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ECONOMIC DISPATCH IN THE ELECTRICITY SECTOR IN CHINA: POTENTIAL BENEFITS AND CHALLENGES AHEAD

Hao Chen   Chi Kong Chyong   Jia-Ning Kang   Yi-Ming Wei

20 June 2018

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JEL Classifications: P28; Q48; L94; L51; L52

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Economic dispatch in the electricity sector in China: potential benefits and challenges ahead

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Unlike the economic dispatch used in most power systems, electricity system dispatch currently used in China is an equal share approach. This form of dispatch has been criticized for its negative influence on system operations, worsening energy security, environmental sustainability and affordability problems. To contribute to on-going electricity market reform discussions, our study employs an optimization model to quantify the economic dispatch savings in the coal-fired power sector. We offer three major findings. First, the heat rates of coal generators in China in 2014 ranged from 273.91 gce/kWh to 348.38 gce/kWh units and as a result of these large differences among generators in different regions, implementing economic (merit order) dispatch will bring economic and environmental benefits. Second, we identify three major political and economic challenges, which hinder the transition from the current dispatch model, namely (i) current running hours are insufficient for cost recovery, (ii) limited cross-border trading due to electricity over-supply and local protectionism, and (iii) political economy problems from generators of different ownership types. Finally, 5.67% of coal used in power generation could be saved if economic dispatch was employed at the provincial level, the value of which equals 0.05% of Chinese GDP in 2014.

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1 Introduction

Half of the world's coal was consumed by China in 2015, of which 47.3% in the power generation sector (BP, 2016; NBS, 2016). However, the Chinese coal reserve-production ratio is only 31 years in 2015, which is much smaller than that of United States (292 years), Japan (296 years) and world average (114 years). Thus, the previous popular description of Chinese energy resource endowments as 'rich in coal' faces big challenges nowadays. Moreover, the coal-dominated power generation mix is also the major source of carbon emissions and air pollutants. 43% of the national carbon emissions came from the power sector in 2014, while the proportion of SO_2, NO_x and PM was 31.4%, 29.8% and 5.6% respectively (Hu and Nan, 2016). Despite coal being a cheap source of power generation industrial electricity prices are higher in China when compared with its competitor countries like United States (Pollitt et al., 2017).[1] Therefore, conserving the energy in the power sector might be a good policy choice to address challenges of energy security, environmental sustainability and affordability (Chang et al., 2017; Chen et al., 2017; Chen et al., 2016; Meng et al., 2017; Wei et al., 2008; Yu et al., 2016).

The amount of coal consumed in the power generation is not only influenced by the advancement in technology, but also affected by the institutional rules governing the sector. Most countries in the world dispatch generators based on their merit order, which is also called economic dispatch. Under this dispatch rule, the lower-cost generation units have the priority to be dispatched first if the grid security is not affected (Bistline, 2015; Gao and Yang, 2010; Lynch et al., 2013; Steinberg and Smith, 1943). However, coal-fired generation units in China are dispatched in a unique way called 'equal share', and all the generators of similar type will have approximately the same allotment of running hours in a year (Kahrl et al., 2013). This will waste energy because the higher efficiency units have the same running hours with the lower ones. Moreover, this dispatch rule is a black box and it is not clear how the exact operation time is allocated. This dispatch rule originated from a period when China suffered serious electricity shortages. To solve this problem, the government promised to provide enough operation time for the generators to recover their investment cost (Kahrl et al., 2011), and fair opportunities were valued most in the allocation during that time. Luckily, this strategy worked, and many new generation units were encouraged to be built in a short time. The equal share strategy has been retained so far due to multiple political and economic reasons (Gao and Yang, 2010; Kahrl et al., 2013; Ma and Zhao, 2015; Robinson and Li, 2017), however, this dispatch mode is often criticized for its low efficiency and cause for more environmental pollution (Pollitt et al., 2017).

There are several other motivations for the Chinese government to push forward economic dispatch in the power sector now. Document No.9, issued by the Chinese

[1] The annual average industrial electricity price in China is about 50% higher than that in the US in 2014 (Pollitt et al., 2017).

State Council in March 2015, signaled a new round of electricity market reform. One of the important tasks of this on-going reform is to change the electricity dispatch rule to a more market-based one (Hu and Cheng, 2017). Moreover, China is now experiencing a serious over-supply problems in the coal-fired power capacity (CarbonTracker, 2016; Kahrl, 2016; Lin et al., 2016), which is partly due to the false signals sent to the investors by the current equal share dispatch. In addition, the lifetimes of coal generators in China are generally about 40 years, and there are great efficiency differences among these generators built in different periods (Chen et al., 2016; Ma and Zhao, 2015). To provide references for the possible benefits from this on-going electricity market reform, this study estimates the economic dispatch savings in the Chinese coal-fired power sector, which is aimed at answering the following three questions:

(1) Are heat rate differences among the coal generators in China big enough to demonstrate the necessity for economic dispatch?
(2) What are the political and economic challenges in China to move away from the current dispatch rule to economic dispatch?
(3) How much energy can be saved if the economic dispatch is implemented in China?

The remainder of this paper is organized as follows：Section 2 presents the literature review. Section 3 describes the methodology and data. Section 4 provides the empirical results, and Section 5 summarizes the conclusions and proposes some policy implications.

2 Literature Review

Power system operation is a complex engineering issue and involves sophisticated optimization algorithms. Many previous studies have analyzed the impacts of operational strategies on the power system (Bhattacharyya, 2007; Kirschen and Strbac, 2004; Moarefdoost et al., 2016; Oggioni et al., 2014; Wang and Shahidehpour, 1993; Wood and Wollenberg, 2012; Zimmerman et al., 2011), but the current studies mainly focus on the following three topics.

The first category analyzes how to model the power system operation when more renewables are integrated into the system. This is a big challenge for the traditional power system operation because the electricity generated from renewables depends on the weather conditions, which are both variable and uncertain. Thus, more sophisticated methods should be employed to model this new power system. Garcia-Gonzalez et al. (2008) investigated the benefits of pumped-storage units to balance the intermittency of wind power in Spain, and concluded that the total income can be increased by 2.53%. Tuohy et al. (2009) employed both deterministic models and stochastic models to analyze the operation costs in the high wind share scenario of Ireland, and found the total cost of stochastic models are 0.25% to 0.9% lesser than that of the deterministic ones. Qadrdan et al. (2014) estimated the impacts of wind power generation on the power system operation in Great Britain, and found that about 1% of the total operational cost can be reduced in stochastic models when compared with that of the deterministic models. Chattopadhyay (2014) evaluated the integration of renewable generation in India, and concluded that it will increase the power operation cost by 5.3%. Reddy and Bijwe (2015) proposed a new real-time dispatch model with consideration of the renewable electricity generation and estimated that it could reduce 3% to 5.4% of the total cost in the traditional dispatch models.

