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Reforming the Operation Mechanism of Chinese Electricity System: Benefits, Challenges and Possible Solutions

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ABSTRACT

A new wave of electricity market reform was launched by the Chinese government in March 2015, and one of its major objectives was to optimize the power system operation by reforming the low-efficient equal share dispatch mechanism. To provide scientific decision-making support for the current reform, we establish a mixed-integer linear programming optimization model to simulate the post-reform results, and the reform benefits are subsequently estimated by comparing those results with the pre-reform results. Then, we develop a political economy framework to identify the challenges associated with implementation of economic dispatch. At last, we propose several regulatory and market measures to address these identified challenges.

Keywords: Power system operation, Economic dispatch, China, MILP, Optimization

JEL Codes: Q41,Q43,Q48,Q50,Q54,Q58

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1. INTRODUCTION

China has the largest electricity system in the world, and it accounted for 25% of global electricity production in 2016 (BP, 2017). The electricity sector is not only the major coal consumer (47% in 2016) and carbon emitter (42% in 2016), but also an important source of air pollutants, such as SO_2, NO_X and $PM_{2.5}$ (Chen et al., 2017; NBS, 2017; Shan et al., 2018). Therefore, it is necessary to develop the power sector in a low-carbon and sustainable manner. To provide scientific decision-making support for this goal, most previous studies were conducted from technological perspectives, such as applications of energy efficiency technologies, renewable technologies, and carbon capture and storage technologies (Davidson et al., 2016b; Zhang et al., 2014; Zhou et al., 2010). Few studies have been conducted from the perspective of power system operation, such as reforming the mechanisms of unit commitments and generator dispatch. Moreover, the power system operation mechanism in China has often been criticized for its low efficiency in administratively allocating the electricity resources, resulting in more air pollutions and higher consumption costs (Kahrl et al., 2013; Pollitt et al., 2017).

The current mechanism of Chinese electricity system operation is characterized by a ‘planned economy’ strategy, which is based on the intensive negotiations between the governments and grid companies. Unlike the economic dispatch mechanism implemented in most countries around the world, generators in China are committed and dispatched according to a unique rule called ‘equal share’ (Davidson and Pérez-Arriaga, 2018; Kahrl et al., 2013). Under this rule, coal generators with similar capacities are administratively allocated the same amount of annual operational hours. Then, they are dispatched to achieve these predetermined allotments (Pollitt et al., 2017). Transmission lines for the cross-border trading are also utilized to achieve the predetermined annual targets, which are set in the yearly plan or the Five Year Plan (FYP). Obviously, this mechanism of power system operation is inherently inefficient and not economically optimal because generators are not operated based on their inherent merit, especially considering the current status of supply side overcapacity (Carbon Tracker, 2016; Lin et al., 2016).

In March 2015, Chinese government launched a new wave of electricity market reform, and one of the major tasks was to reform the power operation mechanism to be more efficient. The implementation of an economic dispatch mechanism in the electricity system would be a potentially good change. This is because the share of market traded electricity keeps increasing since the 2015 reform, reaching 40% in 2018.[1] An efficient power operation mechanism is in desperate need for supporting the electricity trading and achieving more benefits. However, the equal share approach still dominates the power system operation in most areas in China after the launching of the 2015 reform, little changes have been made to implement the economic dispatch. This is because reforming the power operation mechanism is a complex task and has widespread impacts (Erdogdu, 2014; Finon and Roques, 2013; Pollitt et al., 2017). Moreover, changing the operation mechanism will face many challenges caused by the benefits reallocation among different stakeholders. To provide decision-making support for the on-going electricity market reform, we conduct this study to answer the following three questions.

(1) What benefits could be achieved by implementing the economic dispatch mechanism in the Chinese electricity system, how large are these benefits, and who gets these benefits?

(2) What are the political and economic challenges faced by the economic dispatch?

(3) How can these challenges be addressed to facilitate the implementation of the economic dispatch?

The remainder of this paper is organized as follows. Section 2 presents a literature review of previous studies in the field of power operation reform. Section 3 describes the main methodology and data used in this study. Section 4 shows the empirical results of implementing the economic dispatch mechanism in the Chinese electricity system. Section 5 summarizes the conclusions and proposes relevant policy implications.

[1] http://www.cec.org.cn/xinwenpingxi/2019-02-21/188945.html.

2. LITERATURE REVIEW

Power system operation must balance the electricity system in real time on a least cost basis while meeting various physical and security criteria. Moreover, the efficiency of power system operation has extensive impacts on the energy consumption, climate change and air pollution (Mi et al., 2017; Teng et al., 2017). Therefore, it has attracted considerable research interests for a long time. The initial focus was developing appropriate models and algorithms to optimize the power system operation (Miller and Happ, 1983; Sakaguchi et al., 1988; Wei et al., 2018; Werner and Verstege, 1999). With the emergence of new technologies and worsening environmental issues, recent studies can be classified into three categories.

The first category involves modelling the impacts of new technologies, such as renewables, electric vehicles, energy storage technologies and Demand Side Responses (DSR) on power system operation (Carrión and Zárate-Miñano, 2015; Galus et al., 2010; Liu et al., 2014; Luo et al., 2015; Nikolakakis et al., 2017; Osório et al., 2015; Yu, 2012). The second category involves analysis of the environmental effects of economic dispatch mechanism to reduce the external influences of electricity production (Eldesouky, 2013; Liao, 2012; Muslu, 2004). The third category involves studies with objectives similar to that of this study, which estimates the benefits from reforming the power operation mechanism, especially for countries that have not implemented the economic dispatch. Zhao et al. (2013) used a nonlinear programming (NLP) optimization model to analyse the benefits of economic dispatch in Liaoning Province, China. They concluded that 2.09%-9.42% of pollutant and greenhouse gas (GHG) emissions could be reduced based on the 2010 levels. Davidson (2014) employed a mixed-integer linear programming (MILP) optimization model to analyse the benefits of economic dispatch mechanism in the Northeast China and found that the operational cost in 2013 could be reduced by 4.3%. Zhong et al. (2015) applied an MILP optimization model to explore the benefits of economic dispatch in Guangdong Province, China, and found that coal consumption could be reduced by 4% compared to the 2012 level.

Reforming the power operation mechanism is associated with both benefits and challenges. These challenges could arise from institutional, technical, political and economic conflicts (Pollitt et al., 2017). Kahrl et al. (2013) reviewed the history of power operation mechanism in China and stated that the benefits reallocation among generators with different ownerships will result in political and economic challenges. Davidson et al. (2016a) developed a political economy framework to analyse the challenges of high-share wind power integration and identified obstacles related to the economic transfers among wind generators and conventional generators, central–local government relationships, and cost-benefit allocation under a more integrated regional dispatch scheme. Hurlbut et al. (2017) compared the cross-border electricity trading in China and the USA and stated that the administrative planning of the network power exchange, pricing and trading rules are the main challenges of reforming the power operation mechanism. Robinson and Li (2017) analyzed the over-capacity status in China's power system and noted that it would hinder the power system optimization over wider areas, such as in inter-provincial or inter-regional trading. Pollitt et al. (2017) explored the theoretical significance, reform experiences and Chinese contexts of dispatch reform and summarized several challenges, such as the lack of a wholesale electricity market, vast revenue impacts, and the lack of necessary software.

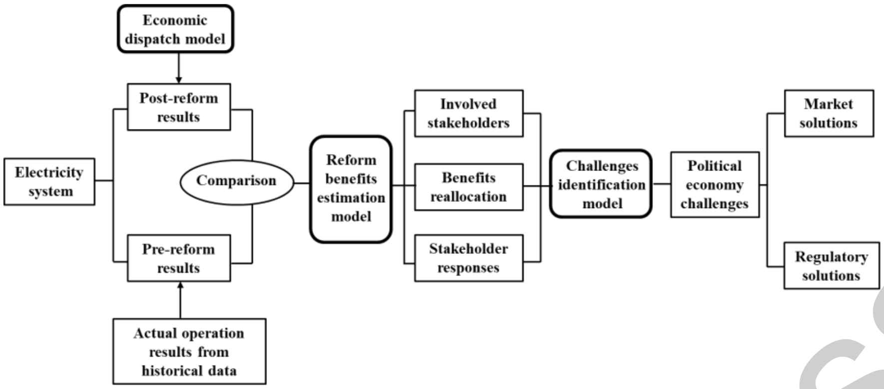
Compared with these previous studies, we contribute to the existing literature from three aspects. First, most previous empirical studies tend to analyze only one region or one province of China in estimating the economic dispatch benefits, evidences at the national level are currently lacking, so our study can provide an additional decision-making reference for the electricity market reform. Second, a novel political economy framework is developed in this study to systematically identify the challenges faced by the power operation mechanism, which can be served as a powerful tool in aiding the electricity policy designs. Moreover, the political economy analysis in this study is based on the quantitative empirical results, few previous studies have this combination before. Third, we have considered the external costs of different generation technologies in optimizing the power system operation, which is important considering the strict environmental regulations in China.

3. METHODOLOGY

3.1 Research framework

This study employs an integrated approach to analyze the benefits, challenges and possible solutions of reforming the power operation mechanism in China, and the research framework of the integrated approach is shown in Figure 1. First, the historical power system operation results are selected and treated as pre-reform results. Then, an economic dispatch model is established to re-operate the power system to obtain the post-reform results, which uses the same input data of the power system (generators, transmission lines and electricity load, etc). After that, a reform benefits estimation model is constructed by comparing the pre-reform results and the post-reform results from perspectives of total operation costs, total coal consumptions and total carbon emissions. At last, an identification model for the political economy challenges is constructed to identify the conflicts caused by the benefits reallocations among involved stakeholders. Several market and regulatory solutions are proposed to address the identified challenges.

