesel oil	2.911	2.012	2.049	2.533	7.391	2.039	2.155	2.277	2.404	2.26

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Electricity	1580.4	1795.6	2047.3	2369.6	2722.9	2790.1	2982.8	3331.9	3833.7	3892.8
Coal	819.77	919.61	1032.64	1187.64	1305.49	1353.52	1439.67	1545.43	1755.79	1785.31
Crude oil	0.94	0.18	0.213	0.229	0.159	0.089	0.044	0.037	0.113	0.109
Fuel oil	10.567	14.292	11.061	9.28	5.656	3.475	1.93	1.239	0.609	0.431
Diesel oil	2.713	3.3492	3.667	3.127	2.314	1.851	1.518	1.139	0.392	0.356

The units of electricity and fossil energies are billion kW h and million tons, respectively.

Table 2
Fossil fuel conversion factors.

Fossil energy	Coal	Crude oil	Fuel oil	Diesel oil
Conversion factor	0.7143	1.4286	1.4286	1.4571

The unit is kg SCE per kg fossil energy.

To evaluate the impact of the market-oriented reforms of 2003 on improvements in generation efficiency, the time series data from 1993 to 2002 and 2003–2012 were used to estimate the parameters of Eq. (1), respectively. As the samples used to estimate the fitting equations are limited, it is difficult to ascertain the specific trend and the most suitable fitting equation of the generation efficiency, we then considered scenarios of 1, 2, and 3 independent variables. The estimated equations are as follows:

$$GE_t = 2.33227 + 0.03506t \tag{4a}$$

$$GE_t = 2.0039 + 0.05404t \tag{4b}$$

$$GE_t = 2.3673 + 0.01775t + 0.00156t^2 \tag{5a}$$

$$GE_t = 2.20725 + 0.02707t + 0.00086t^2 \tag{5b}$$

$$GE_t = 2.38854 + 0.01198t + 0.00105t^2 + 0.00010t^3 \tag{6a}$$

$$GE_t = 2.31979 + 0.01809t + 0.00058t^2 + 0.00002t^3 \tag{6b}$$

Eqs. (4a), (5a) and (6a) were obtained by using the data from the years 1993–2002, and Eqs. (4b), (5b) and (6b) were obtained by using the data from the years 2003–2012. The parameter estimation algorithm was the above mentioned PLS. When estimating the parameters, $t = 1$ represented the year 1993.

To ascertain the appropriate number of variables, the goodness of fit of Eqs. (4a)–(6b) was considered. The coefficient of determination, denoted by R^2, is an overall measure of goodness of fit. R^2 gives the proportion of the total variation in the dependent variable

Table 4
Coefficients of determination of different fitting equations.

	Eq. (4a)	Eq. (4b)	Eq. (5a)	Eq. (5b)	Eq. (6a)	Eq. (6b)
R^2	0.8223	0.9593	0.8271	0.9544	0.8069	0.9464

that is explained by all the independent variables, and can be clearly seen in Table 4.

As shown in Table 4, the goodness of fit of equations with 1, 2, and 3 independent variables are very close. Considering the linear equation can only represent the trends with no curvature and the trend of the cubic item is very sheer, Eqs. (4a), (4b), (6a), and (6b) have larger potential errors. This paper adopted Eqs (5a) and (5b) to fit the generation efficiency curve.

The Chow test is a statistical and econometric test of whether the coefficients in two linear regressions from different data sets are equal. Given the 2-variable form of Eq. (1) was ascertained, to use the Chow test, the equation estimated by all samples and PLS algorithm was also required:

$$GE_t = 2.38004 + 0.01768t + 0.00081t^2 \tag{7}$$

4. Discussion

4.1. Evaluation of the quantitative effect

To use the Chow test to evaluate the qualitative influence of the 2003 market-oriented reforms, the fitting results of Eq. (5a) to the generation efficiencies of the years 1993–2002, Eq. (5b) to 2003–2012, and Eq. (7) of the years 1993–2012 were firstly calculated. By further calculating the sum of squared residuals of the above three equations, the F statistic of Chow test was obtained. It was 2.96, larger than 2.52, the threshold for a confidence level of 90% [32], indicating that the "natural" change trend of China's generation efficiency curve of the thermal power industry has changed since 2003.

To clearly demonstrate the above impact, curves of the recorded generation efficiency, the fitting results of Eqs. (5a) and (5b), and

Table 3
Generation efficiency of China's thermal power industry.