The second category focuses on environmental economic dispatch, which integrates the environmental cost of different generation technologies into the power system operation. This is particularly important due to the serious air pollution and climate change issues facing by many countries today. Zhao et al. (2013) implemented the environmental economic dispatch in Liaoning's power sector for the year of 2010, and estimated that the air pollutants and carbon emissions can be reduced by 2.09% to 9.42%. Khan et al. (2015) optimized the power system operation in Pakistan with consideration of both fuel cost and carbon emissions cost and found that the highest daily share of solar generation could range from 25.73% to 27.13%.

The third category estimates the energy saving or cost reduction potentials from economic dispatch, and these researches pay more attention to countries where economic dispatch has not been implemented yet. Gao and Yang (2010) investigated the economic dispatch potential among 54 coal generators in Jiangsu province in China, and found that 6.38% of the coal can be conserved from economic dispatch in 2008. Kahrl et al. (2013) estimated the energy saving potential from energy efficient dispatch in Guangxi province in China,[2] and found that 2-4% of the coal could be saved from the coal generators. Zhong et al. (2015) explored the energy efficient dispatch in Guangdong's power sector in 2012, which also considered the impacts of different loads on the generators' coal consumption. They found that 4% of the coal can be reduced from energy efficient dispatch. Nikolakakis et al. (2017) evaluated the cost reduction potentials of economic dispatch in Bangladesh power sector, and found that the operational cost can be reduced by a very large share (76%).

These existing studies have provided good references for this research, based on which we could estimate the economic dispatch saving potentials in Chinese coal-fired power sector. We contribute to the existing literature from two aspects. First, most previous studies take only one province in China as a case study for economic dispatch. While we apply economic dispatch rule to all the coal generators in China, which is of great significance for the on-going electricity market reform in the whole country. Secondly, we have quantified and compared the energy saving potential if economic dispatch is implemented in different geographical scopes and identified the political and economic challenges in implementing economic dispatch rule in China. Therefore, relevant compensation and transition mechanisms could be better established to achieve these benefits.

[2] The energy efficient dispatch here equals to the economic dispatch, this is because the coal prices within one province are the same in China.

3 Methodology and data

3.1 Research Framework

The research framework of this study is shown in Fig. 1. We firstly calculate the heat rate (HR) of each coal generator in China, and compare their distributions in different geographical levels, thus proving the necessity for implementing economic dispatch rule. Then, we analyze the political and economic challenges in China to move away from the present dispatch mode to economic dispatch. Lastly, we estimate the energy saving potentials when economic dispatch is implemented in a provincial, regional and national level respectively. Based on these analysis, some important conclusions are summarized, and policy implications are proposed for the on-going electricity market reform in China.

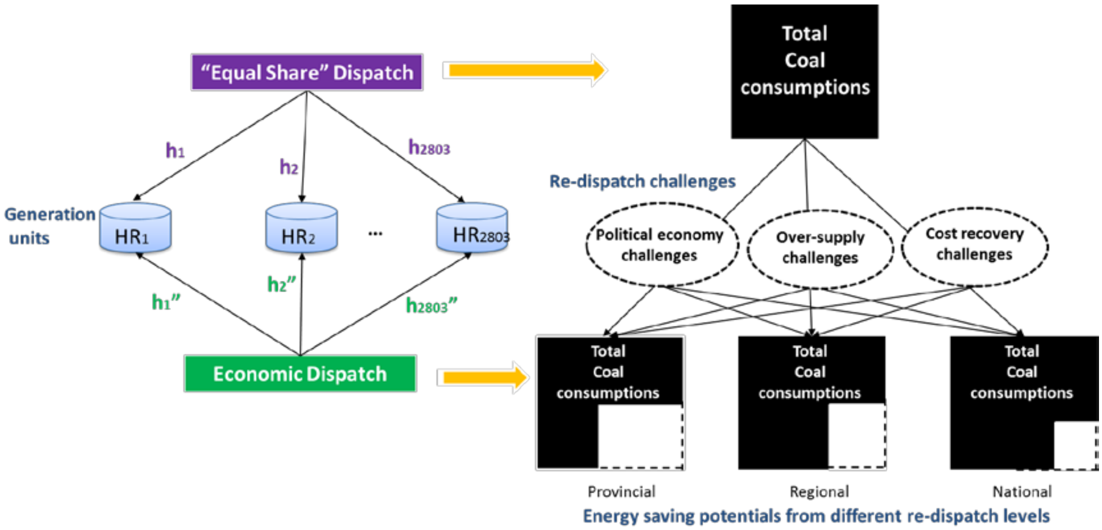


Fig. 1. Research framework

3.2 Data

This study analyzes the economic dispatch savings from all the coal generators in 2014 (2803 generation units with total generation capacity of 832 GW), which are in 30 provinces and six regional grid areas in China (Table 1). The economic dispatch savings are mainly influenced by the heat rate differences and total coal-fired power generation. However, the heat rates of coal generators are not publicly available, and the amount of coal generation is mixed in the thermal generation (coal and gas), so we have devised a methodology to calculate these indicators. The details of how we calculate them are provided in the appendix.

Table 1 Six regional power grids in China

Regional grid	Provinces
North China	Beijing (BJ), Tianjin (TJ), Hebei (HB), Shandong (SD), Shanxi (SX), West Inner Mongolia (IMG-W)
Northeast China	Liaoning (LN), Jilin (JL), Heilongjiang (HLJ), East Inner Mongolia (IMG-E)
Northwest China	Gansu(GS), Qinghai(QH), Ningxia(NX), Shaanxi(SHX), Xinjiang (XJ)
East China	Zhejiang(ZJ),Shanghai(SH),Jiangsu(JS), Fujian (FJ),Anhui (AH)
Central China	Hubei (HUB), Hunan (HUN), Jiangxi (JX), Chongqing (CQ), Henan (HEN), Sichuan (SC)
South China	Guangdong (GD), Guangxi (GX), Yunnan (YN), Guizhou (GZ), Hainan (HAN)

Notes: Hong Kong, Taiwan, Macao and Tibet are not included in the six regions due to data unavailability. The East Inner Mongolia grid includes Hulunbeier, Xing'an, Tongliao and Chifeng, while the West Inner Mongolia grid contains the rest of Inner Mongolia except for East Inner Mongolia.