Figure 1: Research Framework



3.2 Economic dispatch model

In this section, we describe a MILP optimization model that is established to estimate the benefits of economic dispatch. The definitions of the parameters and variables in the model are shown in Table 1.

Table 1: Major Subscripts, Sets, Parameters and Variables in the Model

Indices and parameters	Definitions	Source
Subscripts		
t	Hour in the year, $t \in [1,8760]$	
g	Generator index	
i, j	Regional grid index, $i, j \in \{1,2,3,4,5,6\}$	
Sets		
$coal$	Coal generators	Platts database, NBS (2015a)
gas	Gas generators	Platts database, NBS (2015a)
$nuclear$	Nuclear generators	Platts database, NBS (2015a)
$hydro$	Hydro generators	Platts database, NBS (2015a)
$wind$	Wind generators	Platts database, NBS (2015a)
$solar$	Solar generators	Platts database, NBS (2015a)
ALL	All generators considered	Platts database, NBS (2015a)
Parameters		
D	Electricity demand	He et al. (2016), Liu et al.(2019), Wang et al.(2016), Li et al. (2014), Cheng et al.(2012), Zhang et al.(2014), Zhao et al. (2008)
C	Generator capacity	Platts database, NBS (2015a)
FP	Fuel price	NDRC website[2], IMCEC website[3]
HR	Heat rate	Wei et al. (2018), Zhang et al. (2012)
OM	Operations and maintenance (O&M) costs	Chen et al. (2016)
CP	Carbon emission price	Pilot carbon emission trading markets in China
EF	Carbon emission factor	Zhang et al. (2012), Shan et al.(2018)
TC	Electricity transmission cost	NDRC website
EC	External cost	Streimikiene and Alisauskaite-Seskiene (2014), Teng (2012)
SC	Start-up cost	GE website[4], Davidson and Pérez-Arriaga (2018)

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2. The website link is http://jgs.ndrc.gov.cn/.
3. The website link is http://www.imcec.cn/zgdm_2014.

SD	Shutdown cost	GE website[5]
CF	Capacity factor	3TIER website, Davidson et al. (2016b)
TL	Transmission capacity limit	Guo et al. (2017), NEA website
TAL	Maximum annual electricity transmission	Guo et al. (2017)
L	Coefficient of transmission line loss	NEA website[6]
$\underline{P}$	Minimum load factor	Yi et al.(2019), GE website[3]
$\overline{P}$	Maximum load factor	Yi et al.(2019), GE website[3]
RU	Maximum ramp-up rate	Qadrdan et al. (2014), GE website[3]
RD	Maximum ramp-down rate	Qadrdan et al. (2014), GE website[3]
UT	Minimum uptime for thermal units	Qadrdan et al. (2014)
DT	Minimum downtime for thermal units	Qadrdan et al. (2014)
$\overline{SP}$	Maximum spinning reserve share	He et al. (2016)
OT	Outage rate	He et al. (2016)
λ	Load adjustment coefficient	NBS (2015)
α_{sp}	Coefficient of the load in the spinning reserve	He et al. (2016)
β_{sp}	Coefficient of renewables in the spinning reserve	He et al. (2016)
$\overline{SP_g}$	Maximum share of the spinning reserve	GE website[3]

3.2.1 Decision variables

The decision variables used in the economic dispatch model are shown in Table 2. Some are continuous variables, which includes the electricity generation ($p_{g,t}$), electricity transmission ($tr_{i,j,t}$) and spinning reserve ($sp_{i,g,t}$).

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4. The website link is https://www.ge.com/power.
5. The website link is https://www.ge.com/power.
6. The website link is http://www.nea.gov.cn/sjzz/dls/index.htm.

Others are binary variables, such as the on/off status of a generator ($i_{g,t}$).

Table 2: Decision Variables Used in the Economic Dispatch Model

Decision variables	Definitions
$p_{i,g,t}$	Electricity generation
$u_{g,t}$	On/off status of a generator (0 or 1)
$su_{g,t}$	Start-up decision of a generator (0 or 1)
$sd_{g,t}$	Shutdown decision of a generator (0 or 1)
$tr_{i,j,t}$	Electricity transmission between different regions
$sp_{i,g,t}$	Spinning reserves provided by a generator

3.2.2 Objective function

The objective function of the economic dispatch model is to minimize the annual total operation cost of the power system, which includes the electricity generation cost, the electricity transmission cost, the start-up cost and the shutdown cost (see equation (1)). The fuel cost and carbon emission cost of one kWh electricity are calculated by equations (2) and (3), respectively.

$$
\begin{aligned}
min\ f = & \sum_t \sum_i \sum_g (FC_{i,g} + OM_{i,g} + CC_{i,g} + EC_{i,g}) \cdot p_{i,g,t} \\
& + \sum_t \sum_i \sum_j TC \cdot tr_{i,j,t} \\
& + \sum_t \sum_i \sum_g SC_{i,g} \cdot su_{i,g,t} \\
& + \sum_t \sum_i \sum_g SD_{i,g} \cdot sd_{i,g,t}
\end{aligned} \tag{1}
$$

$$
FC_{i,g} = HR_{i,g} \cdot FP_i \quad g \in \{coal, gas, nuclear\} \tag{2}
$$

$$
CC_{i,g} = HR_{i,g} \cdot EF_{i,g} \cdot CP_i \quad g \in \{coal, gas\} \tag{3}
$$

3.2.3 Constraints

Power system operation faces both physical and economic constraints, and the proposed model considers five main types of constraints.

Demand-meeting constraints: For each operation interval t, power system operation must satisfy the demand of a specific region. In region i, the total electricity generation from region i, plus the imported electricity after deducting the line loss, and then minus the exported electricity, should be no less than the electricity demand of region *i*. λ_i is used to represent the load met by the generation technologies considered in this study.[7]

$$
\sum_i \sum_{g \in \{ALL\}} p_{i,g,t} + \sum_j tr_{j,i,t} \cdot (1 - L_{i,j}) - \sum_j tr_{i,j,t} \geq \lambda_i \cdot D_{i,t} \tag{4}
$$

Electricity transmission constraints: For any transmission line, the hourly electricity transmission should be no greater than the capacities of the inter-regional transmission lines, as shown in equation (5). Moreover, the annual electricity transmission between different regions are subjected to the operational requirements, see equation (6).

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[7] Due to data availability, we only considered six generation technologies in the empirical analysis. Therefore, λ_i is used to represent the share of the load met by the six technologies considered in this study.

$$0 \le tr_{i,j,t} \le TL_{i,j} \tag{5}$$

$$\sum_{t}`tr_{i,j,t} \le TAL_{i,j} \tag{6}$$

Generation constraints: For fossil fuel generators, hourly generation is subject to the minimum and maximum output constraints, as shown in equation (7). The generation in an adjacent time period should also meet the maximum ramp-up and ramp-down constraints of the generator, as shown in equations (8) and (9). Nuclear generators are assumed to serve as base load providers in this study according to He et al. (2016), and their hourly generation is shown in equation (10). The hourly generation of renewable generators can be calculated based on the generation capacity, capacity factors, and average outage rates (see equation (11)).

$$\underline{P_{i,g}} \cdot (1-OT_{i,g}) \cdot u_{i,g,t} \le p_{i,g,t} \le \overline{P_{i,g}} \cdot (1-OT_{i,g}) \cdot u_{i,g,t} \qquad g \in \{coal, gas\} \tag{7}$$

$$p_{i,g,t} - p_{i,g,t-1} \le RU_{i,g} \qquad g \in \{coal, gas\} \tag{8}$$

$$p_{i,g,t-1} - p_{i,g,t} \le RD_{i,g} \qquad g \in \{coal, gas\} \tag{9}$$

$$p_{i,g,t} = C_{i,g} \cdot (1-OT_{i,g}) \qquad g \in \{nuclear\} \tag{10}$$

$$p_{i,g,t} \le C_{i,g} \cdot (1-OT_{i,g}) \cdot CF_{i,g,t} \qquad g \in \{hydro, wind, solar\} \tag{11}$$

Minimum up/down time constraints: Fossil fuel generators have two statuses (on or off). The relationship between the on/off status of a generator and up/down decisions is shown in equation (12). Fossil fuel generators cannot be frequently started up or shut down to avoid damage and to increase their lifespans. Therefore, when a generator is on or off, it should retain this status for a certain amount of time. The constraint for the minimum up/down time of a generator is shown in equations (13) and (14), which are based on the minimum up time (UT) and minimum down time (DT).

$$u_{i,g,t} = u_{i,g,t-1} + su_{i,g,t} - sd_{i,g,t} \qquad g \in \{coal, gas\} \tag{12}$$

$$u_{i,g,t} \geq \sum_{t'=t-UT}^{t} su_{i,g,t'} \qquad g \in \{coal, gas\} \tag{13}$$

$$1 - u_{i,g,t} \geq \sum_{t'=t-DT}^{t} sd_{i,g,t'} \qquad g \in \{coal, gas\} \tag{14}$$

Reserve constraints: Due to load forecasting errors and generator outages, minimum reserves are needed to ensure reliable operation in the case of unpredicted changes in either load or supply. Fossil fuel generators and hydro generators are assumed to provide spinning reserves, which are shown in equations (15) and (16), respectively. Moreover, the spinning reserves provided by a fossil fuel generator are assumed to be within a certain share (see equation (17)). The spinning reserve requirement of a specific grid region is shown in equation (18), and it should be no less than a share of the electricity load and a share of the intermittent renewable generation.

$$p_{i,g,t} + sp_{i,g,t} \leq \overline{P_{i,g}} \cdot (1 - OT_{i,g}) \cdot u_{i,g,t} \qquad g \in \{coal, gas\} \tag{15}$$

$$p_{i,g,t} + sp_{i,g,t} \leq C_{i,g} \cdot CF_{i,g,t} \cdot (1 - OT_{i,g}) \qquad g \in \{hydro\} \tag{16}$$

$$sp_{i,g,t} \leq C_{i,g} \cdot \overline{SP_{i,g}} \qquad g \in \{coal, gas, hydro\} \tag{17}$$

$$\sum_{g \in \{coal, gas, hydro\}} sp_{i,g,t} \geq \alpha_{sp} \cdot D_{i,t} + \beta_{sp} \cdot \sum_{g \in \{\text{wind, solar}\}} p_{i,g,t} \tag{18}$$

3.3 Reform benefits estimation model

This study takes a counterfactual approach to estimate the benefits from reforming the power operation mechanism, which compares the actual operation results with that simulated by the established economic dispatch model. In establishing the estimation model, we have made the following major assumptions.