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
Generation efficiency	2.392	2.464	2.389	2.398	2.474	2.54	2.604	2.686	2.667	2.637

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Generation efficiency	2.608	2.631	2.697	2.735	2.884	2.863	2.886	3.009	3.053	3.05

The unit is kW h per kg SCE.

the forecasting results of Eq. (5a) by trend extrapolation are shown in Fig. 1 (unit: kW h per kg SCE).

As shown in Fig. 1, the trend of improvements in generation efficiency of the thermal power industry has decreased since the reforms. The differences between the fitting results of Eq. (5b) and the extrapolation results of Eq. (5a) can be considered to be the quantitative change in the generation efficiencies. Two factors have contributed to the above change: one is the shift of the extrapolation curve of Eq. (5a); the other is the change of the curve shape of the above extrapolation curve. By shifting up the fitting curve of Eq. (5b) until it coincides with the extrapolating curve of Eq. (5a) for the year 2003, the above two parts can be partitioned. Fig. 2 shows the partition results (unit: kW h per kg SCE).

Using the partition relationship shown in Fig. 2 and Eqs. (5a) and (5b), the quantitative influence of each factor in each year was obtained. These are listed in Table 5.

As the trend in improvement in the generation efficiency of the thermal power plants has decreased since 2003, China has to consume more fossil energy to meet it's electricity demand. Using the quantitative influence data listed in Table 5, the electricity generation data in Table 1, and generation efficiency data in Table 3, the additional fossil energy consumption for each factor in each year can be calculated, listed in Table 6.

Table 6 reveals that there has been a colossal waste of fossil energy since 2003. Summing the values of the last row, it can be concluded that China wasted up to 739 million tons of SCE during 2003–2012, with the curve shift and shape change accounting for 555.8 and 183.2 million tons of SCE, respectively. The wasted energy, as a result of the curve shift, is more than the primary energy consumption of Canada, Germany, Brazil, France, the UK (475.3, 444.4, 422.9, 339.3, and 268.4 million tons of SCE, respectively) and many other countries in 2014 [33].

4.2. Cause analysis

The above results may be surprising, but can be attributed to change in electricity policy since 2003.

The original intention of the 2003 reforms was to accelerate the improvement in the generation efficiency of China's thermal power industry by introducing market competition. To realize this goal, there were two key steps: to divest the state-owned generation assets from the "vertically integrated" power system and to implement a competitive electricity pricing mechanism. The former ensures that the thermal power plants operate as independent enterprises, accounting for their costs and profits. The latter enables market competition to optimize resource distribution and as a result, accelerate improvements in the generation efficiency. Both these steps were considered in the design of the reforms, and although as discussed previously, the former was successfully completed when most of the state-owned thermal power plants which accounted for the major part of the generation assets were divided into five power generation groups with similar competitive strengths, the later has never been fully implemented.

China designed several pilots for competitive price bidding in Shandong, Shanghai, Zhejiang and other provinces as early as 1999. Thermal power plants in these pilot regions quoted their prices for amounts of different electricity at different times to the electric dispatch department of the grid company. To meet the forecasting electricity load, the dispatch department bought electricity from the lowest to the highest price. To increase profits, these power plants tried hard to decrease their generation costs. As fuel expenditure usually accounts for over 70% of the total cost, with most other expenditures (e.g. depreciation) being fixed, increasing the generation efficiency becomes the main way in which generation costs can be reduced. Most of these pilot projects have, however, been terminated, and to date, China has never carried out competitive price bidding on a large scale for the following main reasons:

a) The balance of electricity supply and demand. Since the foundation of the People's Republic, China has generally had supply-demand equilibrium or supply shortage, except for some special periods (e.g. the Southeast Asian financial crisis in 1997 and 1998). As a socialist country, China has paid great attention to meeting electricity demand, which has been more important than the profitability of the electricity enterprises. This situation renders competitive price bidding almost meaningless.
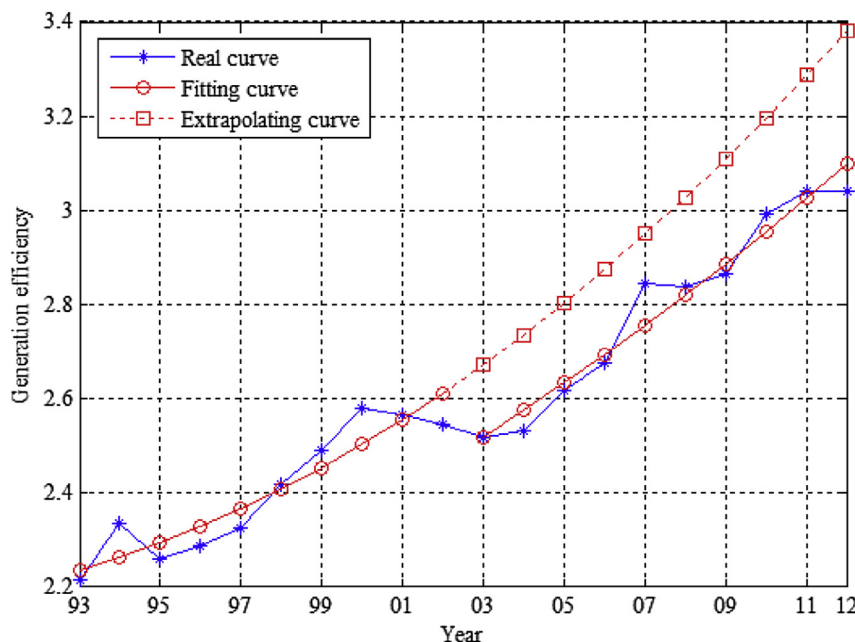

Fig. 1. Real, fitting and forecasting curves of generation efficiency.
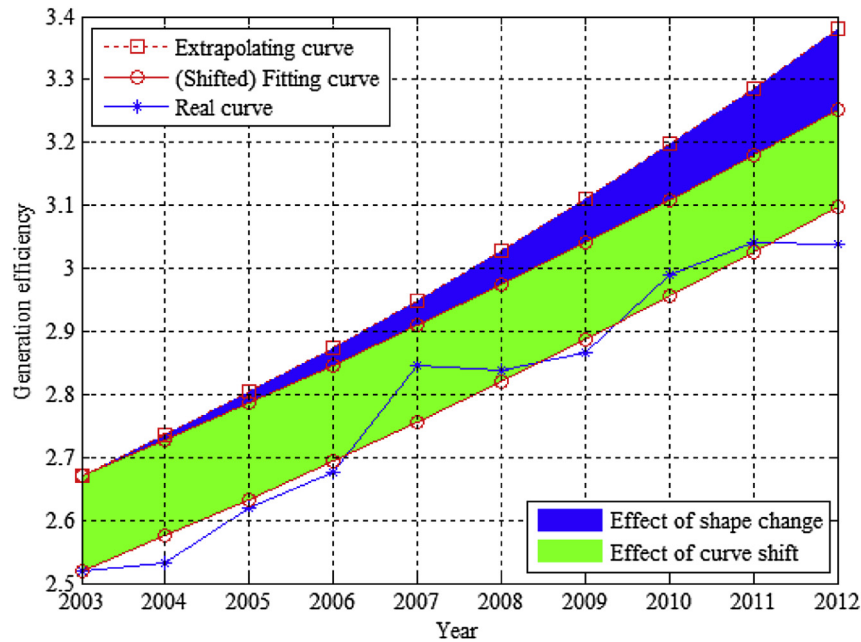
Fig. 2. Partition results for the changes in generation efficiency.

Table 5
Quantitative change in the generation efficiency of each factor in each year.

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Curve shift	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142	0.142
Shape change	0	0.007	0.015	0.024	0.035	0.048	0.061	0.077	0.093	0.111
Total	0.142	0.149	0.157	0.166	0.177	0.19	0.203	0.219	0.235	0.253

The unit is kW h per kg SCE.

Table 6
Additional fossil energy required to meet the electricity demand.

Year	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Curve shift	52.6	60.3	58.5	58.8	53.9	52	52.5	53	57	57.2
Shape change	0	2.9	6.1	10.1	13.4	17.5	22.7	28.5	37.3	44.7
Total	52.6	63.2	64.6	68.9	67.4	69.4	75.2	81.5	94.3	101.9

The unit is million tons of SCE.

b) Development barriers for new energy sources. Given the environmental impact and China's dependence on important fossil fuels, it is essential to develop new energy sources. Aside from technological factors, higher generation costs put new energy sources at a competitive disadvantage in a competitive electricity bidding market At present, China's purchase prices for hydropower, thermal power, nuclear power, wind power, and photovoltaic power are about 0.2−0.4, 0.3−0.5, 0.43, 0.49−0.61, and 0.8−1.1 yuan, respectively. Wind and photovoltaic power plants are unlikely to sell their electricity in a competitive electricity bidding market, if they are bound by the same trading rules.

c) Resistance from some local governments and power plants. Prior to the reforms, China's electric power system operated as a branch of the government, without the responsibilities of an enterprise, e.g. paying taxes. However, many power plants have become important financial resources for local governments since the reforms, especially in underdeveloped areas. Furthermore, to support local economic development, many local governments are reluctant to transmit electricity outside of their area before local demands for electricity are fully met. As a result, many local governments prefer to generate more electricity in the local power plants, to meet local demand and reap the associated profits. In addition, many old thermal power plants also resist competitive price bidding because of their higher generation costs. Such factors will obviously hinder the building of a uniform electricity market.