3.3 Economic dispatch optimization model for the coal-fired power sector

To analyze the economic dispatch conservation potentials in the Chinese coal-fired power sector, an optimization model (eq. 1) which minimizes the total operational cost is established as below.

$$min \sum_i p_i \times \alpha_i \times c_i \times h_i \tag{1}$$

$$\sum_{i \in K} c_i \times h_i \times (1-\lambda_i) = e_K \tag{2}$$

$$h_i \leq H \times \phi_i \tag{3}$$

$$h_i \geq 0 \tag{4}$$

where p_i is the coal price paid by unit i， which is the annual average coal price in the province where unit i locates;[3] α_i is the heat rate of unit i， which is calculated in section 3.2； c_i is the installed capacity of unit i; h_i is the annual running hours of unit i, which is the decision variable in this model； λ_i is the share of self-used electricity in unit i,which is drawn from NBS (2015a); e_K is the actual (2014) total

[3] This data is drawn from Inner Mongolia Coal Exchange Center: http://www.imcec.cn/.

electricity generated by coal-fired power plants in area K; H is the total number of hours in one year; ϕ_i is the annual maximum availability coefficient of unit i, which is drawn from NBS (2015a).

The constraint (2) ensures that the total electricity generation under the new economic dispatch rule in area K is the same as under equal share dispatch; The constraint (3) limits the running hours of unit i within its maximum available hours.

4 Result analysis and discussion

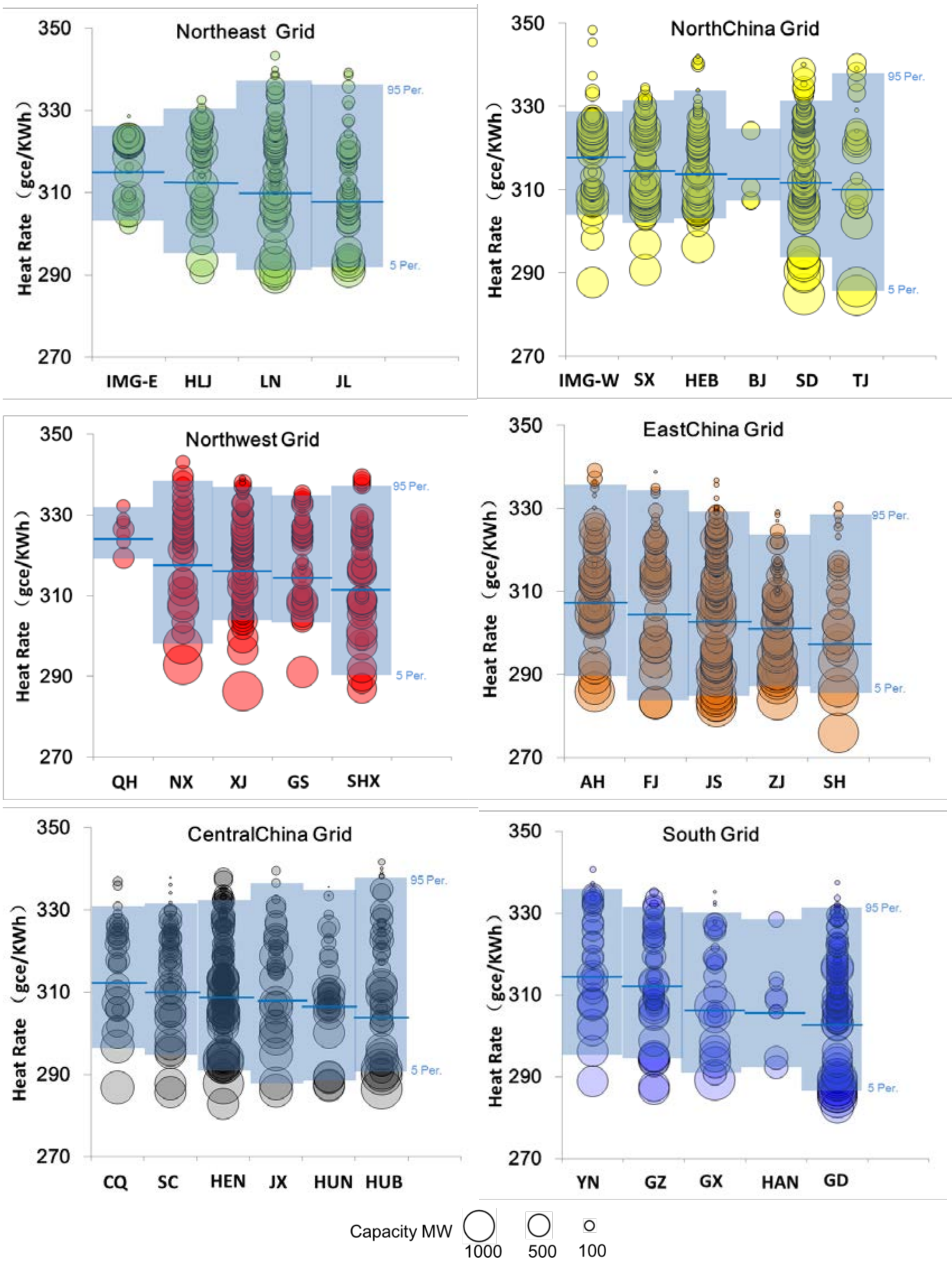
4.1 Heat rate differences exhibits the necessity for reforms of 'equal share' dispatch

The calculated generation heat rates of the 2803 units in 2014 are shown in Fig. 2. As seen from this figure, the heat rates of Chinese coal generators range from 273.91 gce/kWh (Waigaoqiao-3 No 2 unit in Shanghai) to 348.38 gce/kWh (Xilinhot-2 No 1 unit in Inner Mongolia). Sun et al. (2015) states that the minimum generation heat rate of Chinese coal-fired power plant is about 276.02 gce/kWh, while CEC (2012) mentions the maximum one is about 344.65 gce/kWh in 2012. Therefore, this proves that our estimation result is reliable to some extent. The capacity-weighted average heat rate of all the generators is 309.11gce/kWh, which is much higher than that of the Japanese average value (292 gce/kWh) (IEA, 2015; NBS, 2015b). Moreover, the generation unit with a larger size tends to have a lower heat rate, which can be evidenced from the fact that bigger bubbles are usually located in the lower places.

