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A multi-regional modelling and optimization approach to China's power generation and transmission planning

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ABSTRACT

Power demand in China has increased rapidly in the past decade, and it is projected to grow even further. To gain insights into how this demand growth could optimally be met, addressing regional differences such as resource distribution and power demand, is crucial. For long-term planning purposes, using a multi-regional mathematical model that divides China's power sector into regions overcomes the limitations of viewing as a single network. Reflecting how inter-regional power transmission could best be utilized is critical in understanding how flows between regions could be optimised. In this paper, a multi-regional model that reflects actual grid infrastructure with an objective function to maximize accumulated total profits gained by the power generation sector from 2013 to 2050 is proposed. A case study is provided to illustrate how inter-regional power transmission could influence the regional deployment of technologies under different policy scenarios. The results show that energy subsidies and national targets will remain important to the deployment of renewable energy in both the short and long term. In addition, potential downside implications of lower demand growth on the long-term prospects of long-distance inter-regional power transmission and options, such as more flexible electricity pricing mechanisms, to limit the effects are discussed.

1. Introduction

Alongside its rapid economic growth, power demand in China has increased sharply from 1347.3 TWh in 2000 to 5342.3 TWh in 2013 [1], and it is expected to further increase in the future [2]. Large and varied coal, natural gas, nuclear power, hydropower, and renewable generation options make determining optimal planning pathways challenging. Options for high voltage transmission to link resource-rich regions to regions with large energy demand adds further complexity when considering a territory as large as China with its uneven geographical distribution of energy resources and demand [3].

Existing studies that analyse development pathways for China's power sector can generally be divided into two groups - those that treat the whole country as a single entity, and those that consider regional variations. In studies following the “single entity” approach, they generally adopt “bottom-up” models such as the Long-range Energy Alternatives Planning System (LEAP) in which the development of China's power sector under various policy scenarios are analyzed [4], and the Integrated Policy Assessment Model developed by the Energy Research Institute of the National Development and Reform Commission (NDRC) of China that assesses China's power sector under three demand scenarios [2]. In addition to the bottom-up models, Zhu et al. apply the portfolio theory to the optimization of China's power sector under three scenarios [5]. Chen et al. adopt scenario analysis to discuss roadmaps for China's future carbon reduction pathways by using the power mix planning model which minimizes total system costs [6]. Zhang et al. developed an optimization model for China's power sector aiming at minimizing total system costs whilst considering carbon markets and Carbon Capture and Storage (CCS) technologies [7]. This work demonstrates two carbon emissions mitigation scenarios and the contributions of different technologies to carbon mitigation in each scenario by 2050. However, these studies do not consider regional differences such as demand variations and natural resource distribution, quality and cost, and thus have limited application in analyzing regional power development challenges.

For studies reflecting regional differences, Gnansounou and Dong's work discusses integrating power markets in Shanghai and

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Shandong by enabling power transmission to minimize total system costs [8]. Wang et al. divide China into coastal and inland areas to consider their regional differences in energy independence [9]. It discusses the effects of environmental policies on the development of clean coal technologies. However, simply dividing China into two macro regions limits the extent to which regional characteristics can be reflected in detail and overlooks the complexity of China's power sector.

In our previous work, Cheng et al. built a multi-regional model and divided China into ten regions according to physical grid infrastructure. The model minimizes total system costs and considers regional demand and resource differentials and neighbouring-region power transmission interconnections. The results highlight the importance of inter-region transmission to the balance of regional power demand and supply and the better utilization of natural resources [10]. Nevertheless, this work does not consider inter-regional transmission capacity and long-distance cross-region transmission, which is an important factor in connecting the resource-rich west areas to the load-centred east areas of China. Although studies for India [11] and Greece [12] take inter-regional electricity transmission capacity into account, electricity markets and policies in these countries are quite different from China. Thus, in order to give an insight into the long-term development of China's power sector, this paper presents a grid-structure based multi-region modelling. Based on our previous single-regional model (Zhang et al.'s work) and the subsequent multi-regional model (Cheng et al.'s work), this grid-structure based, multi-regional model includes existing and proposed transmission lines and incorporates nationwide energy subsidy policies. An important departure for this model is its requirement to maximize total profits generated by power generators in order to try to give insights into the impacts of China's electricity market mechanism on installed generating capacity and power transmission.

This paper is organized as follows:

Section 2 explains the methodology and key assumptions used in this study.

Section 3 provides a case study based on regional specific assumptions.

Section 4 concludes the main findings and proposes optimal pathways for capacity expansion and power transmission.

2. Methodology

2.1. Model structures and assumptions

2.1.1. Power transmission

Power transmission has always been an important issue in meeting China's regional power demand and better allocating natural resources, especially from the west to the east, or from the resource-rich regions to the load-centred regions. In this work, we focus on the division of China's grid in this model based on the physical infrastructure, both existing and planned power transmission lines, and varying regional characteristics.

After years of development, nine main regional power grids in the main land of China are formed as follows: Northeast, North, Central, East, South, Northwest, Xinjiang, Tibet and Hainan [13]. Amongst these grids, Tibet and Hainan grids are relatively independents and their demand loads are almost negligible compared to the others. Consequently they are not considered in this model. International transmission is also neglected due to its relatively small amount compared to domestic power demand [14].

Recently, the rapid construction of large capacity high voltage transmission lines has accelerated the development of China's grid. As listed in Table 1, Extra-High Voltage (EHV) and Ultra-High Voltage (UHV) transmission lines have been extensively constructed from 2000. These power transmission facilities aim to unlock hydropower and coal reserves in the west, and transmitting them to the east where the major demand centres are located. In order to reflect power transmission and resource endowment, we divide China into eight areas as shown in Fig. 1. In areas with rich hydroelectric resources, hydropower exporting largely relies on the transmission lines i.e. Sichuan (line No.14, 15, 17), Hubei (line No.1,3,6) and Yunan (line No.18,19) provinces. For regions with abundant coal reserves, such as Xinjiang, Northwest region and Inner Mongolia, more coal power plants have been constructed accompanying the development of the grid in order to deliver electricity from these areas of low fuel costs.

According to the plans released by the State Grid Corporation of China (SGCC) [15] and announced by the government [16], as listed in Table 2, eighteen UHV lines have been proposed and lines No.1–3 are under construction. As shown in Fig. 2, the eighteen lines are denoted by dashed lines with black and blue colours indicating UHV DC and AC lines, respectively. The UHV DC lines are for long-distance power transmission, enabling abundant coal resource in Inner Mongolia and northwest areas as well as rich hydroelectric power in Yunnan and Sichuan to be accessed. On the other hand, the UHV AC lines link the North, East and Central regions provide better inter-regional power transmission capacity. These proposed lines further certify the importance of power transmission to future power generation and supply, and thus this model considers the optimal development of transmission facilities and inter-regional power transmission to closely reflect the real-world actual situations.