- This study estimates the reform benefits from a supply-side perspective, and the benefits are defined as the saved cost, conserved coal and reduced carbon emissions brought by the reform. The pre-reform results before 2015 are drawn from the historical data, while the post-reform results are simulated by the economic dispatch model using the same power system data. The demand side of the electricity system is assumed to be not affected by the economic dispatch implementation, which remains the same before and after the reform. This study does not consider the impacts of the market transaction issues, such as the market power and market clearing rules.

With these assumptions, the reform benefits can be estimated from equation (19) to (21).

$$\Delta f = f_0 - f^* \tag{19}$$

$$\Delta CC = CC_0 - \sum_t \sum_i \sum_g HR_{i,g} \cdot p^*_{i,g,t} \qquad g \in \{coal\} \tag{20}$$

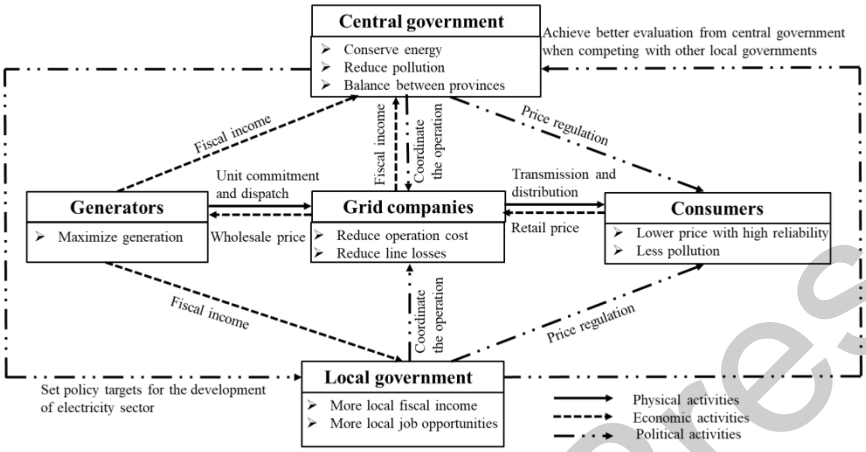
$$\Delta CE = CE_0 - \sum_t \sum_i \sum_g HR_{i,g} \cdot EF_{i,g} \cdot p^*_{i,g,t} \qquad g \in \{coal, gas\} \tag{21}$$

Where f_0, CC_0 and CE_0 are the actual total power operation cost, total coal consumptions and total carbon emissions of a pre-reform year respectively; f^* and $p^*_{i,g,t}$ are the post–reform results of power operation costs and electricity generation; Δf, ΔCC and ΔCE are the cost reductions, coal savings and carbon emission reductions achieved by the reform respectively.

3.4 Identification model for the political economy challenges

Similar to all reforms, changing the power operation mechanism will create winners and losers, thus resulting in benefits reallocation problems among different stakeholders. To help identifying the challenges faced by the economic dispatch implementation, a political economy framework is developed which includes the involved stakeholders and the physical, economic and political interactions between them (see Figure 2).

Figure 2: Political Economy Framework for Power System Operation



As shown in Figure 2, there are five types of stakeholders related to power operation mechanism reform. All of them play different roles in the power system operation and have different targets. Generators are committed and dispatched by the grid companies, and their interests are to maximize the generation shares and recover their investment costs. Customers pay for dispatch operations, and their interests are to consume cheap and reliable electricity. Governments coordinate the power system operation for the national and local development. Grid companies conduct the power system operation and their goals are to reduce the cost and line losses. Using this framework, the challenges can be identified under the following steps. First, the economic impacts of reform on different stakeholders will be analysed. Second, the potential response strategies of stakeholders will be explored when they face the predicated benefit changes. At last, the challenges can be summarized by identifying the conflicts caused by their response strategies.

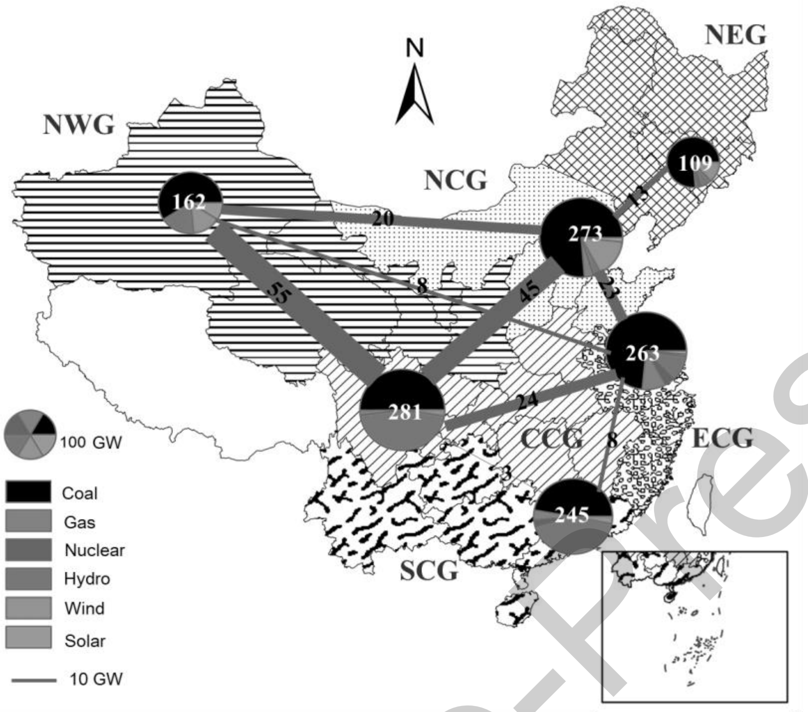
3.5 Data

The Chinese electricity system in 2014 is selected as a case study to estimate the reform benefits of power operation mechanism. On the generation side, six major generation technologies are considered based on the data availability, which includes coal-fired power, gas-fired power, hydropower, nuclear power, wind power and solar power generators. On the transmission side, the interregional electricity trading among six regional grids are considered, whose geographical scopes are shown in Table 3. The generation capacity mix and inter-regional transmission capacity in 2014 are shown in Figure 3.

Table 3 Geographical Scopes of Six Regional Grids in China

Regional grid	Provinces
North China Grid (NCG)	Beijing, Tianjin, Hebei, Shandong, Shanxi, and West Inner Mongolia
Northeast China Grid (NEG)	Liaoning, Jilin, Heilongjiang, and East Inner Mongolia
Northwest China Grid (NWG)	Gansu, Qinghai, Ningxia, Shaanxi, and Xinjiang
East China Grid (ECG)	Zhejiang, Shanghai, Jiangsu, Fujian, and Anhui
Central China Grid (CCG)	Hubei, Hunan, Jiangxi, Chongqing, Henan, and Sichuan
South China Grid (SCG)	Guangdong, Guangxi, Yunnan, Guizhou, and Hainan

Figure 3: The Structure of Electricity Supply in China



Notes: The pie charts show the generation capacity, and number on each pie chart is the total generation capacity in the regional grid. The sector sizes of the pie charts represent the generation capacities of different generation technologies. The widths of the lines between different regions reflect the transmission capacities, and the numbers on the lines are the total capacities of the transmission lines.

The technical and economic parameters of the six generation technologies are shown in Table 4. To save space, we have put descriptions of other data used in this study in the Appendix section.