The greater the differences in generation heat rates within a balancing zone the more important it is to implement economic dispatch rule. If all else are kept equal, the bigger the distribution differences are, the larger share of coal can be saved from the economic dispatch. As shown in Fig. 2, at the national level, the gap between the maximum and the minimum heat rate is 74.47 gce/kWh, which is about 24% of the capacity-weighted average heat rate in China. At the regional level, the weighted average heat rate of units in Northwest grid is the highest (317.06 gce/kWh), while the weighted average heat rate of units in East China grid is the lowest (302.22 gce/kWh). This is because the economically developed regions can afford more advanced generation equipment. In addition, they have retired or retrofitted most of the older or lower efficiency units during the previous reform process. At the provincial level, Qinghai has the highest capacity-weighted average heat rate (324.93 gce/kWh), but the shortest band length with a confidence level of 95% (12.89 gce/kWh).[4] Although Shanghai has the lowest average heat rate (296.57 gce/kWh), it also has the longest band length with a

[4] The reason why we use the 95% confidence band is that we want to analyze the distribution scope of the most generation units, and eliminate the influences of some 'outliers'.

confidence level of 95% (52.54 gce/kWh). Consequently, there are distinct differences among the heat rates of generation units in different geographical levels, which indicates the necessity for economic dispatch.



Notes: The bubble size denotes the capacity of the generation unit. The light blue band denotes the 95% confidence interval, and the dark blue line denotes the capacity-weighted average heat rate of the corresponding province.

Fig.2. Heat rates of Chinese coal-fired generation units in 2014

Another way to prove the necessity for reforming the present 'equal share' is to check whether the current dispatch mode is efficient in the running time allocation. To verify this hypothesis, we have analyzed the correlation coefficients between the efficiency and the allocated running hours for some sample provinces. The actual annual running time data we got are those power plants over 1GW,[5] and their efficiency is calculated based on the heat rates.[6] The estimated correlation coefficients for the sampled provinces are shown in Fig. 3.

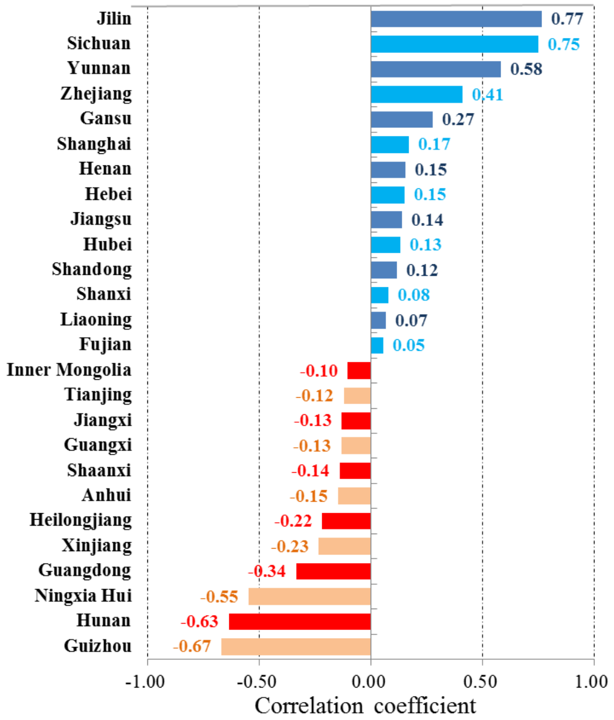


Fig.3 Relationship between efficiency and annual running hours

As seen from Fig. 3, 12 of the sampled provinces do have negative correlations between the generation efficiencies and the allocated operation hours. The correlation coefficients range from -0.67（Guizhou）to -0.10 (Inner Mongolia). Moreover, these provinces do not only have the economically underdeveloped provinces, but also have some economically developed provinces like Guangdong and Tianjing. Therefore, this fact further demonstrates the significance to implement economic dispatch rule for the coal-fired power generation units.

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5 There are 320 power plants and 1005 generators in this sampled data set, which accounts for 56.7% of the total national installed capacity of coal generators.

6 The generation efficiency is the result of electricity output divided by the thermal energy input. The theoretical heat value of the electricity output is drawn from Sun et al. (2015). In addition, the share of national average self-use electricity in a power plant is set as 5.84% according to NBS (2015a).

4.2 Political and economic challenges of electricity dispatch reform

Potential implementation of economic dispatch rule in the Chinese power sector has been under debate for a long time, and there are even some provinces who pilot in implementing energy efficient dispatch from 2007. However, the original ‘equal share’ dispatch mode is still active for most places in China. There may be some political and economic challenges to move away from the current dispatch to economic dispatch, which we elaborate below.

The first major challenge is the current insufficient running hours for most generation units to recover their huge sunk investment cost, thus influencing the implementation of economic dispatch at a national level. Investing into the coal-fired power plants is a capital intensive business, once the construction is finished, the generation units need certain amount of running hours to recover their cost (Gao and Yang, 2010; Ma and He, 2008). The break-even running time of the coal-fired power plants in China is about 5500 hours per year,[7] which is above the average running time in 2014 of all the generators (see Fig. 4).

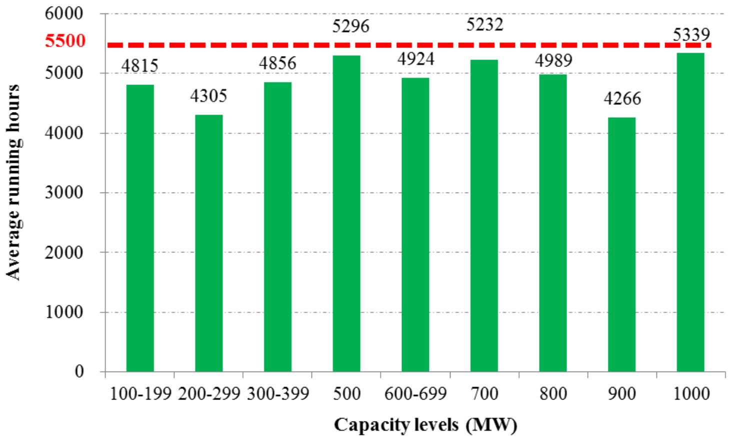

Fig. 4. Average annual running hours of coal-fired power generation units in 2014
Notes: data are drawn from NBS (2015a)

Therefore, there is a great tendency of protest for the dispatch reform since many generators already have difficulties in recovering their investment cost. No generation unit would like to reduce their running time without any corresponding compensation mechanism established for them. Moreover, this situation is faced by almost all the generation units in China, so a dispatch reform that affects the benefits of most players will in general have difficulty in its implementation.