As discussed above, the development of power transmission facilities will have great impacts on China's power generation and supply. Thus, to reflect regional differences in power demand, resource endowment and transmission facilities, China is divided into 17 areas according to these characteristics, as shown in Table 3 and Fig. 3. These characteristics are summarized from the Twelfth Five-year Plan for Energy Development [17], in which coal, hydropower, wind and solar energy bases are defined.

2.1.2. Power generation

Seven types of power generation technologies with great developing potentials [17] are included in the model. They are Subcritical and Super-critical Pulverized Coal (SPC) representing most of the existing coal-fired power plants in China, Ultra-Supercritical Pulverized Coal (UPC), Natural Gas Combined Cycle (NGCC), Nuclear (NU), Hydropower (HD), Wind Power (WD) and solar Photovoltaic (PV). In China, the electricity market is highly regulated and on-grid prices for different forms of power generation are fixed for each region. In line with the on-grid pricing mechanism, these technologies are divided into two groups. The first group includes SPC, UPC, NGCC and HD, whose on-grid prices are regulated at all times. The second category includes NU, WD and PV, whose on-grid prices are either a strike price or a feed-in tariff determined by the time when the plant is put into operation. Amongst these technologies, only SPC plants are allowed to retire earlier than its expected lifespan considering its relatively low efficiency compared to UPC. The other technologies are assumed to operate for their entire expected lifespan. In addition, the model considers the clean energy targets announced by the government [18] that installed capacity of nuclear, hydropower, wind and solar will reach 58 GW, 350 GW, 200 GW and 100 GW by 2020, respectively. Furthermore, it is assumed that no nuclear power plants will be deployed in the resource-rich areas stated before.

The model optimizes future investment trends mainly on an economic basis from the power generation sector only. Transmission costs are excluded from the total system costs since they are borne by the grid companies in China.

Table 1
Completed EHV and UHV transmission lines in China (Data collected from the State Grid Corporation of China (SGCC) [15]).

No.	Name (Pathway)	Operation year	Category	Voltage(kV)	Length(km)	Capacity(MW)	Linked regions
1	Gezhou Dam - Shanghai	1990	EHV DC	±500	1045	3000	Central-East
2	Tianshengqiao - Guangzhou	2001	EHV DC	±500	960	1800	South
3	Three Gorges - Changzhou	2003	EHV DC	±500	860	3000	Central-East
4	Guizhou - Guangdong	2004	EHV DC	±500	882	3000	South
5	Three Gorges - Guangdong	2004	EHV DC	±500	960	3000	Central-South
6	Three Gorges - Shanghai	2006	EHV DC	±500	1040	3000	Central-East
7	Guizhou - Shenzhen	2007.12	EHV DC	±500	1194	3000	South
8	Baoji - Deyang	2009.12	EHV DC	±500	534	3000	Northwest-Central
9	Hulunbeir - Liaoning	2010.9	EHV DC	±500	908	3000	InnerM.-Northeast
10	Ningdong - Shandong	2011.2	EHV DC	±660	1335	4000	Northwest-North
11	Zhejiang north - Fuzhou	2015.3	UHV AC	1000	596	6000	East
12	Jin southeast - Jingmen	2008.12	UHV AC	1000	654	6000	North-Central
13	Wan - Shanghai	2013.9	UHV AC	1000	656	21,000	East
14	Xiangjia Dam - Shanghai	2010.7	UHV DC	±800	1892	6400	Central-East
15	Jinping - Suzhou south	2012.12	UHV DC	±800	2100	7200	Central-East
16	Hami south - Zhengzhou	2014.1	UHV DC	±800	2192	8000	Northwest-Central
17	Xiluodu Dam to Zhejiang	2014.7	UHV DC	±800	1653	8000	Central-East
18	Yunnan to Guangdong	2009.12	UHV DC	±800	1413	5000	South
19	Nuozhadu Dam to Guangdong	2013.9	UHV DC	±800	1413	5000	South
20	Lingbao	2005	Back to Back DC Converter			1110	Northwest-Central
21	Liaoning Gaoling	2012.11	Back to Back DC Converter			3000	Northeast-North

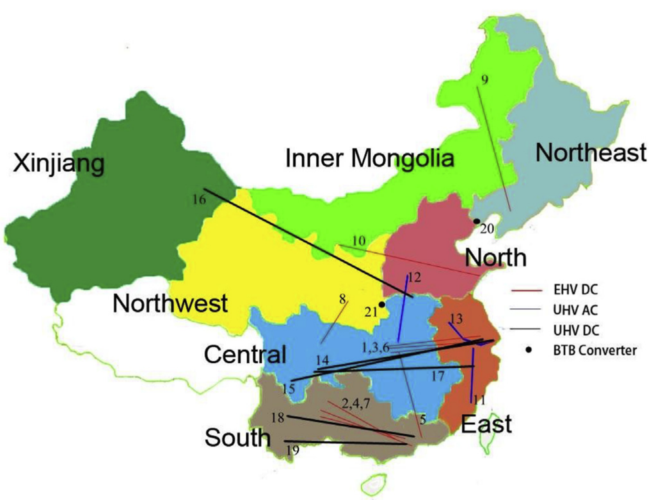

Fig. 1. Completed EHV and UHV transmission lines in China.

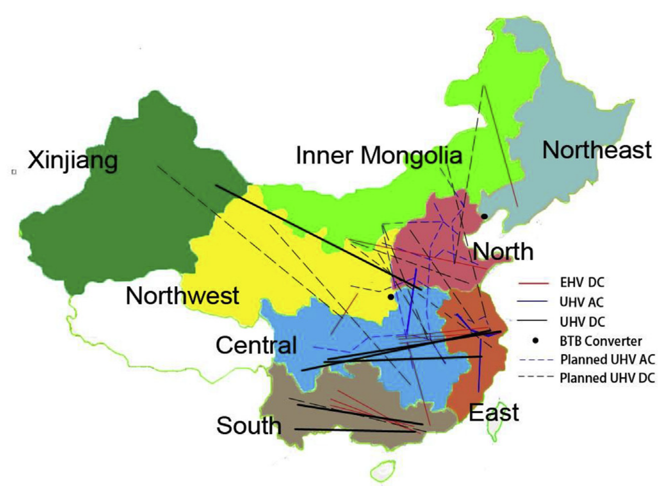

Fig. 2. Planned and under-construction UHV lines by 2020.