Table 4: Major Parameters of the Six Generation Technologies

Indicators	Unit	Coal	Gas	Nuclear	Wind	Solar	Hydro
O&M cost	yuan/kWh	0.0131	0.0224	0.0567	0.1560	0.1268	0.0203
External cost	yuan/kWh	0.1673	0.1207	0.0188	0.0044	0.0175	0.0036
Start-up cost	yuan/MW	600	250	-	-	-	-
Shut-down cost	yuan/MW	80	30	-	-	-	-
Heat rate	gce/kWh m^3/kWh g/kWh	309.11	0.18	0.03	-	-	-
Carbon emission factor	kg/kg kg/m^3	2.42	2.19	-	-	-	-
Minimum uptime	h	8	4	-	-	-	-
Minimum downtime	h	4	4	-	-	-	-
Ramp-up rate	MW/h	200	720	-	-	-	-
Ramp-down rate	MW/h	200	720	-	-	-	-
Minimum load factor	%	40	35	-	-	-	-
Maximum load factor	%	100	100	-	-	-	-
Outage rate	%	5.0	7.3	11.1	2.0	2.0	5.1

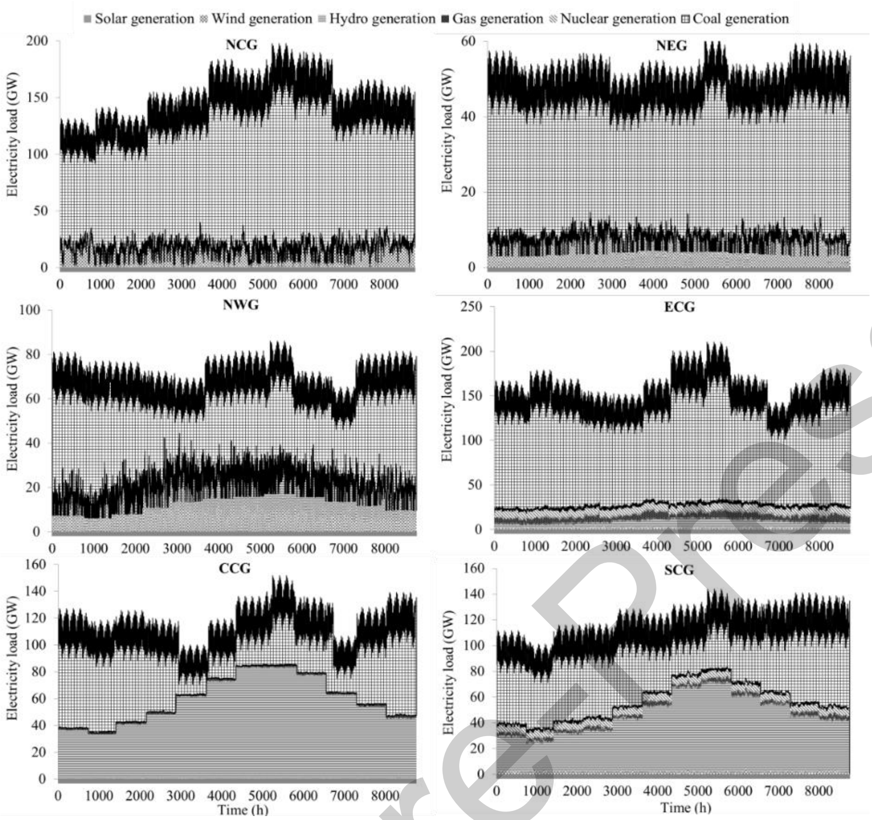
Notes: The fuel costs of coal generators and gas generators are the average values of all the generators.

4. RESULTS AND DISCUSSIONS

4.1 The benefits estimated from economic dispatch implementation

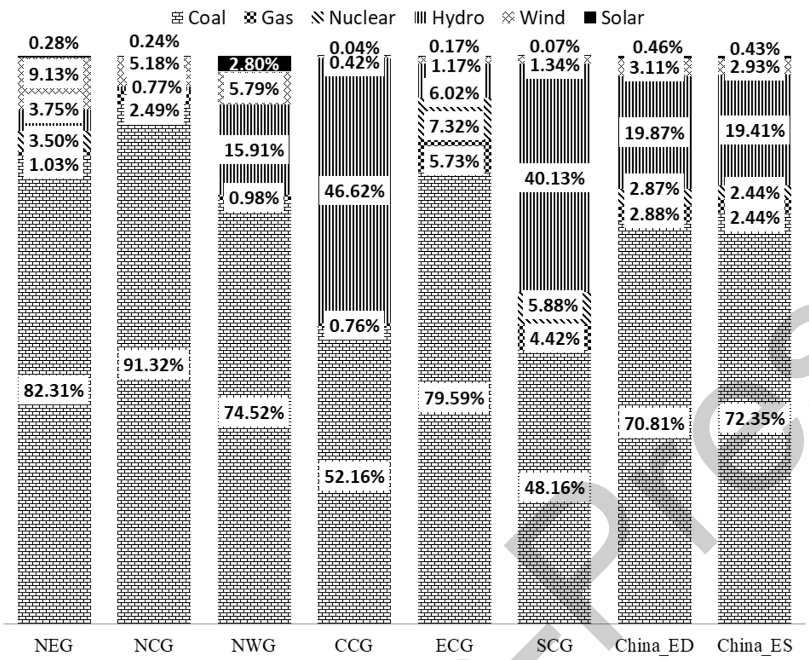
Using the economic dispatch model established in section 3.2, we can obtain the hourly power system operation results of six regional grids in 2014 (see Figure 4). Coal generation accounts for the largest generation share in all the six regional grids, even hydro generation represents a very large share in the CCG region (46.62%) and the SCG region (40.13%). Renewable energy curtailment shares have declined greatly after the economic dispatch implementation, such as wind from 8.53% to 2.86%, solar from 9.62% to 3.41%, and hydropower from 4.30% to 1.97%. Renewables are cheaper than the coal generation, so they can have more generation shares when the administratively allocated generation quotas of coal generation are abolished by the reform.

Figure 4: Economic Dispatch Results in the Six Regional Grids



In addition, considerable differences exist among the generation mixes of different regions (see Figure 5), the NCG has the largest coal generation share (91.32%), and the ECG has the largest gas generation share (5.73%). Additionally, the CCG has the largest share (46.62%) of hydropower, while the ECG has the largest nuclear generation share (7.32%).

Figure 5: Annual Generation Shares of Different Technologies in Different Regions



Notes： China_ED represents the results under the Economic Dispatch Mechanism, while the China_ES represents the results under the Equal Share Dispatch Mechanism

The benefits of economic dispatch implementation can be obtained from the estimation model, as shown in Table 5. We can see that the implementation of economic dispatch in the Chinese power system could save 66.44 billion RMB, which is much bigger than the annual benefits achieved by other sub-reforms proposed in 2015. The annual benefits from transmission and distribution reform are estimated to be 48 billion yuan,[8] while the annual benefits from the government electricity funding reform are assessed to be 35

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[8] http://www.cec.org.cn/xinwenpingxi/2018-03-02/178242.html.

billion yuan.[9] Therefore, the economic dispatch is well worth implementation considering its advantages compared with other reforms. The amount of reduced cost equals to 3.10% of the actual total power operation cost. In addition, the economic dispatch scheme could conserve the coal consumption by 6.40% and reduce the carbon emissions by 6.17% in the electricity sector. The shares of estimated benefits seem to be small, but it should not be neglected if we benchmark them with other countries. For example, the conserved coal consumption in 2014 represents 24.6 % the total coal consumption of EU's electricity sector, while the reduced carbon emissions in 2014 accounts for 30.5% of the carbon emissions of EU's electricity sector.[10]

Table 5: Benefits from Economic Dispatch in the Six Regional Grids

Regional grid	Coal conservation (Mtce)	Carbon emission reduction (Million tons)	Generation cost reduction (Billion yuan)	Transmission cost reduction (Billion yuan)	Total cost Reduction (Billion yuan)
NCG	20.40 (5.70%)	67.65 (5.58%)	17.80 (3.22%)	/	/
NEG	12.16 (8.18%)	44.05 (8.05%)	9.54 (4.55%)	/	/
NWG	14.37 (9.12%)	44.31 (8.97%)	10.44 (4.60%)	/	/
ECG	16.71 (5.97%)	51.70 (5.59%)	15.35 (2.87%)	/	/
CCG	9.87 (5.52%)	32.47 (5.36%)	8.44 (2.69%)	/	/
SCG	7.41 (5.22%)	23.21 (4.82%)	6.16 (2.12%)	/	/
National	80.93 (6.40%)	263.39 (6.17%)	67.73 (3.18%)	-1.29 (-11.30%)	66.44 (3.10%)

Notes: The numbers in parentheses are the corresponding shares in the electricity sector. '/' indicates that cell does not apply the calculation.

Different regional grids benefit differently from the economic dispatch. The generation cost reduction shares range from 2.12% (SCG) to 4.60% (NWG), the shares of coal conservation are between 5.22% (SCG) and 9.12% (NWG), and the shares of carbon emission reductions range from 4.82% (SCG) to 8.97%

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[9] http://www.cec.org.cn/yaowenkuaidi/2017-06-01/168996.html.

[10] http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do.

(NWG). In addition, the NCG has the largest absolute potential for cost reductions, coal conservations and carbon emission reductions, while the NWG owns the largest share of these three types of benefits. Therefore, the NCG and NWG could be selected as pilot areas for implementing the economic dispatch mechanism considering the significant economic benefits.

4.2 Sensitivity analysis of some key influencing factors

To explore the impacts of electricity system parameters on the estimated benefits, this study conducts a sensitivity analysis of four key parameters in the economic dispatch model, including the transmission capacity, the carbon emission prices, the natural gas prices and the minimum load factors of coal generators. Moreover, several scenarios are designed in the sensitivity analysis, the scenario using the original input parameters is set as the Business as Usual (BAU) scenario, while 12 other scenarios have been defined to investigate the impacts of these considered parameters (see Table 6). In designing these scenarios, we use the forecasted values of these parameters in 2025 to simulate how the estimated benefits will be affected by the development of electricity sector in the future (see Figure 6).[11]

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[11] The year 2025 is selected due to the data availability of all the input parameters.