The second major challenge is the over-supply of provincial coal-fired power will hinder cross-border trade among different provinces, thus affecting the implementation of economic dispatch at a regional level. Fig. 5 has been drawn to illustrate the current supply surplus problem in the Chinese coal-fired power sector.

[7] This data source is from http://www.thepaper.cn/newsDetail_forward_1682429.

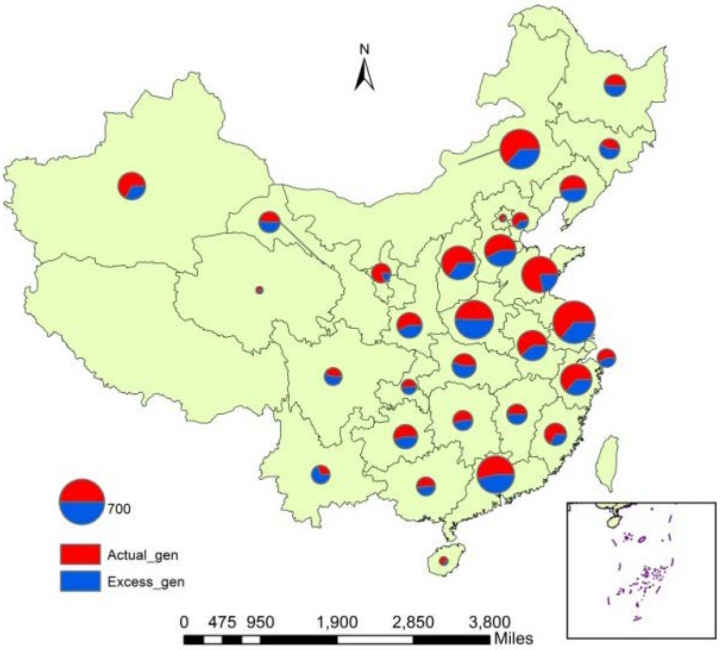

Fig.5. Actual and surplus power generation in 2014 (TWh)

Notes: The excess generation is calculated as a result of theoretical generation minus the actual generation in 2014; the theoretical generation is the result of installed capacity multiplied by the maximum available running hours.

We can see from the Fig.5 that all the 30 provinces have different extents of coal-fired power over-supply, and the average surplus ratio is 41%. Yunnan has the highest surplus ratio (69%), while Beijing has the lowest surplus ratio (16%). Moreover, the income from power generation within one province is directly related to its fiscal income, which is not only important for its economic development, but also an important indicator for measuring the top leaders' political performance. No province wants his piece of cake to be eaten by others (Kahrl et al., 2013). In addition, the wholesale electricity prices are administratively set by the NDRC for every province, and how to allocate the generation benefits of the cross-border electricity is still an unsolved issue. This can also be proved by the current limited share of interprovincial electricity trading in China，which is 16% in 2014 and the State Grid Corporation of China (SGCC) holds a share of 13% (Kahrl et al., 2011; Zeng et al., 2016).[8] Accordingly，even though there may be some energy saving potentials from wider dispatch areas (regional or national), there are political and economic obstacles to move dispatch reform forward.

The third major challenge is the dispatch reform will induce the benefits re-allocation among generators of different ownership types, thus affecting the provincial economic dispatch. The coal generation units are owned by three types of companies in China, namely the state-owned companies, the local government or investors owned companies, and the foreign investor owned companies. Under the current regulation regime, the generation income of state owned companies will be directly in charge of

[8] The total electricity consumption is 5520 TWh in 2014, while the interprovincial electricity trading is 872.7 TWh. These data are drawn from http://www.stats.gov.cn/.

the one department of the central government (SASAC),[9] which contributes little to the local fiscal income. However, the generation incomes of the remaining two types are closely related to the fiscal income of the local government. Therefore, such companies will persuade their directly related government to fight for more allocated running time for them during the economic dispatch, because this is a win-win game for them. At last, it will increase the tensions between the central government and local government.

Fig. 6 has been drawn to illustrate this political economy challenge, the X axis shows the share of total installed capacity related to the local government within one province. The smaller the share is, the weaker their persuasive ability is. The Y axis shows the heat rate differences between the local government related generators and central government related generators, which indicates the tension intensity between them. The bubble size illustrates the amount of total installed capacity within one province.

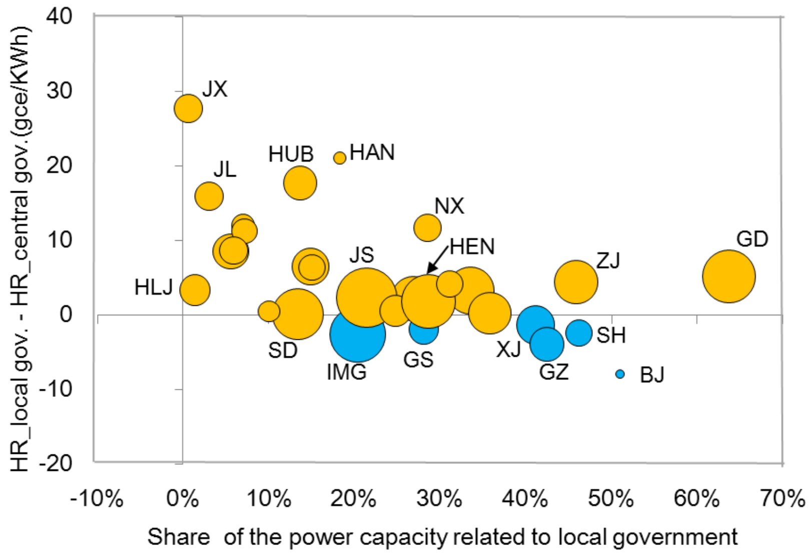

Fig. 6 The political economy between central and local government under economic dispatch

In most provinces, the heat rates of central government related generators are lower than that of the local government related ones, the five exceptions are Inner Mongolia, Shanghai, Beijing, Guizhou, Xinjiang and Gansu, which are highlighted in blue in Fig. 5. This means that the implementation of economic dispatch will reduce the fiscal income of the local government, while increase the fiscal income of the central government. Additionally, the promotion opportunities of the top leaders and the salary of the people who work in the local generation companies will be affected. Note as well that many provinces with large sizes of installed capacity have a local government involved share over 20%. For example, the share of local government related capacity in Guangdong is more than 50%, which indicates that it has enough impetus and motivations to bargain with the central government in the setting operation time quotas. Therefore, the political economy impacts resulting from economic dispatch should not be underestimated (Kahrl et al., 2013; Robinson and Li, 2017).