Table 2
Planned and under-construction UHV lines (Note:data with a symbol of "~" are currently unavailable and estimated based on our best efforts. Line numbers with a symbol of "*" are included in the government's plan.).

No.	Name (Pathway)	Expected year	Category	Voltage(kV)	Length(km)	Power(MW)	Linked regions
*1	Huai south - Shanghai	2016.12	UHV AC	1000	779.5	12,000	East
2	Xilingele - Shandong	2017	UHV AC	1000	730	9000	InnerM.-North
3	Ningdong - Shaoxing	2016	UHV DC	±800	1720	8000	Northwest-East
4	Ya'an - Wuhan	2020	UHV AC	1000	1294.9	2 × 6000	Central
5	InnerM. West - Changsha	2020	UHV AC	~1000		15,000	North-Central
6	Zhangbei - Nanchang	2020	UHV AC	~1000		~15,000	North-Central
7	Longshan - Yu north	2020	UHV AC	~1000		~15,000	Northwest-North-Central
*8	Yuhuang - Huaifang	2017	UHV AC	~1000	1093	~12,000	Northwest-North
9	Jiuquan - Hunan	2020	UHV DC	±800		8000	Northwest-Central
10	Hulunbeir - Shandong	2020	UHV DC	~±800		~10,000	InnerM.-North
11	InnerM. west - Hubei	2020	UHV DC	±800		~10,000	North-Central
12	Shaanxi north - Jiangxi	2020	UHV DC	±800		~10,000	Northwest-Central
*13	Huai east - Sichuan	2020	UHV DC	±1100		~10,000	Northwest-Central
*14	InnerM. - Shandong	2020	UHV DC	±800		10,000	InnerM.-North
*15	Shanxi - Jiangsu	2017	UHV DC	±800		~10,000	North-East
*16	Xilingele - Jiangsu	2017	UHV DC	±800		~10,000	InnerM.-East
*17	InnerM. West - Tianjin	2017	UHV DC	~±800		~10,000	InnerM.-North
*18	Yunan- Guangdong	2017	UHV DC	±800		5000	South

Table 3
Seventeen areas considered in the model.

Areas	Included provinces	Characteristics
1	Inner Mongolia	Rich in coal, wind and solar
2	Xinjiang	Rich in coal, wind and solar
3	Ningxia	Rich in coal
4	Shanxi	Rich in coal
5	Sichuan and Chongqing	Rich in hydropower
6	Hubei	Rich in hydropower
7	Heilongjiang, Jilin and Liaoning (Northeast area)	Rich in wind
8	Beijing, Tianjin and Hebei	Load centred
9	Shandong	Load centred
10	Shaanxi, Gansu and Qinghai (Northwest area)	Rich in wind and solar
11	Henan	Transmission lines crossing
12	Jiangxi and Hunan	Not mentioned in the Plan
13	Shanghai, Jiangsu, Zhejiang, Anhui and Fujian (East area)	Load centred
14	Yunnan	Rich in hydropower and solar
15	Guizhou	Rich in coal
16	Guangxi	Not mentioned in the Plan
17	Guangdong	Load centred

2.2. Mathematical formulation

This section mainly describes the mathematical equations in the model. Firstly, the objective function and its relative equations are explained. Secondly, physical constraints such as resource and transmission capacity are presented. Four sets, t, r, g and f, stand for time, region, power generation type and fuel type, respectively. Meanwhile, t and t' (or t''), r and r' (or r'') share the same set in the equations. Physical meanings of parameters and variables in the model are shown in Appendix A to provide more detail.

2.2.1. Objective function

The objective function of this model is to maximize accumulated total profits gained by the power generation sector from 2013 to 2050. As expressed in Equation (1), profit equals revenue minus cost. Regional profits are totted up and discounted to the base year of 2012.

$$atc = \sum_{t=2013}^{2050} \frac{\sum_r (rreve_{t,r} - rc_{t,r})}{(1+I)^{(t-2012)}} \tag{1}$$

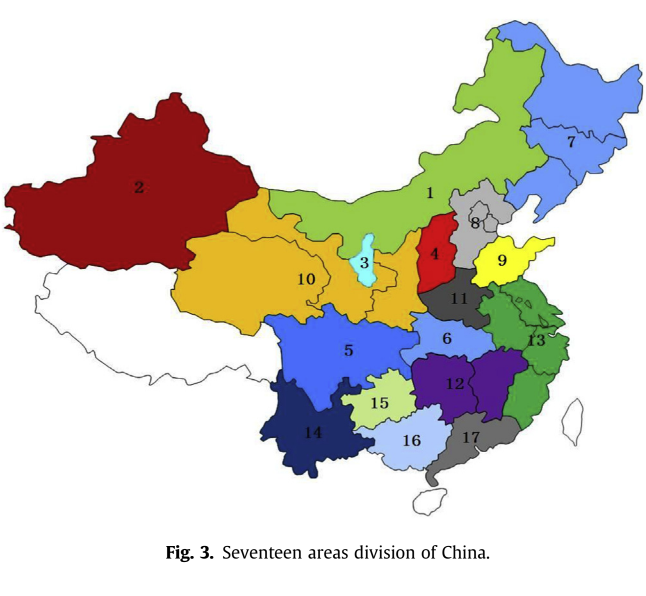

Fig. 3. Seventeen areas division of China.