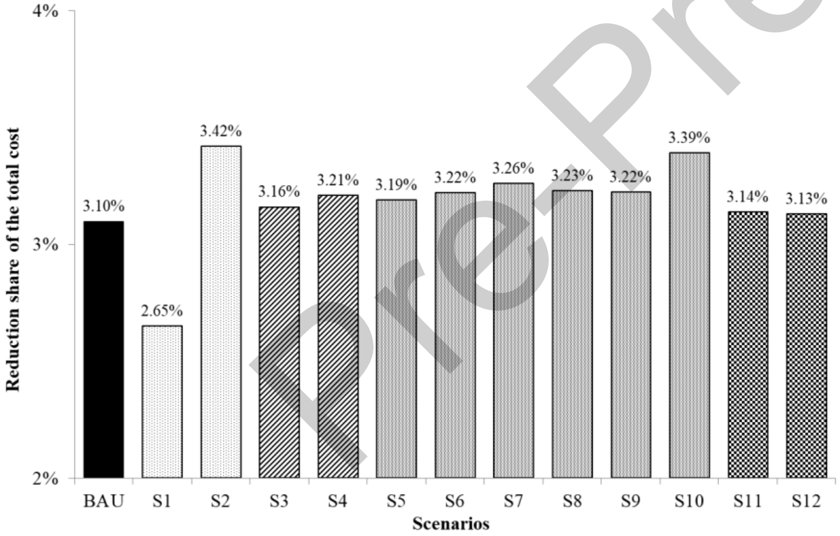
Table 6: Definitions of the Sensitivity Analysis Scenarios

Scenario	Setting	Source
BAU	Carbon price= 100 yuan/ton	National Center for Climate Change and International Cooperation (NCSC)
	Natural gas price= 3.41/m^3	National Development and Reform Commission
	Transmission capacity in 2014	National Energy Association (NEA)
	Minimum load factor= 40%	Yi et al.(2018)
S1	Carbon price= 35 yuan/ton	Survey results for 2025 from China Carbon Forum
S2	Carbon price= 158 yuan/ton	Survey results for 2025 from China Carbon Forum
S3	Natural gas price increase by 11%	Henry hub natural gas forecast from Wood Mackenzie
S4	Natural gas price increase by 26%	Henry hub natural gas forecast from Wood Mackenzie
S5	NWG to NCG capacity + 6 GW	State Grid Corporation of China website
S6	NWG to CCG capacity + 16 GW	State Grid Corporation of China website
S7	NWG to ECG capacity + 20 GW	State Grid Corporation of China website
S8	CCG to ECG capacity + 8 GW	State Grid Corporation of China website
S9	NCG to ECG capacity + 18 GW	State Grid Corporation of China website
S10	Add all capacity from S5 to S9	State Grid Corporation of China website
S11	Minimum load factor= 20%	Advanced coal generators in the world
S12	Minimum load factor= 30%	Electricity sector' 13th Five Year Plan from NEA

Notes: the minimum load factors of advanced coal generators in the world are drawn from http://www.sohu.com/a/214992363_722664.

We can see that all these factors will influence the reform benefits significantly. Carbon emission price have the largest impacts, the total cost reduction share will increase to 3.42% if the carbon emission prices increases to 158 yuan/ton, so the operation mechanism reform will become more worth-taking with the development of national carbon market in China. As to the natural gas price scenarios (S3 and S4), the total operation cost will further decrease by around 0.06% when the when the natural gas price increase by 10%. The natural gas generation has been promoted by the government to address the air pollution problems nowadays. Considering the limited gas resources and the soaring demand in China, the gas prices will exhibit a long-term increasing trend in China, so the positive impacts of increasing gas prices on the reform benefits should not be neglected. The increased interregional transmission capacity from Ultra High Voltage (UHV) power lines will also bring more reform benefits. The transmission capacity additions between NWG to ECG will contribute most to the cost reduction shares (3.26%). Moreover, the total annual power operation cost will reduce by 3.39% when all the transmission capacity additions between six regional grids are considered (S10). As to the minimum load factors, the cost reduction shares will increase to 3.14% and 3.13% when we benchmark it with that of international advanced generators (S11) and the flexibility transformation targets of Chinese coal generators (S12).

Figure 6: Sensitivity Analysis Results



4.3 Identification of political economy challenges faced by economic dispatch

Based on the political economy analysis framework established in section 3.4, we have identified three major challenges, namely the inadequate compensation for the ancillary services, the local protectionism against uneven benefits reallocation and no-incentive business models of grid companies for renewable integration.

4.3.1 Inadequate compensation for the ancillary services

Due to the lower marginal cost of renewable generation, implementing the economic dispatch rule in the electricity system will increase the intermittent renewable generation. Wind generation and solar generation will increase by 9.90 TWh and 1.61 TWh respectively when the economic dispatch is implemented. The increased renewable generation will become sources of political economy challenges. On the one hand, coal generators and renewable generators are competitors in power system operation, the generation share of coal generators will shrink with the integration of more renewables, thus reducing their generation incomes. On the other hand, wind and solar generation are characterized by variability and unpredictability, so more ancillary services are required for the reliable operation of the power system (Yatchew, 2016). Typical ancillary services include spinning reserves, ramping and start-up operations, which are primarily provided by coal generators in China. These ancillary services induce efficiency losses as the coal generators run up against their technical limits or causing opportunity cost. The additional ancillary service cost caused by the increased wind generation and solar generation are estimated to be 63.38 million yuan and 2.42 million yuan in 2014 respectively. [12]

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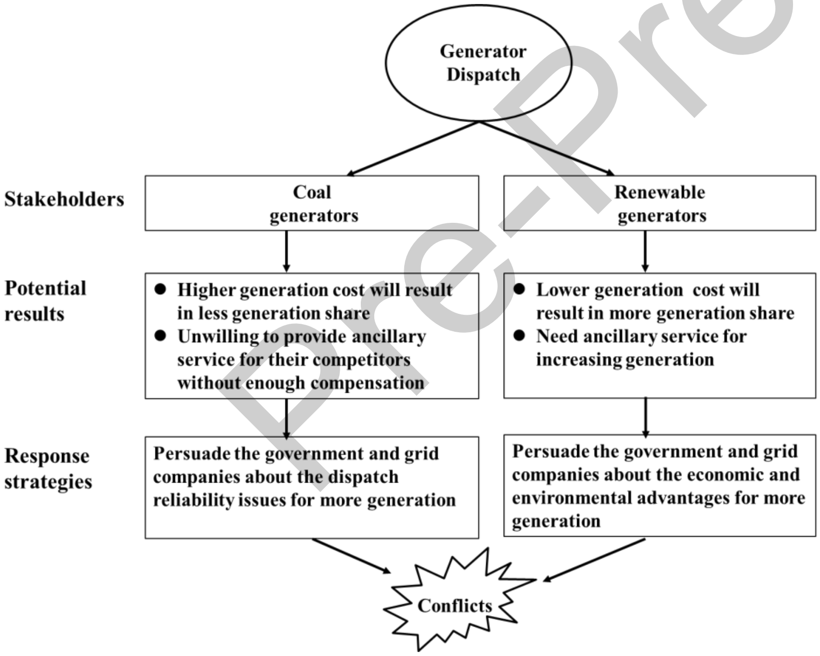
[12] In calculating the additional ancillary service cost, we use average ancillary service cost caused by wind generation and solar generation based results from Guo (2013). The ancillary service cost

However, the official compensation regimes for ancillary services are still lacking or insufficient in China. A large share of the ancillary services in China is mandatory and uncompensated (Zeng et al., 2014). Coal generators will have to provide ancillary services without adequate compensation. In response to these potential changes, the coal generators will likely to emphasize the potential power system reliability issues to the government and system operators, and the renewable generators will lobby the government and system operators regarding the economic and environmental advantages of renewables to increase their generation shares. Finally, conflicts will likely occur between coal and renewable generators in the power system operation (see Figure 7).

Figure 7: Challenges Related to Inadequate Compensation for Ancillary Services



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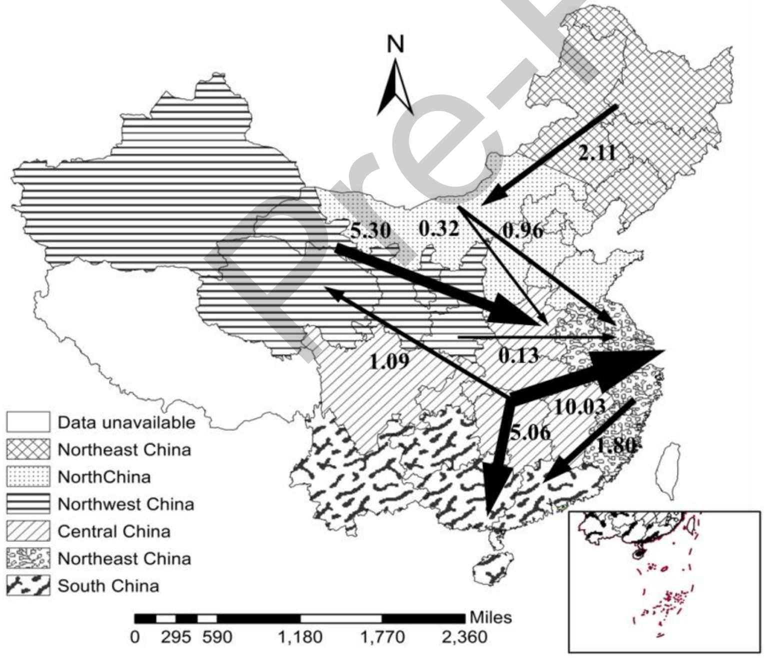
caused by the wind generation and solar generation is 0.0064 yuan/kWh and 0.0015 yuan/kWh respectively.