[9] State-owned Assets Supervision and Administration Commission of the State Council (SASAC)

4.3 Energy saving potentials from economic dispatch

Although there are many political and economic challenges, the energy saving potentials from economic dispatch will still deserve to be estimated to provide references for the dispatch reform. This section evaluates the energy saving potentials when economic dispatch is implemented in the provincial, regional and national levels respectively.

The total coal savings from economic dispatch in the provincial level is 71.78 Mtce in 2014, accounting for 5.67% of the national coal used for power generation. If we translate the coal savings to monetary value, that will equal to 0.05% of Chinese GDP in 2014. Shandong has the largest amount of coal conservation (6.82 Mtce), while Beijing has the smallest energy savings (0.07 Mtce). Since every province has different amount of coal consumption used for power generation, it is more meaningful to compare the share of saving potentials among different provinces. As seen from Fig. 7, Liaoning province has the largest share (8.85%) of coal savings from economic dispatch, while Beijing has the smallest share (2.06%) of coal conservation. Moreover, the provinces with bigger saving shares are mostly concentrated in Northeast China region and Northwest China region. This can provide references for the selection of provinces to pilot the economic dispatch reform, because the provinces with higher saving shares will show more enthusiasm for supporting the dispatch reform.

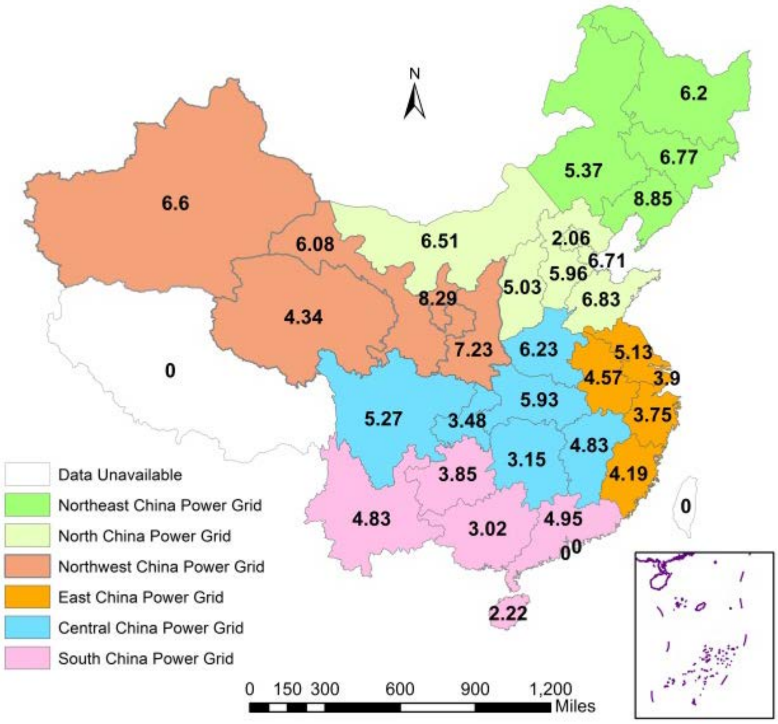

Fig. 7 Share of coal conservation from economic dispatch (%)

If the economic dispatch scope is enlarged from provincial level to regional grid level, the coal savings and their shares are shown in Fig. 8. As shown in this figure, the total coal savings from regional economic dispatch will be reduced to 45.89 Mtce. This is because the great coal price differences among different provinces will distort the energy efficient dispatch, and some less efficient generation units will be dispatched for more running time because their coal prices are much lower.[10] From the perspective of absolute coal savings, NorthChina grid region has the largest conservation potential (13.82 Mtce), while the SouthChina grid region has the smallest conservation potential (4.76 Mtce). From the perspective of the share of coal savings, Northwest grid region has the biggest share of coal savings (5.90%), while the South China region has the smallest share of coal savings (3.35%). This can also provide references for the selection of places to conduct the pilot regional economic dispatch.

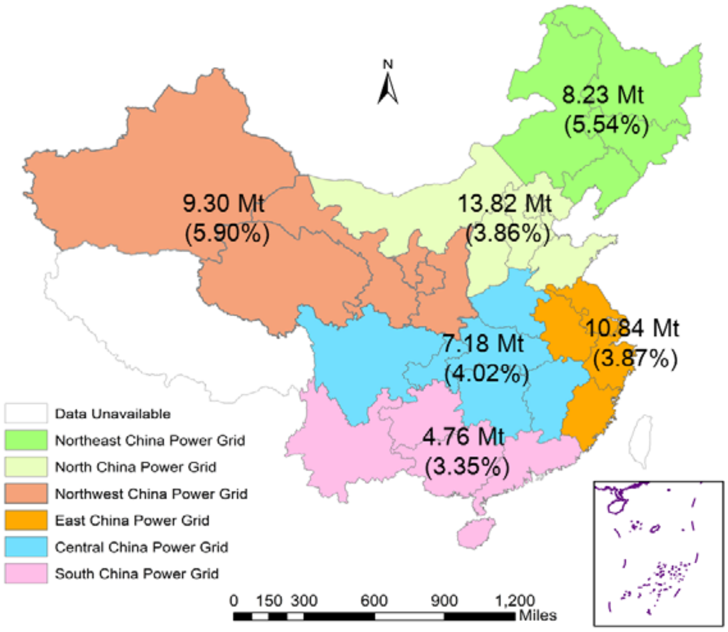

Fig.8. Energy conservation from economic dispatch in regional level

At last, if the economic dispatch is further expanded to the national level, the total coal conservation will be reduced to 43.40 Mtce. It is interesting to find out that less energy conservation potentials will be earned if the dispatch scope becomes bigger predominantly because of large locational differences in coal prices; so the coal policy and in particular support and pricing of local coal production is an important factor that affects the energy saving potentials from economic dispatch in the electricity sector.