2.2.1.1. Regional revenues.

Regional revenues depend on on-grid prices and feed-in tariffs. For the first groups of technologies, whose on-grid prices are regulated by the government at any time, revenues can be calculated by Equation (2). For the second group, their feed-in tariffs are decided by the time when new capacity is taken into operation and the revenue is expressed in Equation (3).

$$rreve_{t,r} = \sum_g (ic_{g,t,r} \cdot OH_{g,t,r} \cdot OGP_{g,t,r}) \tag{2}$$

$$rreve_{t,r} = \sum_g \left(\sum_{t'=t-TLT_g+1}^{t} \left(nbc_{g,t',r} \cdot OH_{g,t,r} \cdot OGP_{g,t',r} \right) \right) \tag{3}$$

2.2.1.2. Regional costs.

Regional costs can be categorized into three parts: capital cost, operation and maintenance (O&M) cost, and fuel cost. Capital cost is the levelized annual investment of the construction cost for each type of power plant. Operation and maintenance costs are associated with the maintenance and repair of equipment and labor costs. Fuel costs arise from the consumption of fossil fuels for thermal plants or uranium for nuclear power. The equation for calculating regional costs in region r in year t is shown in Equation (4). The calculation of the three parts of the costs refers to a previous study [19] and is explained in Appendix B.

$$rc_{t,r} = \sum_g (inv_{g,t,r} + om_{g,t,r} + fc_{g,t,r}) \tag{4}$$

Notably, due to the assumption that SPC plants could be retired early before its lifespan, its capital investment should be split into its working years as expressed in Equation (5).

$$inv_{g,t,r} = \sum_{t'=t-TLT_g+1}^{t} \left(\sum_{t''=t+1}^{t'+TLT_g-1} \left(CAP_{g,t'} \cdot er_{g,t',r}^{t''} \cdot \frac{I\cdot(1+I)^{-1}}{1-(1+I)^{-(t''-t')}} \right) + CAP_{g,t'} \cdot \left(nbc_{g,t',r} - \sum_{t''=t+1}^{t'+TLT_g-1} er_{g,t',r}^{t''} \right) \cdot \frac{I\cdot(1+I)^{-1}}{1-(1+I)^{-TLT_g}} \right) \tag{5}$$

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2.2.2. Physical constraints

2.2.2.1. Power demand and supply. Regional power demand can be met either by its own regional generation or by inter-regional transmission imports, as written in Equation (6).

$$PD_{t,r} = \sum_{g} pg_{g,t,r} + ttr_{t,r} = \sum_{g} ic_{g,t,r} \cdot OH_{g,t,r} + ttr_{t,r} \tag{6}$$

2.2.2.2. Power transmission. Total power transmission in region r equals power transmitted out from r to r' (negative value for $itr_{t,r,r'}$) plus power transmitted in from r'' to r (positive value for $itr_{t,r,r''}$ and transmission losses are included) as shown in Equation (7). Ideal transmission power from r' tor equals the negative value of that from r' to r as expressed in Equation (8). Inter-regional transmission is limited by transmission capacity as shown in Equation (9). In addition, annual change in transmission utilization is set to be within 20% of its capacity as shown in Equation (10). The assumption of the transmission utilization change limit is based on our analyses of an UHV transmission line during a 5-year operating period, the Xiangjia Dam - Shanghai (line No.14 in Table 1), and its capacity and operating data are acquired from the SGCC [15] and public news.

$$ttr_{t,r} = \sum_{r',r''\neq r} \left[itr_{t,r,r'} + \left(1 - TRLOSS_{r,r'}\right) \times itr_{t,r,r''}\right] \tag{7}$$

$$itr_{t,r,r'} = -itr_{t,r',r} \tag{8}$$

$$itr_{t,r,r'} \leq TRLIMIT_{t,r,r'} \tag{9}$$

$$\left|itr_{t+1,r,r'} - itr_{t,r,r'}\right| \leq 20\% \cdot TRLIMIT_{t,r,r'} \tag{10}$$

2.2.2.3. Installed capacity. This model assumes that all types of technologies except for SPC will decommission at the end of their lifespan. Thus installed capacity of the six technologies excluding SPC in region r in year t can be expressed as Equation (11).

$$ic_{g,t,r} = \sum_{t'=t-TLT_g+1}^{t} nbc_{g,t',r} \tag{11}$$

SPC plants are assumed to be able to retire earlier than its expected life in the model, thus its installed capacity in year t should deduct all early retired capacity as shown in Equations (12)–(14).

$$ic_{g,t,r} = \sum_{t'=t-TLT_g+1}^{t} nbc_{g,t',r} - \sum_{t'=t-TLT_g+1}^{t} \sum_{t''=t'+1}^{t} er_{g,t',r}^{t''} \tag{12}$$

$$nbc_{g,t',r} = er_{g,t',r}^{t'+1} + rm_{g,t',r}^{t'+1} \tag{13}$$

$$rm_{g,t',r}^{t''} = er_{g,t',r}^{t''+1} + rm_{g,t',r}^{t''+1} \tag{14}$$

2.2.2.4. Other constraints. Other constraining inequalities such as regional maximum renewable capacity, annual construction limits for technologies and fuel supply refer to the previous study and are shown in Appendix B.

2.3. Key parameters and assumptions

2.3.1. Costs and lifespan for technologies

The costs and lifespan mainly refer to OECD's report [20], in which data for some specific power plants in China are listed. Capital cost, expecting decreasing rate, O&M costs and expected life span are listed in Table 4.

2.3.2. Fuel costs

Regional fuel costs take the prices in April 2015 [21] as the reference and coal prices are converted into standard coal equivalent (7000 kcal/kg) based on heating values (as listed in Table 5). Uranium price is set to be 800 RMB/kg (around $125/kg at the end of 2012 [22]).

2.3.3. On-grid prices and feed-in tariffs

Regional on-grid prices for coal plants are regulated by the National Development and Reform Commission (NDRC) [23] and published by local Development and Reform Commissions. On-grid prices for gas plants are limited with an addition compared to local coal on-grid prices [24]. On-grid price for hydropower takes the average of prices of several hydro stations. Feed-in tariffs for Wind [25] and PV [26] refer to governmental policies. A strike price for nuclear was announced by NDRC in 2013 [27]. In addition, the feed-in tariffs for Wind and PV were planned to cease by 2020 and 2030, respectively [28]. Details are listed in Table 6.

2.3.4. Assumptions for economical parameters

Owing to the overcapacity issue of China's coal industry and shrinking growth of coal demand, coal price is expected to remain at a relatively low level. Referring to Chen et al.'s work [6], the model assumes that the fuel prices for coal and gas stated above are set to remain flat through to 2050. On-gird prices for coal-fired plants, gas plants, nuclear and hydropower will remain stable. On-gird prices for Wind and PV will decline gradually to local coal on-grid prices by 2020 and 2030, respectively, referring to the policies. Discount rate is assumed to be at 7%.

2.3.5. Installed capacity

Existing capacity for technologies are based on statistic books released by China Electricity Council [29] and China electricity year books from 2010 to 2013 [30–33].