Before the reforms, the grid company electricity dispatch departments were free to arrange the generation schedule based on their experience of a feasible generation schedule, and thermal power plants didn't care about how much electricity they generated. Although the efficiency of this mode is lower than a competitive bidding model, it was reasonably successful. After the reform, as state-owned monopolies with the characteristics of public utilities, China's grid companies did not pay close attention to their profits. Their dispatch decisions were easily influenced by both power plants and local governments, with older plants usually having a close relationship to the local government and the grid company and able to acquire profitable generation schedules. In

other words, the decisions of the electric dispatch departments before the reforms were based on experience and after the reforms were based on experience and negative interference. Since the reforms in 2003, as the dispatch departments didn't know how to deal with the complex situation, they usually arranged the same number of operating hours for all thermal power plants, regardless of efficiency or cost [8], with the downward shift of the extrapolation curve in Fig. 1 as a consequence.

Moving on to consider the change of the fitting curve shape shown in Fig. 1, this can be explained by innovations in heating systems for buildings in northern China. According to statistics, about 7.5 billion square meters are heated in winter in northern China, with an energy consumption equivalent to 143 million tons of SCE per year [34]. Most households traditionally used a distributed heating system supported by small boilers. Due to the low efficiency of this heating system, China published "Rules Relating to the Development of Heat and Power Cogeneration" on Aug. 20, 2000, from which time China began to upgrade its heating system to centralized systems supported by heat and power cogenerating systems. From 2003 to 2012, China's centralized heating area has increased from 1.89 to 6.09 billion square meters [35]. If the overall efficiency is considered, the cogenerating system is very efficient, but if the electricity generation efficiency alone is considered; cogenerating systems have a lower efficiency than ordinary thermal power plants. With the rapid development of the heat and power cogenerating systems, the speed of improvements in the generation efficiency of China's thermal power industry has decreased accordingly. That said, given the improvements in overall efficiency, this reform should obviously be encouraged.

4.3. Design of a competitive electricity bidding mechanism

The above analysis suggests that the key to improve the generation efficiency of China's thermal power industry is the implementation of a competitive electricity bidding mechanism, according to the following principles.

a) Electricity price bidding should be promoted by sub-region and designed according to unified trading rules designed by the central government. To implement electricity price bidding, a certain degree of excess generation capacity is essential. Based on experience, only when the annual average utilization hours of generation capacity is less than 4500 h, can excess generation capacity be identified. Although China has built a great many new power units in recent years, this indicator for thermal power generation equipment of the country in 2014 was still 4706 h [36]. That is, excess generation capacity doesn't generally exist. However, the balance of supply and demand for different areas varies widely; many provinces have already less than 4500 h power plant utilization. For example, the annual average utilization hours of thermal power generation plant in Jilin, Heilongjiang and Liaoning provinces, which are located in north-east China, were 3680, 4121 and 4388 h, respectively in 2014 [36], making them suitable for early implementation of this policy. In other areas, electricity bidding could also be implemented when they achieve generation capacity surpluses in the future. To overcome the influence of local governments and build a uniform electricity market in the future, the above sub-regional electricity price bidding system should be designed according to the unified trading rules set by the central government.

b) Over-the-counter transactions should be permitted. In China, the industrial sector is the single largest electricity consumer. Since the 2003 market-oriented reforms, it accounted for nearly 73.51% of the total electricity consumption [30]. In many areas, a few industrial enterprises consume a large portion of the electricity. Considering scale of consumption, the generation efficiency of this part of the electricity system has a great influence on the country's total. As a result, big users should be permitted to acquire electricity supply by over-the-counter transactions, especially in the absence of a wider electricity market. In this mode, electricity users can negotiate with the power plants directly, and the grid enterprise collect the toll for electricity transmission. Considering the volume of these transactions may be very big, their contracts must be recorded by the manager of the electricity market. The "Further strengthening the institutional reform of electric power industry" document, published by the Central Committee of the Chinese Communist Party and the State Council on Mar. 15, 2015 has indicated that China will encourage transactions between multiple participants [2], offering a policy framework for over-the-counter transactions.