4.3.2 Local protectionism against uneven benefits reallocation

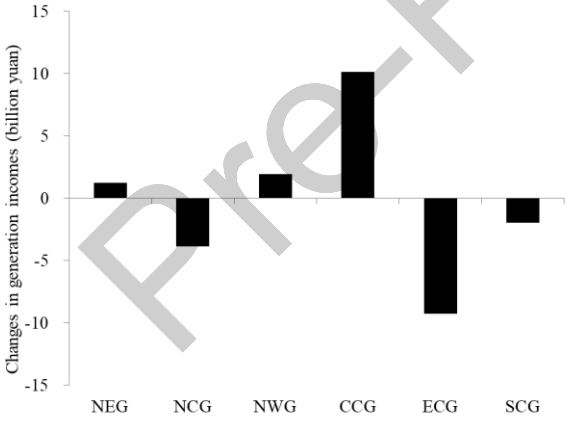
With the economic dispatch implementation, more benefits could be achieved when regions with high generation costs could import cheap electricity from other regions to meet their electricity demand. The annual electricity trading changes brought by economic dispatch are summarized in Figure 8. We can see that the total interregional electricity trading will increase by 26.80 TWh, accounting for 10.58% of the actual total interregional electricity trading in 2014. Moreover, the cross-border electricity trading from CCG region to ECG region increases the most (10.03TWh).

Figure 8: Interregional Electricity Trading Changes Caused by Reform (TWh)



The changes of interregional electricity trading will result in generation income reallocation among the importing and exporting regions (see Figure 9). We can see that different regions are affected differently by the changed cross-border trading. CCG region benefits most from the increased generation, while ECG region suffers most from the reduced generation. The uneven benefits reallocation brought by the dispatch mechanism reform will affect their local fiscal income, job opportunities, and opportunities for leader promotion, thus hindering the economic dispatch implementation due to the corresponding political and economic challenges. Moreover, provinces will prefer to meet their electricity demand via local generation considering the current over-capacity status in the Chinese electricity system (Wei et al., 2018). In addition, the imported electricity does not pay for the cost of ancillary services, which are shared by the generators within the importing provinces (Hurlbut et al., 2017).

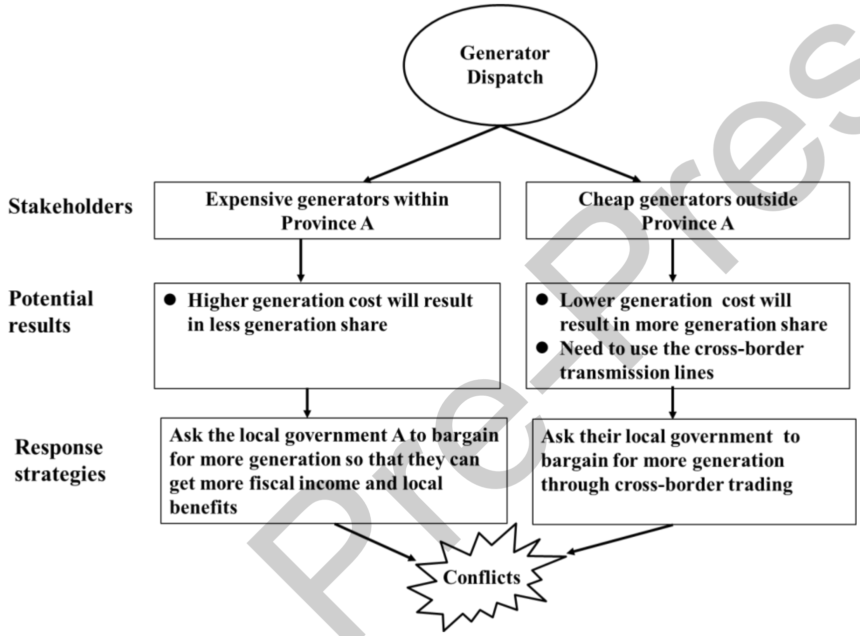
Figure 9: The Generation Income Changes Due to Increased Electricity Trading



Notes: the generation income changes are calculated as results of multiplying the electricity sale prices by the changed electricity generation amount. The average electricity sale prices are 0.59 yuan/kWh (NEG), 0.63 yuan/kWh (NCG), 0.45 yuan/kWh (NWG), 0.64 yuan/kWh (CCG), 0.72 yuan/kWh (ECG) and 0.60 yuan/kWh (SCG).

In response to the benefits reallocation problems, generator owners in the high-cost regions would likely to ask their local governments to fight for more generation shares considering the local benefits, while generator owners in the low-cost regions will ask their governments to bargain for higher generation shares through cross-border trading due to their cost advantages. Finally, conflicts related to cross-border trading will likely occur among different regions (see Figure 10).

Figure 10: Challenges Associated With Increased Cross-Border Trading



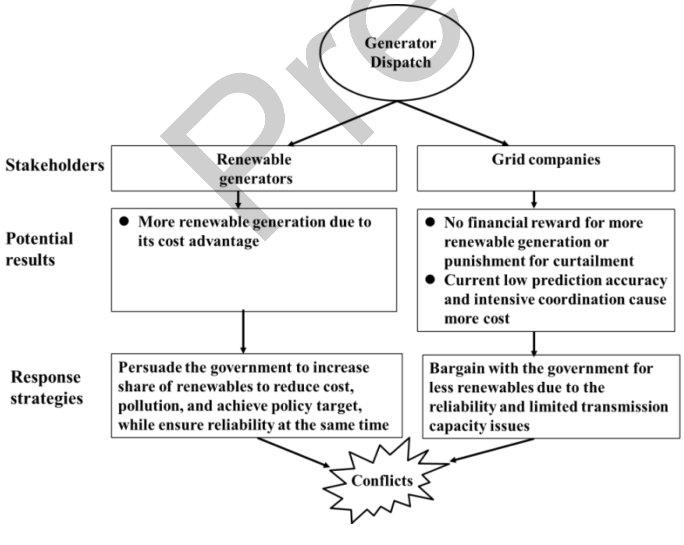
4.3.3 No-incentive regulation frameworks for grid companies

Considering the variability and unpredictability of renewable resources, more renewable integration (from economic dispatch) will increase the costs of grid companies. This is because more monitoring equipment, information exchange tools and negotiations are needed to ensure the reliable operation of the electricity system. Guo et al. (2013) estimated that the operation cost of gird companies will on average increase by 0.025 yuan when the intermittent renewable generation increase by one kWh, so the total grid operation cost will increase by 0.29 billion yuan when the economic dispatch is implemented.

However, there is neither an official reward mechanism for renewable integration nor a punishment mechanism for renewable curtailment for the grid companies, according to the current regulation rules. Therefore, grid companies are reluctant to increase the shares of renewable generation, this is because it increases their operational costs rather than benefits them.

In response to these potential cost changes, the grid companies will likely to bargain with the government for less renewable integration based on system reliability issues and transmission capacity limits, and the renewable generators will ask the government to put more pressure on grid companies to increase renewable generation. Finally, conflicts will likely occur between the grid companies and renewable generators in reforming the power operation mechanism (see Figure. 11).

Figure 11: Challenges Associated with No-incentive Regulations of Grid Companies



4.4 Possible solutions for the identified political economy challenges

To facilitate economic dispatch implementation, we propose several potential solutions to address the identified challenges among relevant stakeholders.

For the challenges related to insufficient compensation for the ancillary services provided by coal generators, an ancillary service market can be established following cost causation principles (Isemonger et al., 2009). The design of market rules, trading products and transaction rules of ancillary service market can be referred to the lessons from developed countries (Danias et al., 2013; Grubb and Newbery, 2018). For example, ancillary services needs to be effectively priced to provide signals for dispatch and investment according to the EU experiences (Newbery, 2018). Moreover, considering the Chinese reform context, it is good to conduct pilots market first and then improve the market design according to the accumulated operational experiences. With the ancillary service market, the operational reserves, ramping services and load following services provided by the coal generators can be reasonably compensated, thus increasing the renewable integration. Moreover, this ancillary service market could motivate the transformation of coal generators to provide ancillary services at lower costs, thus increasing the flexibility of the power system.

For the challenges related to local protectionism in the cross-border trading, it is necessary to develop a benefit sharing mechanism to encourage electricity trading among different regions. In designing the benefit sharing mechanism, it is good to simulate the power system operation results with and without the cross-border trading. Based on the simulation results, a thorough cost-benefit analysis should be conducted to estimate the net gains from the increased cross-border trading (Loureiro et al., 2019). Then, rules should be scientifically designed to allocate the additional benefits brought by the cross-border trading (Agostini et al., 2019). The United States has equally shared the total costs and benefits from regional economic dispatch among all the trading states (Hurlbut et al., 2017). The pricing mechanism of inter-regional power exchange could also be reformed to motivate the cross-border trading of electricity. In addition, since the cross-border trading is conducted by the grid companies, it is also important to reform the business models of grid companies to motivate them to conduct more cross-border trading. With the benefit sharing mechanism of the cross-border trading, more inter-regional power exchange will be achieved, this is because more benefits can be achieved through cross-trading and they are reasonably distributed among the involved stakeholders. Moreover, the enhanced cross-border trading can better reflect the electricity supply and demand status from a whole country perspective, thus providing more sensible signals for the infrastructure investment and electricity pricing.