2.3.6. Operating hours

Operating hours mainly refer to regulation report [34] and that of Wind and PV is taken from Huber and Weissbart's study [35] as listed in Table 7. UPC plants will become base load and its operating hours are assumed to gradually increase to 6000 h by 2020. Owing to the overcapacity of SPC plants and the development of wind and PV, nationwide operating hours of SPC have dropped in recent years. However, with the ease of overcapacity and improvement of power transmission and distribution management, regional SPC operating hours are expected to increase in the medium and long term. Thus we assume that operating hours of SPC plants in Area 1, 2, 7 and 10 will decline by 10% by 2020 due to the development of renewable and then increase to 5000 h by 2030. Operating hours of SPC plants in Area 3, 8, 13 and 17 will keep at their current high levels due to high demand and that of SPC in other areas will gradually increase to 5000 h by 2030 owing to better management. Operating hours of the other technologies are assumed to remain constant.

2.3.7. Power demand

Power demand refers to studies [2] as well as regional historical growth rates [1]. Projected power demand for the regions is listed in Table 8.

Table 4
Costs and lifespan for technologies. (Note: Lifespan for UPC is longer than SPC mainly considering that existing UPC plants were built within the last decade.)

Technologies	Capital costs (million RMB/MW)	Decreasing rate of capital costs per annum	O&M costs as a percentage of capital costs	Expected lifespan (year)
SPC	4.3	0.2%	1.8%	40
UPC	4.7	0.5%	1.8%	45
NGCC	3.8	1.0%	3.7%	30
NU	17.0	0.0%	2.7%	60
HD	6.0	−0.1%	0.9%	70
WD	7.9	3.0%	2.9%	25
PV	17.6	5.0%	1.0%	25

Table 5
Regional fuel costs.

Areas	Coal (RMB/t)	Gas (RMB/m^3)
1	259	2.0
2	210	2.1
3	283	2.6
4	407	3.6
5	574	3.3
6	574	3.4
7	773	4.1
8	455	3.7
9	602	4.1
10	364	2.2
11	568	3.2
12	763	3.7
13	686	4.3
14	805	3.7
15	588	4.0
16	643	4.2
17	681	4.9

Table 6
Regional on-grid prices and feed-in tariffs for technologies (Unit: RMB/MWh. Note: these data were acquired in April 2015.).

Areas	SPC and UPC	NGCC	NU	HD	WD	PV
1	305	655	430	340	490	900
2	262	612	430	340	490	900
3	279	629	430	340	560	900
4	377	727	430	340	610	950
5	450	800	430	340	610	950
6	459	809	430	340	610	1000
7	404	754	430	340	560	950
8	412	762	430	340	520	950
9	440	790	430	340	610	1000
10	359	709	430	340	520	900
11	419	769	430	340	610	1000
12	479	829	430	340	610	1000
13	442	792	430	340	610	1000
14	373	723	430	340	610	950
15	381	731	430	340	610	1000
16	457	807	430	340	610	1000
17	502	852	430	340	610	1000

2.3.8. Transmission limits

Transmission limits mainly consider the transmission lines discussed before with an estimation of current inter-regional transmission capacity. Annual equivalent working hours for the grid are set to be 5000 h [36]. Inter-regional transmission capacity by 2020 is shown in Table 9.

2.3.9. Transmission losses

Transmission losses are calculated based on distance and characteristics of UHV lines [36] as listed in Table 10.

2.3.10. Capacity limits for renewable energy

Renewable resource endowment largely depends on regions. According to studies [10,37], upper limits for renewable energy among areas are listed in Table 11.

Table 7
Annual operating hours for technologies in the model in 2013. (Unit: hours. Note: regional operating hours for Wind and PV take the average of its component provincial data in the study.)

Areas	SPC	UPC	NGCC	NU	HD	WD	PV
1	5032	5032	2937	7822	2685	1628	1173
2	4422	4422	2937	7822	4281	1063	1158
3	5805	5805	2937	7822	4419	1009	1152
4	4897	4897	2937	7822	1811	1129	1122
5	4150	4150	2937	7822	3836	842	1026
6	3970	3970	2937	7822	4076	624	990
7	4207	4207	2937	7822	1985	1468	1079
8	5317	5317	2937	7822	611	1229	1157
9	4754	4754	2937	7822	111	1457	1125
10	4828	4828	2937	7822	4253	1085	1097
11	4650	4650	2937	7822	2403	837	1077
12	4031	4031	2937	7822	3369	715	1026
13	5350	5350	2937	7822	2878	1404	1056
14	3466	3466	2937	7822	3751	600	1265
15	4785	4785	2937	7822	3241	783	1089
16	4339	4339	2937	7822	3434	937	1145
17	5150	5150	2937	7822	2289	1072	1095

2.3.11. Construction capacity

Based on international and domestic experiences [38], annual construction limits for technologies are listed in Table 12.

2.3.12. Fuel consumption rates

Fuel consumption rates based on statistic yearbooks [39] and reports [22] are assumed to decrease over years for thermal plants as shown in Table 13.

2.3.13. Fuel supply

Fuel supply limits refer to historical supply capacity [39] and studies [7,22] as listed in Table 14.

3. Results and discussions

The Linear Programming Solver of the General Algebraic Modelling System (GAMS, GAMS Development Corporation, Washington, DC, USA) was used in this paper for modelling and optimization. A case study was provided and its results were shown and discussed as follows.

3.1. Overall developing trends and profits of the power generation sector

Nationwide installed capacity of technologies is shown Fig. 4. As we can see, existing sub-critical and super-critical coal plants will gradually retire and be replaced, especially after 2040. By contrast, ultra-super-critical coal plants will expand rapidly through to 2050 owing to its better economic performances. NGCC will experience a

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Table 8
Projected power demand for regions (Unit: PWh).

Areas	2013	2020	2030	2040	2050
1	0.211	0.291	0.417	0.554	0.684
2	0.113	0.141	0.181	0.221	0.256
3	0.077	0.098	0.129	0.160	0.188
4	0.181	0.218	0.269	0.316	0.357
5	0.262	0.309	0.372	0.432	0.481
6	0.154	0.183	0.221	0.256	0.285
7	0.342	0.387	0.445	0.495	0.536
8	0.480	0.578	0.710	0.837	0.943
9	0.391	0.481	0.607	0.730	0.836
10	0.274	0.332	0.413	0.491	0.556
11	0.283	0.348	0.439	0.527	0.603
12	0.227	0.276	0.343	0.407	0.462
13	1.246	1.547	1.971	2.386	2.746
14	0.136	0.171	0.220	0.269	0.312
15	0.107	0.129	0.159	0.187	0.211
16	0.119	0.145	0.181	0.217	0.247
17	0.475	0.576	0.715	0.849	0.962

Table 11
Regional upper limits for renewable energy (Unit: GW).