To understand the importance of coal prices, we have also calculated the energy efficient dispatch savings in different geographical levels, which are shown in Fig. 9. Energy efficient dispatch ignores the fuel input prices (coal prices) and takes only heat rates into account. The energy efficient dispatch was implemented in five pilot provinces（Guangdong, Guizhou, Henan, Jiangsu, Sichuan）from 2007, and this rule dispatches generation units only in ascending order of their heat rates. In contrast to the economic dispatch, the amount of energy savings from energy efficient dispatch increases when the dispatch scope enlarges. Compared with the provincial efficient

[10] For example, the average annual coal price in Jiangxi is 3.30 times than that of Xinjiang. The monthly coal price in every province can be drawn from http://www.imcec.cn.

dispatch, the regional economic dispatch will get further 2.01 Mtce coal savings, among which the Northwest China grid region obtains the largest additions (0.55 Mtce). The total amount of energy savings from energy efficient dispatch in a national level is 78.27 Mtce, which equals to 6.19% of the national coal used for generation in 2014.

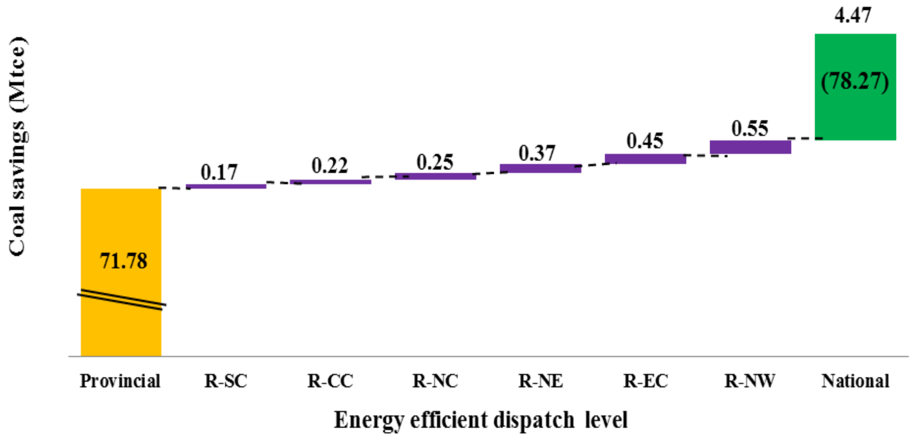

Fig. 9. Coal savings from energy-efficient dispatch

Notes：R-SC indicates the South China grid region, R-CC Central China grid region, R-NC North China grid region, R-NE Northeast China grid region, R-EC East China grid region, and R-NW Northwest China grid region

5 Conclusions and policy implications

5.1 Conclusions

The current equal share dispatch approach has been criticized for its negative influences on the security, environmental sustainability and affordability of Chinese electricity sector. Implementing economic dispatch in the electricity sector may be a good policy to address these challenges. To provide references for the cost-benefit analysis of the on-going electricity market reform, this study pioneers in quantifying the economic dispatch savings in Chinese coal-fired power sector. The heat rates of all the coal generators in China are estimated, based on which we prove the necessity for the reform of the current dispatch rules. Then, three main political and economic challenges to move away from the current dispatch mode to economic dispatch have been identified. At last, an optimization model is employed to calculate the energy saving potentials from economic dispatch in provincial, regional and national levels, and the results are also compared with that from energy efficient dispatch approach. During this process, some major conclusions are drawn as follows:

(1) The heat rates of coal generators in China range from 273.91gce/kWh to 348.38gce/kWh in 2014, and great differences exist among these generators in different geographical levels. This indicates the possibility that some energy could be saved from economic dispatch, when compared with that from the current equal share dispatch. Moreover, the fact that negative correlations between the generator efficiencies and

their allocated running time do exist in some provinces, further proves the necessity to implement economic dispatch.

(2) The transition from current dispatch mode to the economic dispatch faces several major political and economic challenges. The current insufficient running hours for cost recovery hinders implementation of economic dispatch in a national level, and no generation unit wants his piece of cake to be eaten by others without any further compensation. The over-supply status of coal-fired generation capacity in all provinces impedes implementation of economic dispatch in a regional level, since provinces are reluctant to import electricity from their neighbors via regional dispatch, which will reduce their own fiscal income and development opportunities. Furthermore, the differences in generator heat rates among different ownership types hinder the reform of existing dispatch rules in a provincial level; this is because benefits of re-allocation among different ownership types will induce the tensions between central government and local government. Consequently, further transition and compensation mechanisms should be established to facilitate the economic dispatch implementation.

(3) 5.67% of the coal used for power generation could have been saved using provincial economic dispatch in 2014, which equals to 0.05% of Chinese GDP in that year (based on cost of coal savings only). Moreover, the provinces with bigger saving shares are mostly concentrated in the Northeast and Northwest China regions. Due to the great coal price differences among provinces, the saved 71.78 Mtce coal from provincial economic dispatch will reduce to 45.89 Mtce (regional) and 43.40 Mtce (national) when the dispatch scope enlarges. However, the energy saved from energy efficient dispatch increases as the dispatch area expands, and 78.27 Mtce of coal in total can be conserved from the national energy efficient dispatch.

5.2 Policy implications

Based on the conclusions obtained above, some policy implications are proposed as follows:

(1) The dispatch reform will no doubt induce the revenue re-allocation among different generators, and the most important challenge is how to reconcile the revenue realignment among generators so that some of them will operate more and others will operate less. A possible approach is to establish a two-part pricing scheme, which contains 1) a capacity price paid in RMB per kW per year, based on the generator availability 2) an energy price paid in RMB per kWh, based on the generator output. This pricing scheme can compensate for the generators whose running time are reduced after the implementation of economic dispatch. Moreover, this approach has already been successfully demonstrated in US and UK.

(2) More economic benefits can be earned from wider dispatch areas, even though the total energy saving potentials may be reduced due to the coal price differences. To achieve these economic returns from wider dispatch areas, the first thing is to introduce explicit carbon pricing at regional (or national) level which will penalize inefficient coal plants with access to cheap local coal resources. The second thing is to develop a

proper mechanism to allocate the extra revenues come from cross-border power exchange in a regional or national economic dispatch. Taken the experience in US as an example, the cost savings or extra revenues are typically split by 50/50 between different involved entities.