For the challenges regarding the no-incentive regulations of grid companies, it is necessary to develop a new incentive regulation framework for grid companies to increase the integration of renewable generation. First, a renewable integration target can be set for the grid companies based on simulation analysis of power system operation, with consideration of both the renewable energy resources and the operational constraints. Then, incentive regulation rules will be established according to the determined integration targets, grid companies will have to pay for penalty costs if the actual renewable curtailment exceeds the pre-determined amount, and receive additional rewards if the actual curtailment is below the pre-determined amount (Poudineh and Jamasb, 2016). At last, grid companies will also be compensated for their cost caused by the increased integration of renewable generation, the compensation amount should be based on evidences from strict cost accounting, which can be referred to the German experiences (Ueckerdt et al., 2013). With this incentive regulation framework, grid companies will have incentives to increase the renewable integration, thereby facilitating the implementation of economic dispatch mechanism.

5. CONCLUSIONS AND POLICY IMPLICATIONS

5.1 Conclusions

The Chinese government launched a new wave of electricity market reform in March 2015, one of its tasks aims at optimizing the power system operation under an economic dispatch mechanism. A cost-benefit analysis of economic dispatch is vital for its successful implementation in the electricity system. Therefore, this study employed an integrated approach to analyze the benefits, challenges and possible solutions of reforming the power operation mechanism in China. The major conclusions drawn from this study are as follows.

(1) Economic dispatch could bring benefits to the Chinese electricity sector, and the total cost of power operation could decrease by approximately 3.10%. The total coal conservation potential from economic dispatch is 80.93 Mtce, and the total carbon emission reduction potential is 263.39 million tons. Different regions benefit differently from the reform. The North China Grid has the largest potential for cost reductions, while the Northwest China Grid has the largest share of cost reductions. These estimated benefits could be served as important decision-making basis for the economic dispatch reform, which will also convince the stakeholders of reform value.

(2) Several challenges faced by economic dispatch implementation have been identified using a political economy framework. Such challenges include inadequate compensation for the ancillary services provided by coal generators, cross-border trading issues related to local protectionism, and the no-incentive regulations of grid companies regarding the renewable integration.

(3) To address these challenges, some potential solutions have been proposed to ensure that economic dispatch mechanism is successfully implemented. An ancillary service market could be designed to reasonably reward all the contributions of generators in the power system operation. Moreover, a benefit sharing mechanism among the trading regions could be developed to motivate the cross-border trading of electricity. Finally, a new

incentive regulation framework for grid companies could be designed to provide more incentives to increase the integration of renewables.

5.2 Policy implications

To achieve a reliable, affordable and sustainable development of the electricity sector in China, we propose three policy implications based on the conclusions obtained above.

(1) According to the reform experiences in the UK and USA, a wholesale electricity market could potentially support the implementation of the economic dispatch mechanism. Although four years have passed since the start of the 2015 reform, market pilots are still slowly progressing in establishing wholesale electricity markets in China. Reforming the electricity system operation is a complex activity that involves political, economic, and engineering issues, and government leaders are cautious because they are worried about the consequences of reform failures. However, wholesale electricity markets should be established considering their important roles in electricity market reform. Moreover, in designing the electricity markets, it is good for China to combine the international experiences and the Chinese unique political and economic features.

(2) The current pricing regime of the Chinese electricity system must be reformed to be more cost reflective. Reforming the operation mechanism in the electricity system involves multiple stakeholders. Under the current regulatory and pricing regime, the implementation of economic dispatch will only result in income reallocations among different generation companies, and the contributions of other stakeholders will be neglected. Therefore, the pricing framework for Chinese electricity should be redesigned to ensure that the benefits from economic dispatch are well received by all relevant stakeholders. Moreover, the distributional impacts of economic dispatch on different stakeholders should be analysed, and relevant compensation mechanisms should also be established if necessary.

(3) Timely and transparent information disclosure about the power system

operation is not only important for increasing the system efficiency and fairness but necessary for the implementation of the economic dispatch scheme. In many developed countries, such as the UK, the USA and Australia, the information of power system operation is already accessible to the public. The Chinese government could help establish platforms to disclose information about the power system operation, thereby providing useful data for decision making by different stakeholders.

Although several important issues concerning economic dispatch implementation have been addressed in this study, some improvements could still be made in future studies. Since this study takes a supply side perspective to estimate the reform benefits, the impacts of demand side responses can be considered in future studies. Non-linear relationships could also be integrated into the economic dispatch model in the future, such as the relationships between heat rates and load factors. Additionally, a game theory model could be established to determine the best strategies for different stakeholders during the reform and provide guidance for policy design. These improvements could improve the economic dispatch implementation in the future electricity system.

APPENDIX A

A.1 Information of Electricity Generators

The generator numbers by region and type in China are shown in Table A1.

Table A1: Number of generators in 2014

Regional grid	Wind generators	Solar generators	Coal generators	Gas generators	Hydro generators	Nuclear generators
NCG	32865	304	754	111	61	0
NEG	11732	36	335	28	88	2
NWG	18264	997	338	35	501	0
ECG	5212	254	575	148	417	10
CCG	2066	67	463	51	1089	0
SCG	6102	70	338	66	1018	8
Sum	76241	1728	2803	439	3174	20

Notes: the numbers of solar generators are the number of power plants rather than the generation units.

The Economic dispatch model (MILP optimization model) was ran using the generator level data at first, but it was difficult for us to obtain the optimization results within an acceptable time length even we use high-performance computers, so we decided to establish a regional aggregated type simplified economic dispatch model, which aggregate generators to 'big generators' with consideration of both the computational efficiency and the accuracy within a region. Some empirical studies have also clustered generators in similar ways (Davidson and Pérez-Arriaga, 2018). The results of generator aggregation are shown in Table A2.

For the coal generators and gas generators, we used their heat rates and capacity sizes during the aggregation. Taking the coal generators as an example, they were first ranked according to their heat rates and then are clustered into 20 groups. Each group has approximately the same number of generators. Then, one large coal generator is then 'formed' from each group, whose heat rate is the capacity-weighted averages of those coal generators belonged to the group. The heat rates of all the coal generators are drawn from one of our previous study (Wei et al., 2018), while the heat rates of gas and nuclear generators are obtained from Zhang et al. (2012). For the other types of generators, we sum the total installed capacity of the generators. The details of the aggregated generators will not be shown here due to the space limitation, but is available upon reasonable request.

Table A2: Results of Generator Aggregation in 2014

Regional grid	Wind generators	Solar generators	Coal generators	Gas generators	Hydro generators	Nuclear generators
NCG	1	1	20	5	1	1
NEG	1	1	20	5	1	1
NWG	1	1	20	5	1	1
ECG	1	1	20	5	1	1
CCG	1	1	20	5	1	1
SCG	1	1	20	5	1	1
Sum	6	6	120	30	6	6

A.2 Hourly capacity factors of renewables

Electricity generation from renewable generators is dependent on the weather conditions. To estimate the hourly renewable generation in six regional grids, we calculated the hourly capacity factors for all the regional grids. The calculation process is described as below.

First, we obtained the hourly wind speed (at the height of 70m) and solar radiation data of all the capital cities in the regional grid from the 3TIER company. The hourly capacity factors of wind and solar were then calculated using the System Advisor Model (SAM) tool from the National Renewable

Energy Laboratory (NREL). Details of how to use the SAM tool can be referred to https://sam.nrel.gov/.Then, the regional grid's wind and solar capacity factors were calculated as the capacity-weighted values of all these cities located in the region. The wind and solar capacity factors of six regional grids are shown in Figure A1 and Figure A2 respectively.

Figure A1: Hourly Wind Capacity Factors in the Six Regional Grids

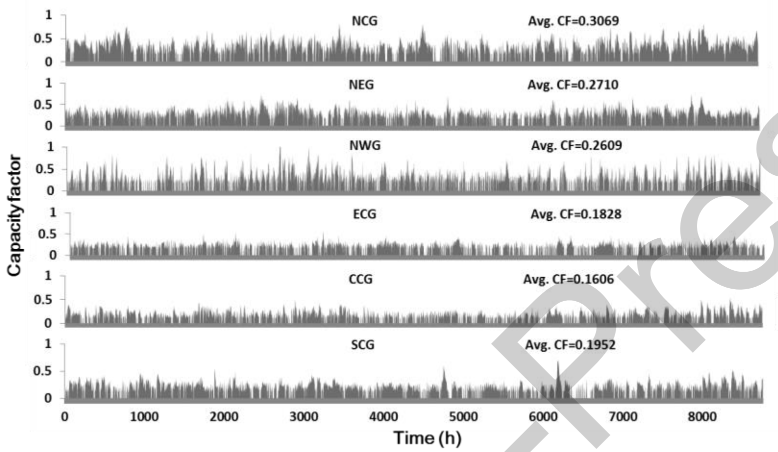
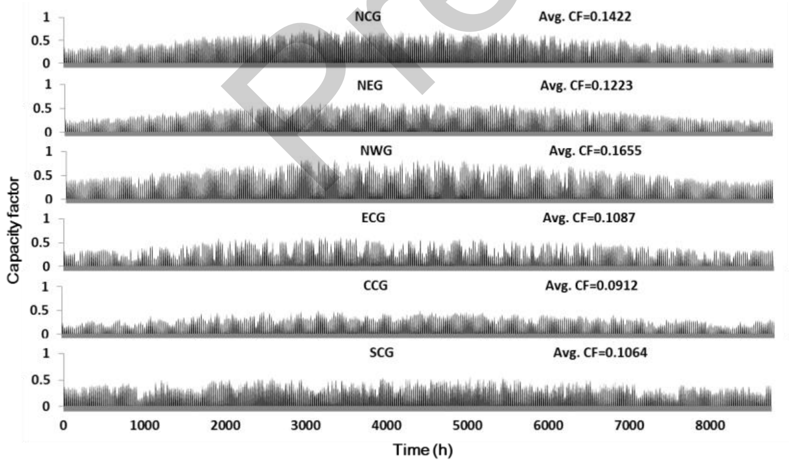
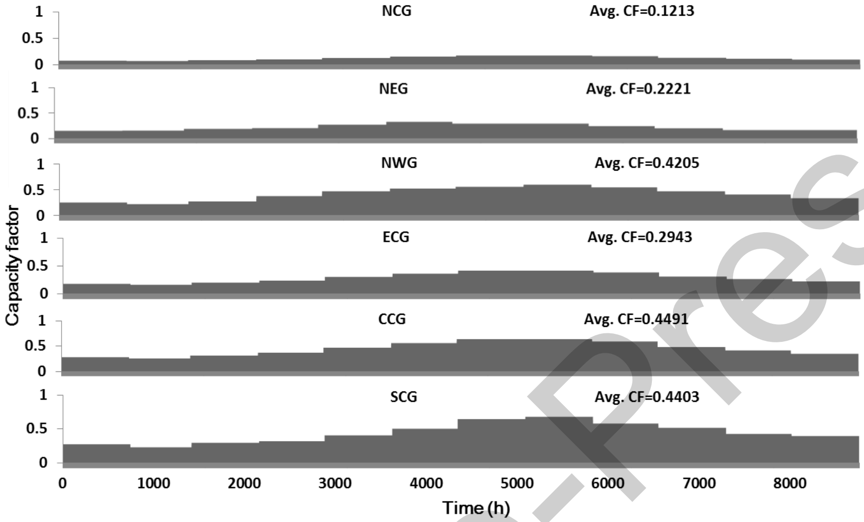