c) Dynamic incentive mechanisms for renewable energy developments should be established. At present, China is the single largest fossil energy consumer and CO_2 emitter in the world, and faces increases pressures from energy security and environment deterioration. To address these problems and because of the higher generation costs of wind and photovoltaic power, China is currently implementing a price support policy. Specifically, China is divided into several areas, with each area setting a purchase price. Wind and photovoltaic energy power plants sell their electricity to the grid at the set price for their area. This non-market management system causes many problems, e.g. disordered development and lack of incentive to decrease the generation cost. To optimize resource allocation and drive the sound development of renewable energy, China should also introduce market competition in this area. The tradable green certificates (TGC), initially implemented in Sweden, have been implemented in northern Europe for over a decade [37]. The main merit of TGC is to promote the development of renewable electricity by market mechanism, especially when the generation cost of renewable electricity is higher than that of thermal power. Similar to TGC, China may build its market-driven new energy promoting system to replace its present fiscal subsidies system.

5. Conclusion and policy implications

To solve the problem of the low generation efficiency of the thermal power industry, China implemented market-oriented reforms in 2003. This paper uses the polynomial functions, PLS algorithm, and generation efficiency data from 1993 to 2012 to evaluate the effect of these reforms.

Empirical results show that the trends in improvements in the generation efficiency of China's thermal power industry have decreased since the reforms. More specifically, along with a shape change in the efficiency curve, a suddenly down shift of 0.142 kW h per kg SCE also occurred in 2003. Further analysis shows that the former is a consequence of innovations in heating system for buildings in northern China. This should be encouraged, although it may lower the general electricity generation efficiency of the industry as a whole. The latter is mainly because of the non-implementation of electricity price bidding which caused inefficient dispatch decisions.

Considering the enormous amount of thermal power generation, the failure to implement electricity price bidding has caused huge wastage of fossil energy (555.8 million tons of SCE during 2003—2012). Introducing market competition into China's thermal power industry should be a priority for the government. Specifically, China should consider the following suggestions: a) Electricity bidding should be promoted by sub-region according to the

supply-demand situation, initially in sub-regions with excess generation capacity. Furthermore, the unified specific rules of the electricity bidding should be designed by the central government. This will facilitate the development of a national electricity price bidding system. b) Considering that several big users usually account for a large share of electricity consumption in many areas, over-the-counter transactions should be permitted. In this mode, electricity users will negotiate with the power plants directly, and the grid enterprise will collect the toll for electricity transmission. c) To mitigate the pressures of energy supply and environment deterioration, China should build dynamic incentive mechanisms for renewable energy development to replace its present fiscal subsidies system.

Acknowledgements

References

[1] Zhao X, Ma C. Deregulation, vertical unbundling and the performance of China's large coal-fired power plants. Energy Econ 2013;40:474—83.
[2] Central Committee of the Chinese Communist Party, State Council. Further strengthening the institutional reform of electric power industry (in Chinese). Available at: <http://www.ne21.com/news/show-64828.html> [accessed 15.12.15].
[3] Shahbaz M, Lean HH. The dynamics of electricity consumption and economic growth: a revisit study of their causality in Pakistan. Energy 2012;39:146—53.
[4] Hamdi H, Sbia R, Shahbaz M. The nexus between electricity consumption and economic growth in Bahrain. Econ Model 2014;38:227—37.
[5] Wolde-Rufael Y. Electricity consumption and economic growth in transition countries: a revisit using bootstrap panel Granger causality analysis. Energy Econ 2014;44:325—30.
[6] Du L, Mao J, Shi J. Assessing the impact of regulatory reforms on China's electricity generation industry. Energy Policy 2009;37:712—20.
[7] Bacon R, Besant-Jones J. Global electric power reform: privatization and liberalization of the electric power industry in developing countries. Annu Rev Energy Environ 2001;26:331—59.
[8] Kahrl F, Williams JH, Hu J. The political economy of electricity dispatch reform in China. Energy Policy 2013;53:361—9.
[9] Proceedings of the CSEE. Electric power installed capacity and output. Proc CSEE 1990;5:72.
[10] Ngan HW. Electricity regulation and electricity market reforms in China. Energy Policy 2010;38:2142—8.
[11] Wang Q, Chen X. China's electricity market-oriented reform: from an absolute to a relative monopoly. Energy Policy 2012;51:143—8.
[12] Zhou X. China electric power Yearbook 1995. Beijing: China Electric Power Press; 1996.
[13] Du L, He Y, Yan J. The effects of electricity reforms on productivity and efficiency of China's fossil-fired power plants: an empirical analysis. Energy Econ 2013;40:804—12.
[14] National Bureau of Statistics of China. China statistical Yearbook (1995—2014).