Areas	HD	WD	PV
1	2.6	382.0	85.9
2	15.7	137.7	130.9
3	1.5	2.5	5.8
4	4.0	2.3	13.3
5	111.5	0.2	55.2
6	35.4	0.3	18.6
7	14.1	60.0	63.6
8	2.8	24.0	18.9
9	1.1	4.4	12.6
10	31.0	90.9	119.7
11	2.7	0.2	14.9
12	17.6	1.3	37.6
13	25.2	7.4	46.7
14	98.0	2.2	39.4
15	19.0	0.6	23.7
16	18.6	0.1	23.7
17	13.0	2.6	20.1

Table 9
Interregional transmission limits by 2020 (Unit: PWh. Note: The first row is exporting areas and the first column is importing areas).

Areas	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
4	0.135	–	–	–	–	–	–	–	–	0.060	–	–	–	–	–	–	–
5	–	0.040	–	–	–	–	–	–	–	0.021	–	–	–	–	–	–	–
6	0.040	–	–	–	0.071	–	–	–	–	–	0.135	–	–	–	–	–	–
7	0.045	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
8	0.165	–	–	0.122	–	–	0.015	–	–	0.060	–	–	–	–	–	–	–
9	0.090	–	0.020	–	–	–	–	0.124	–	–	–	–	–	–	–	–	–
10	–	0.035	0.021	–	–	–	–	–	–	–	–	–	–	–	–	–	–
11	–	0.040	–	0.135	–	–	–	0.060	–	–	–	–	–	–	–	–	–
12	–	–	–	–	–	0.103	–	–	–	0.080	–	–	–	–	0.015	–	–
13	0.040	–	0.040	0.040	0.108	0.045	–	–	–	–	–	–	–	–	–	–	–
14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
15	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
16	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
17	–	–	–	–	–	0.015	–	–	–	–	–	–	–	0.075	0.030	0.009	–

Table 10
Interregional transmission losses.

Areas	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2																	
3																	
4	1.05%									1.20%							
5		7.20%								3.00%							
6	5.18%				3.00%						1.35%						
7	3.25%																
8	1.20%			1.00%			1.50%			1.20%							
9	2.93%		4.28%					0.75%									
10		7.20%	1.75%														
11		8.55%		1.05%				1.05%									
12						0.90%				5.40%					3.00%		
13	6.08%		7.20%	4.95%	7.20%	4.28%											
14																	
15																	
16																	
17						3.83%								5.63%	3.60%	3.60%	

rather slow developing trend and take a low share in the future. Nuclear power will develop continuously, keeping a high pace of 10 GW/a. As an option for clean and relatively cheap energy, hydropower will be fully exploited, reaching its maximum capacity in an early stage. Wind and PV have a similar developing pattern. They

Table 12
Annual construction limits for technologies (Unit: GW).

Technologies	SPC	UPC	NGCC	NU	HD	WD	PV
Limits	90	45	45	10	30	25	20

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Table 13
Fuel consumption rates for technologies.

Technologies	Fuel types	2013	2030	2050
SPC	Coal: g/kWh	320	301	280
UPC	Coal: g/kWh	279	270	260
NGCC	Gas: m^3/kWh	0.17	0.16	0.15
NU	Uranium: g/kWh	0.021	0.021	0.021

Table 14
Annual fuel supply limits.

Fuel types	Coal(Gt)	Gas(Tm^3)	Uranium(kt)
Limits	3	0.5	70

will be deployed in a large scale to meet the nation target by 2020. However, due to insufficient subsidies, their capacity will begin to shrink rapidly after 2035.

By comparing the results with actual installed capacity data in 2014 [1], several findings can be concluded. In terms of thermal plants, total installed capacity would decline from 820 GW in 2012 to 789 GW in 2014 in the model owing to the fast development of clean energy. On the contrary, actual total capacity of thermal plants further increased to 923 GW in 2014. Consequently, even lower operating hours and aggravating over-capacity issue for coal-fired plants were reported by the government, and approaches to ease the situation were announced such as the prohibition of constructing new coal-fired plants in many regions. On the other hand, installed capacity of renewable energy in actual situations was even slightly more than the results in the model. Companies competed to build more renewable capacity to earn subsidies and this certifies the importance of such targets. However, the disordered development of the power sector results in many problems such as the severe overcapacity issue and the increasing discarding of renewable energy. Thus it is of great importance to optimize the development in advance.

Annual profits of the power generation sector are shown in Fig. 5. Annual profits will increase from 1188 billion RMB in 2013 to 2495 billion RMB in 2050. The optimized accumulated total profit of the power generation sector is 20,553 billion RMB, which calculates the discounted cash flow of the annual profits.

3.2. Regional power generation trends for technologies

3.2.1. Resource-rich areas

Power generation profiles in some resource-rich regions are investigated to find out how profit margins would stimulate the development of technologies. As shown in Fig. 6, power generation and demand in four typical areas with different resource characteristics are demonstrated. For coal-fired power plants, ultra-supercritical coal plants will gradually replace existing sub-critical and super-critical coal plants in areas at different time points in relation to various regional coal prices. This can be understood as the retirement of old sub-critical and super-critical coal plants and the replacement of high-efficiency ultra-supercritical coal plants, which would be more profitable especially in areas with high coal prices.

For NGCC plants, only Inner Mongolia (Fig. 6(a)), Xinjiang (Fig. 6(b)) and the Northwest area will deploy after 2025 owing to relatively low gas prices in these areas. Though gas plants have higher on-grid prices compared to that of coal-fired plants, still the high gas prices in China will result in little increase in NGCC. This indicates that the development of NGCC plants in China requires even more economical subsidies to compete with other

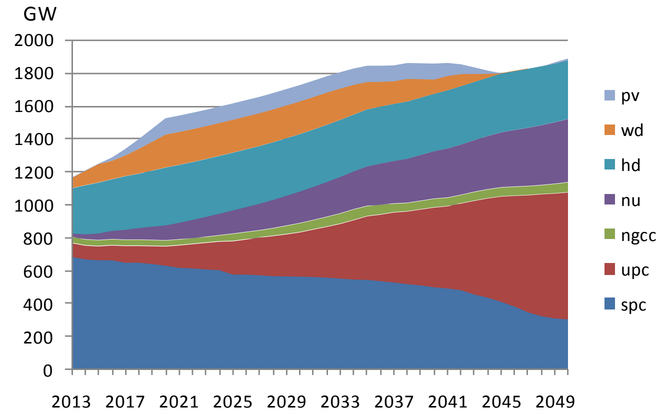

Fig. 4. Nationwide developing trends of technologies.

technologies without the consideration of peak regulation.