Figure A2: Hourly Solar Capacity Factors in the Six Regional Grids



The hourly capacity factors of hydropower in 2014 were taken from Davidson et al. (2016b) (see Figure A3).

Figure A3: Hourly Hydro Generation Capacity Factors in the Six Regional Grids

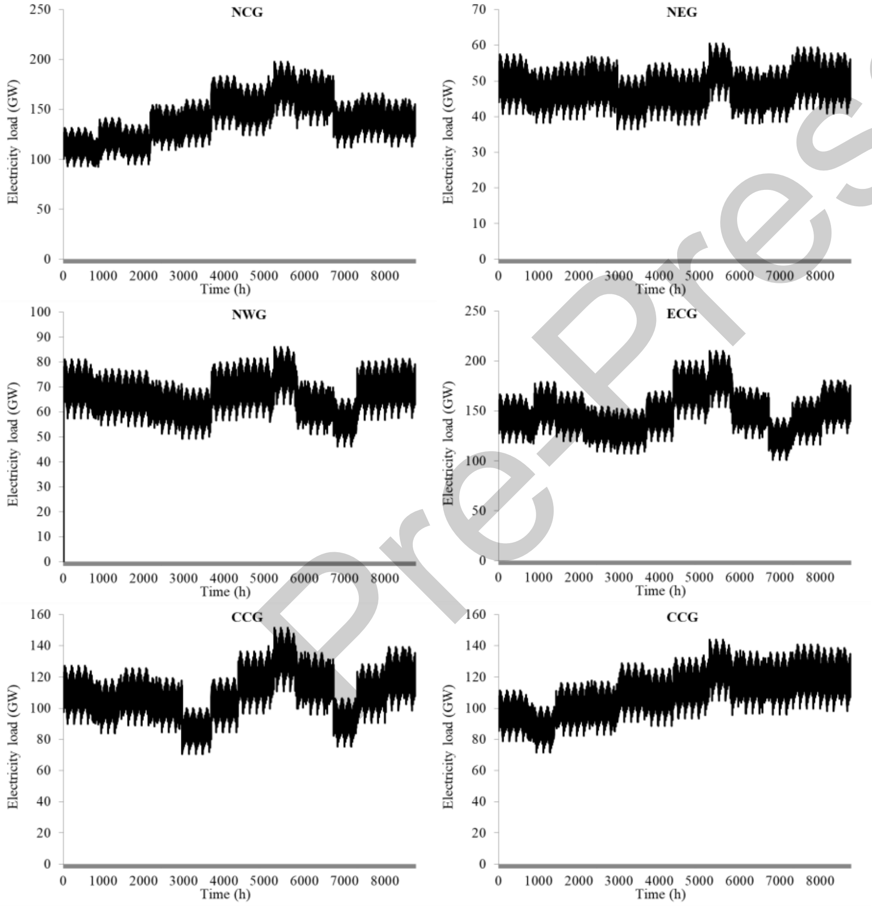


A.3 Hourly electricity load

The electricity loads in the six regional grids in China are shown in Figure A4. For every regional grid, the load curve of one inner province is selected to represent the regional load curve. As to NEG, the load curve of Liaoning province is used and its data is drawn from Liu et al.(2019). As to NCG, the load curve of Hebei province is used and its data is drawn from Wang et al.(2016). As to ECG, the load curve of Shanghai province is used and its data is drawn from Li et al. (2014). As to CCG, the load curve of Hunan province is used and its data is drawn from Cheng et al.(2012). As to SCG, the load curve of Yunnan province is used and its data is drawn from Zhang et al.(2014). As to NWG, the load curve of Shaanxi province is used and its data is drawn from Zhao et al.

(2008). Moreover, it is difficult to obtain all the regional load data of the same year (2014 in this study), so we use the regional load shapes in these studies and the actual total regional electricity consumption to work out the load curves in 2014. The method of using the load shapes to simulate the load curves can be referred to He et al. (2016).

Figure A4: Regional load curves in 2014



A.4 Interregional Electricity Transmission

The Interregional Electricity Transmissions between the six regions in 2014 are shown in Table A3.

Table A3: Interregional Electricity Transmission in 2014

Electricity Transmission (TWh)	Regional Grids	To					
		NEG	NCG	NWG	CCG	ECG	SCG
From	NEG	0	20.56	0	0	0	0
	NCG	0	0	0	9.25	18.83	0
	NWG	0	55.60	0	7.41	8.00	0
	CCG	0	0	14.92	0	96.29	14.33
	ECG	0	0	0	0	0	0
	SCG	0	0	0	0	8.00	0

A.5 Operation Cost of Electricity in 2014

The total power system operation cost is 2139.79 billion yuan, which is calculated based on the power operation results in 2014 (see table A4). The total operation cost consists of the generation cost and the interregional electricity transmission cost.

Table A4: The Actual Power Operation Results in 2014

Regional Grid	Coal generation (TWh)	Gas generation (TWh)	Hydro generation (TWh)	Nuclear generation (TWh)	Wind generation (TWh)	Solar generation (TWh)	Total generation (TWh)
NCG	1089.97	25.56	8.07	0.00	58.13	2.62	1184.35
NEG	373.21	2.70	14.70	12.00	38.81	1.12	442.54
NWG	482.79	4.42	100.60	0.00	34.34	16.84	638.99
ECG	964.82	57.50	66.90	66.40	12.79	2.06	1170.47
CCG	562.90	5.70	492.10	0.00	3.89	0.27	1064.86
SCG	477.00	37.43	377.09	54.90	11.87	0.59	958.88

The actual generation cost in 2014 is shown in Table A5. As to the calculation of fuel cost, the coal consumption and gas consumption are obtained from NBS (2015b), the Uranium consumption is calculated as the heat rates multiplying the nuclear generation. The regional coal prices are drawn from the Inner Mongolia Coal Exchange Center. The gas prices and Uranium prices are obtained from National Development and Reform Commission. The total O&M cost is the result of multiplying the regional electricity generation by the unit O&M cost. As to the carbon emission cost, the total carbon emissions are obtained from Shan et al. (2018),while the carbon emission price is set as 100 yuan/ton based on the prices in the pilot markets. The pollution cost is the result of multiplying the regional electricity generation by the unit pollution cost (caused by SO_2, NO_X, PM_x). The pollution cost of one kWh of different electricity generation is drawn from Streimikiene and Alisauskaite-Seskiene (2014) and Teng (2012). The Start-up/Shut-down cost is calculated as a result of multiplying the Start-up/Shut-down times by the average Start-up/Shut-down cost, the average Start-up/Shut-down cost is obtained from GE website and Davidson and Pérez-Arriaga (2018), and the Start-up/Shut-down times are drawn from the Ministry of Ecology and Environment of China.

Table A5: The Actual Generation Cost in 2014

Regional Grid	Fuel cost (Billion yuan)	OM cost (Billion yuan)	Carbon cost (Billion yuan)	External cost (Billion yuan)	Start-up cost (Billion yuan)	Total cost (Billion yuan)
NCG	218.33	24.42	122.28	185.79	1.07	551.89
NEG	79.00	12.12	54.84	63.24	0.36	209.56
NWG	78.78	15.96	49.59	82.12	0.41	226.86
ECG	247.69	21.31	94.81	169.96	1.27	535.03
CCG	137.55	18.13	60.79	96.68	0.68	313.84
SCG	134.35	19.78	49.59	86.79	0.67	291.18
Total	895.71	111.72	431.90	684.58	4.46	2128.37

The total electricity transmission cost is shown in Table A6. The transmission cost is calculated as a result of multiplying the total transmitted electricity by the unit cost.

Table A6: The Actual Electricity Transmission Cost in 2014

Electricity transmission (TWh)	Cost （yuan/kWh）	Total cost (Billion yuan)
253.19	0.0451	11.42

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