[15] Beijing: China statistics press; 2015.
[16] Zhu T, Ertekin E. Phonon transport on two-dimensional graphene/boron nitride superlattices. Phys Rev B 2014;90:195209.
[16] Huber M, Weissbart C. On the optimal mix of wind and solar generation in the future Chinese power system. Energy 2015;90:235—43.
[17] Würfel P, Würfel U. Physics of solar cells: from basic principles to advanced concepts. 3rd ed. Berlin: Wiley; 2016.
[18] Energy Research Observer. Coal efficiencies of the thermal power industries of main countries. 1970—2006. Available at: http://www.chinaero.com.cn/nysj/nyytj/06/32250.shtml (accessed 20.12.15).
[19] Mou D. Understanding China's electricity market reform from the perspective of the coal-fired power disparity. Energy Policy 2014;74:224—34.
[20] Zhu T, Ertekin E. Generalized Debye-Peierls/Allen-Feldman model for the lattice thermal conductivity of low-dimensional and disordered materials. Phys Rev B 2016;93:155414.
[21] Motie S, Keynia F, Ranjbar MR, Maleki A. Generation expansion planning by considering energy-efficiency programs in a competitive environment. J Electr Power Syst 2016;80:109—18.
[22] Choi HI, Moon HP. Weierstrass-type approximation theorems with Pythagorean hodograph curves. Comput Aided Geom Des 2008;25:305—19.
[23] Jadhav NH, Kashid DN, Kulkarni SR. Subset selection in multiple linear regression in the presence of outlier and multicollinearity. Stat Methodol 2014;19:44—59.
[24] Demirhan H. The problem of multicollinearity in horizontal solar radiation estimation models and a new model for Turkey. Energy Convers Manag 2014;84:334—45.
[25] Bry X, Trottier C, Verron T, Mortier F. Supervised component generalized linear regression using a PLS-extension of the Fisher scoring algorithm. J Multivar Anal 2013;119:47—60.
[26] Huang L, Chen Y, Liu G, Li S, Liu Y, Gao X. Non-isothermal pyrolysis characteristics of giant reed (Arundo donax L.) using thermogravimetric analysis. Energy 2015;87:31—40.
[27] Wang H, Wu Z, Meng J. Partial least squares regression—linear and nonlinear methods (in Chinese). Beijing: National Defense Industry Press; 2006.
[28] Meng M, Niu D. Annual electricity consumption analysis and forecasting of China based on few observations methods. Energy Convers Manag 2011;52: 953—7.
[29] Chow GC. Tests of equality between sets of coefficients in two linear regressions. Econometrica 1960;28:591—605.
[30] National Bureau of Statistics of China. China energy statistical yearbook (1994—2013). Beijing: China Statistics Press; 2014.
[31] General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration of the People's Republic of China. General principles for calculation of total production energy consumption. Beijing: China Standard Press; 2008.
[32] Critical values (percentiles) for the F distribution. Available at: <http://faculty.washington.edu/heagerty/Books/Biostatistics/TABLES/F-Tables/> [accessed 01.07.16].
[33] BP. Statistical review of world energy. 2015. Available at: http://www.bp.com/statisticalreview (accessed 15.01.16).
[34] Liu L, Fu L, Jiang Y, Guo S. Major issues and solutions in the heat-metering reform in China. Renew Sustain Energy Rev 2011;15:673—80.
[35] Ministry of Housing and Urban-Rural Development of the People's Republic of China. Statistical bulletin of urban-rural construction (in Chinese). 2013. Available at:, http://www.mohurd.gov.cn/zcfg/jsbwj_0/jsbwjcw/201408/t20140805_218642.html (accessed 20.01.16).
[36] National Energy Administration. Annual average utilization hours of installed capacity (in Chinese). 2014. Available at:, http://www.chinapower.com.cn/newsarticle/1228/new1228304.asp (accessed 20.01.16).
[37] Boomsma TK, Linnerud K. Market and policy risk under different renewable electricity support schemes. Energy 2015;89:435—48.