For hydropower, areas with abundant hydroelectric reserves, such as Sichuan and Chongqing area in Fig. 6(d), will largely exploit their hydropower resources, and hydroelectric power will become the main source for its local electricity supply as well as power exporting. This indicates a sufficient on-grid price margin for hydropower considering its costs, though the price is relatively low compared to that of the others.

Wind will be rapidly deployed in Inner Mongolia (Fig. 6(a)) and the Northeast area from 2013 and remain plateau, then drop significantly after 2035. The increase at the beginning mainly results from high feed-in tariffs at the early stage as well as the national clean energy targets in which wind is planned to reach 200 GW by 2020. However, due to the lack of sufficient subsidies as well as the cease of strong national targets for wind power after 2020, its capacity will start to drop from around 2030 with the retirement of previously installed capacity. National targets and feed-in tariffs are crucial to the development of wind power and should last long enough to sustain its development in the long term.

PV will experience the same situation as wind power in Guangxi and Guizhou. With the cease of feed-in tariff for PV by 2030, no new capacity will be added though considering its continuously decreasing capital costs. Thus, it is important to subsidize PV in both the short and long term.

In addition to these changes in power generation for technologies, the power exporting status for these areas is noteworthy. As shown in Fig. 6(a) and (b), both areas will initially export power, but the exporting amount will become less and less and reach zero eventually. This was further discussed later when analyzing the utilization rate of the grid.

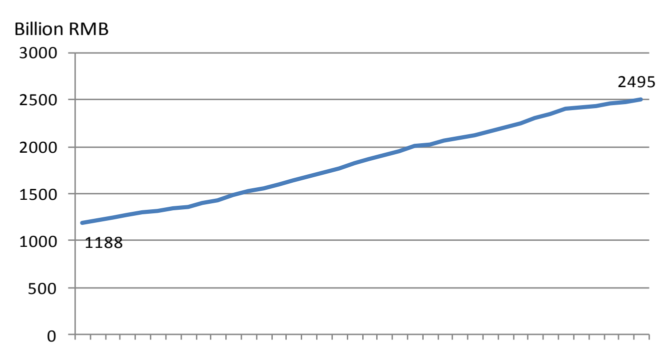

Fig. 5. Annual profits of the power generation sector in China.

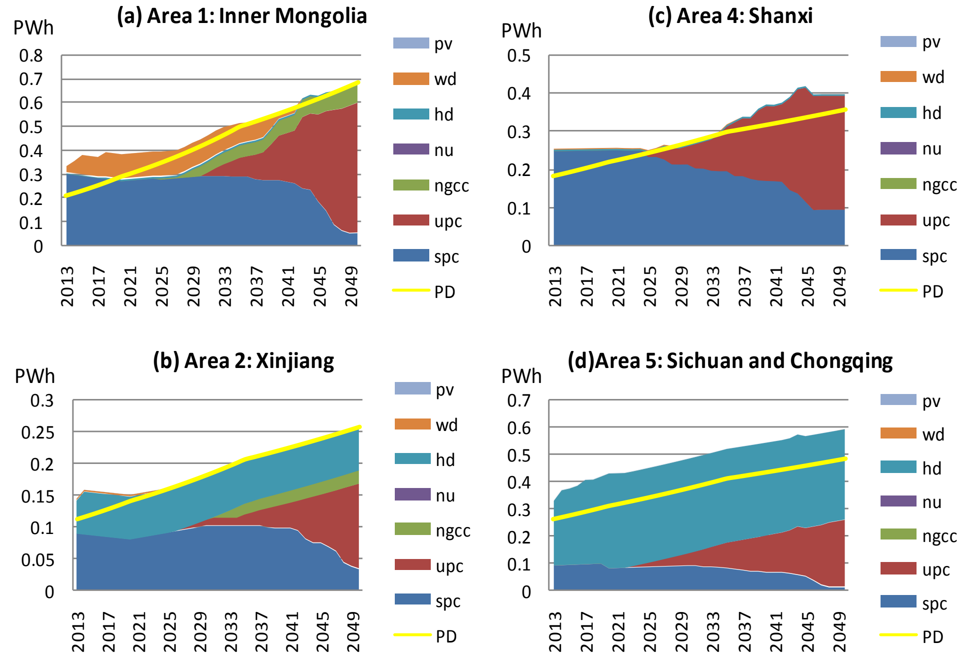

Fig. 6. Power generation mix in some resource-rich areas.

3.2.2. *Load-centred areas*

Ultra-supercritical coal plants will gradually replace existing sub-critical and super-critical coal plants. As shown in Fig. 7, power generation profiles for each technology in four load-centred areas are demonstrated. Ultra-supercritical coal plants will develop rapidly owing to fast increasing power demand in these areas and its high efficiency compared to the existing sub-critical and super-critical coal plants (coal prices are relatively high in these load-centred regions). Notably, nuclear power will expand in Shandong and the East area (Fig. 7(b) and (c)) owing to high coal prices, which make coal-fired plants less competitive than nuclear power. In addition, nuclear power will also expand in the Northeast area and Henan and become the major power supply form.

For these load-centred areas, they will all import power at the beginning. However, Beijing, Tianjin and Hebei area will begin to export power from around 2020 (Fig. 7(a)), whilst the other three will remain their importing status. This situation together with the