(3) Under the current power operation regime in China, the power grid companies are in charge of the actual generator dispatch, and the consumers are the rate-payers who bear the power generation cost. Without any change in the pricing mechanism, the energy economic dispatch reform is simply an income transfer among these generation companies, which is the major reason why the pilot energy efficient dispatch started in 2007 has failed. Therefore, it will be better to establish a cost pass-through mechanism to the retail prices, then the benefits of the lower overall system cost will be received by both the grid companies and rate-payers. Moreover, this will ensure the support from all players in the power system when the dispatch reform processes.

(4) The government should make the dispatch rule more transparent and improve the power operation data availability, thus more valuable researches could be done to support the current electricity market reform, and help it making wiser decisions.

Although we have answered several important questions related to the economic dispatch in Chinese coal-fired power sector, some issues are still needed for further improvement. The economic dispatch model could be revised to be closer to the real system operation. For example, the constraints of ramp up and down and the line losses could be added to the model when new data is available. In addition, an economic dispatch model for the whole electricity sector could be developed to provide more references for the dispatch reform.

Appendix

Since the economic dispatch savings are mainly influenced by the heat rate differences and total coal-fired power generation, we will describe the source of these two data as below.

1) **Coal-fired power generation**

The amount of provincial coal-fired power generation could not be obtained directly from public source, this is because they are mixed together with other generations as thermal power in the Chinese official statistics documents.[11]Therefore, we have tried our best to separate the coal-fired power from the aggregated thermal power, that is, the coal-fired power equals to the amount of thermal power minus the gas-fired power, oil-fired power, residual temperature, gas and pressure generation, waste burning power generation and biomass generation (straw, bagasse and woody burning generation). The provincial gas-fired power is calculated as a result of multiplying the provincial share of natural-gas used for generation by the national gas-fired power generation (NBS, 2015b); The provincial residual temperature, gas and pressure generation is obtained through multiplying the provincial share of blast furnace used for power generation by the national residual temperature, gas and pressure generation (NBS, 2015b); The provincial waste burning power generation is calculated via multiplying the provincial share of burning power generation capacity by the national burning power generation (CNREC, 2015); The provincial biomass power generation is calculated as a result of multiplying the provincial share of biomass generation capacity by the national biomass power generation (CNREC, 2015). The amount of oil-fired power is too small and so we neglect it in this study.

In addition, since the East Inner Mongolia power grid and West Inner Mongolia power grid belong to the same province, we split their coal-fired power generation according to their GDP share of Inner Mongolia.

2) Heat rate estimation

The heat rates of coal generators are also not available from public source, and we have to estimate them by ourselves. Our estimation approach can be described as two steps, the first one is to set a reference coal generation unit, whose heat rate and technical parameters are already known. The second one is to add the heat rate differences resulting from the different technical parameters, when compared with that of the reference unit. The influence factors of heat rates are based on the 16 items summarized by IEA (2010), and the technical parameters of all the generators are drawn from World Electric Power Plants Data Base (WEPP) provided by EPRG.[12] One thing needs to be specified is that we have to focus on the most important rather than all the factors due to the data unavailability. Moreover, we have compared the estimated results with some of the publicly known generators to verify the credibility of our estimation.

[11] According to NBS (2015a), the total national thermal power in 2014 includes coal-fired power (3951 TWh), gas-fired power (133.3 TWh), oil-fired power (4.4 TWh), residual temperature, gas and pressure generation (89.2 TWh), waste burning power generation(24.5 TWh) and Straw, bagasse and woody burning generation (21.6 TWh).

[12] http://www.platts.cn/products/world-electric-power-plants-database

The reference generation unit is a sub-critical one (16.7MPa/538℃/538℃), cooled by water and without any installation of SO_2, NO_x and PM emission reduction equipment,[13] whose generation heat rate is 304.3455 gce/kWh with an efficiency about 38%.

Firstly, we analyze the improvements of steam condition (temperature and pressure) on the heat rates based on Figure 3.12 in IEA (2010), this is because the steam condition is one of the most important factors for heat rates (Staudt and Macedonia, 2014).The regression results are shown in Table A1. Therefore, we can get the changes of heat rates caused by improvements of steam conditions.

Table A1 The impacts of steam conditions on heat rates

	C	Pressure	Steam temperature	Reheat temperature	R^2
Coefficients	397.4927*** (1.9343)	-0.0673*** (0.0018)	-0.0737*** (0.0064)	-0.0814*** (0.0054)	0.9839

Notes: ***, ** and * denote significance at 1%, 5% and 10% levels, respectively. The numbers in the brackets are stand errors.

However, about one third of the steam condition data of the 2803 units are missing in the WEPP database. Therefore, we firstly calculate the heat rates for generators that have full data set of these steam conditions, and then analyze the relationship between their heat rates and their online years, capacity sizes based on the results from Ma and Zhao (2015). Moreover, we have classified them into three groups, and the results are shown in Table A2. Then, we use these regression results to fill up the heat rates for the remaining generators. At last, we can get the improvements of heat rates of all the generators when only the steam conditions are considered.

Table A2 the relationship between heat rates and online year and capacity size

	Subcritical	Supcritical	Utrcritical
C	1660.1944*** (332.0389)	1835.6483*** (305.9414)	2798.3257*** (399.7608)
Year	-0.6742** (0.3210)	-0.7684* (0.4520)	-1.2483** (0.4545)
Capacity	-0.0043* (0.0025)	-0.0045* (0.0026)	-0.0046* (0.0027)
R^2	0.2335	0.3647	0.2689

Notes: ***, ** and * denote significance at 1%, 5% and 10% levels, respectively. The numbers in the brackets are stand errors.

Then, we add the heat rate influences from other factors. According to the *Action plan for the coal-fired power plants retrofit 2014-2020* published by the National Development and Reform Commission (NDRC), the heat rate of generator cooled by

[13] The data source of the parameters of this generator is drawn from Sunrui et al. (2015), and http://baike.baidu.com/view/3121388.htm.

air will be about 16.95 gce/kWh more than that of same unit cooled by water. The heat rate of coal generator equipped with SO_2 emission control will be 3.01 gce/kWh higher than the one without installation, while the heat rate of generator with NOx emission control will be 1.47 gce/kWh higher than the one without installation (IEA, 2010).

At last, a generator's ultimate estimated heat rate is the result of summing all these heat rate numbers obtained from the above two steps, and they are further used to evaluate the economic dispatch savings in the Chinese coal-fired power sector.

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