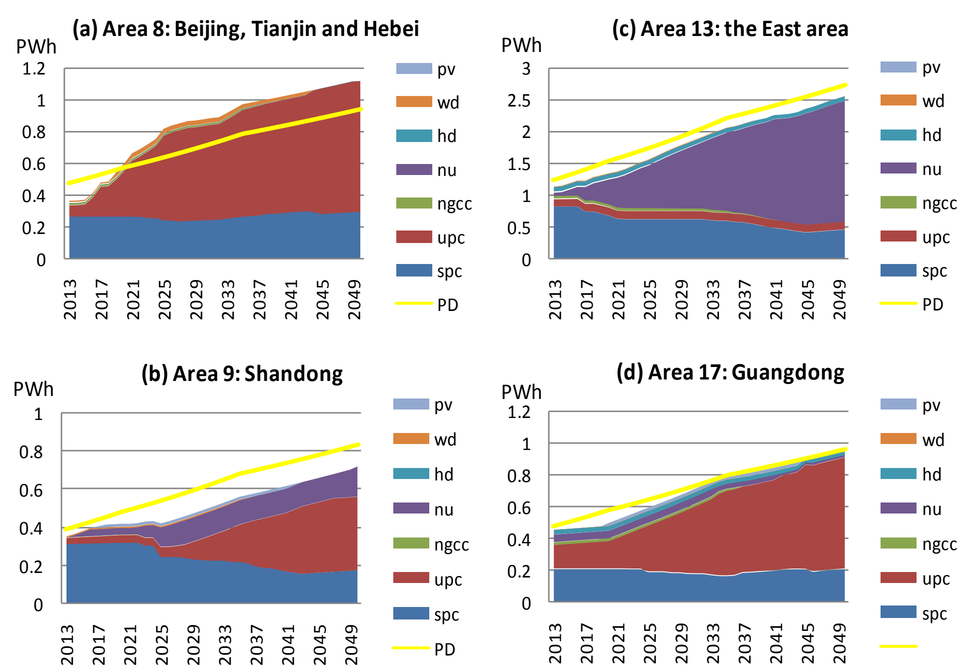

Fig. 7. Power generation mix in some load-centred areas.

(a) current pathway

(b) around 2025

(c) around 2045

Fig. 8. Power transmission pathway in different periods.

power exporting issues mentioned in the last section was discussed in the next section.

3.3. Power transmission

Transmission pathway at present, by 2025 and 2045 are compared as shown in Fig. 8. From Fig. 8(a) and (b), we can see that the rapid development of UHV girds will enable cross-region power transmission, especially from Inner Mongolia, Shanxi and the Northwest areas to east coastal areas. Meanwhile, some transmission lines such as from Xinjiang to Sichuan would not be fully utilized. This is mainly because of the abundant hydropower resources in Sichuan and its relatively high profit margin.

By comparing Fig. 8(b) and (c), we can see that in the long term, some power transmission lines will be abandoned such as lines from Xinjiang and Yunnan. This can be explained by the profits gained by the power generation sector rather than the costs afforded by the sector. For instance, though Xinjiang has relatively cheap coal, its on-grid price is also low. Thus, operating coal-fired power plants and selling the power to Henan may not be as profitable as constructing one in Henan. This could explain why Beijing, Tianjin and Hebei area will shift from power importing to exporting as well, because the on-grid price margin there is higher. The result indicates that the current highly regulated electricity market with unbalanced regional on-grid prices would result in low utilization rates for some power transmission lines and may not reasonably allocate resources.

4. Conclusions

In this study, a model reflecting regional power demand, natural resources and inter-regional power transmission is built to maximize total profits gained by the power generation sector in China. A case study was performed considering various on-grid prices and feed-in tariffs for technologies as well as the national clean energy targets.

For thermal power, ultra-supercritical coal plants will gradually replace existing sub-critical and super-critical coal plants from 2020, but at a relatively late stage in the Northwest area, Xinjiang and Inner Mongolia, where coal prices are low, and NGCC will only develop in these three areas due to low-cost gas. Nuclear will be competitive in the East area, Northeast, Shandong and Henan due to relatively high regional prices for fossil fuel. With respect to clean energy, hydropower will be fully exploited. Energy subsidies and national targets are important to the deployment of wind and PV in both the short and long term.

Utility of transmission lines between regions varies significantly. Concerning some resource-rich areas, such as Xinjiang and Inner Mongolia, due to the lack of profit margins, these areas will tend not to export power in the long term though export at the beginning. On the other hand, load-centred areas such as Beijing, Tianjin and Hebei area will shift from power importing to exporting. These indicate that means such as a more flexible electricity pricing mechanism including subsidies for renewable and incentives for coal plants are required to stimulate power exporting from the resource-rich areas.

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Appendix A. Nomenclature

Table A.1
Physical meanings of parameters.

Symbol	Unit	Physical meaning
$CAP_{g,t}$	RMB/kW	Capital cost for construction of 1 kW capacity of power plants of type g in year t
$FCR_{f,g,t}$	t/kWh (m^3/kWh for NGCC)	Consumption rate for fuel f by plants of type g in year t for generating 1 kWh electricity
$FP_{f,t,r}$	RMB/kW (RMB/N m^3 for NGCC)	Price of fuel fin region r in year t
FSC_f^{ub}	t	Upper limit of supply capability for fuel f
I	%	Discount rate
$IC_{g,r}^{ub}$	kW	Upper limit of total installed capacity of power plants of type g in region r
NB_g^{ub}	kW	Upper limit of annual building capacity of plants of type g in the country
$OGP_{g,t,r}$	RMB/kWh	On-grid prices of power plants of type g in region r in year t
$OH_{g,t,r}$	hour	Annual operational hours of power plants of type g in region r in year t
$PD_{t,r}$	kWh	Power demand in region r in year t
TLT_g	year	Expected lifetime of power plants of type g
$TRLIMIT_{t,r,r'}$	kWh	Power transmission limits from region r' to region r in year t
$TRLOSS_{r,r'}$	%	Loss ratio of power transmitted from region r' to region r in year t
μ_g	RMB/kW	Ratio of annual O&M cost over the total installed capacity of type g plant

Table A.2
Physical meanings of variables.

Symbol	Unit	Physical meaning
atp	RMB	Accumulated total profits gained by the power sector over the planning horizon
$er_{g,t,r}^{t'}$	kW	Early retiring capacity of power plants of type g (built in year t) in region r in year t'
$fc_{f,t,r}$	RMB	Cost for fuel f in region r in year t
$fd_{g,f,t,r}$	t (N m3)	Demand for fuel f by power plants of type g in region r in year t
$ic_{g,t,r}$	kW	Installed capacity of power plants of type g in region r in year t
$itr_{t,r,r'}$	kWh	Ideal power transmission from region r' to region r in year t (regardless of transmission loss)
$inv_{g,t,r}$	RMB	Capital cost in region r in year t for building power plants of type g
$nbc_{g,t,r}$	kW	New-built capacity of power plants of type g in region r in year t
$om_{g,t,r}$	RMB	O&M cost of power plants of type g in region r in year t
$pg_{g,t,r}$	kWh	Power generation of power plants of type g in region r in year t
$rc_{t,r}$	RMB	Total cost paid by the power sector in region r in year t
$rfd_{f,t,r}$	t (N m3)	Total demand for fuel f by power plants in region r in year t
$rreve_{t,r}$	RMB	Total revenue received by the power sector in region r in year t
$rm_{g,t,r}^{t'}$	kW	Existing or left capacity of power plants of type g built in year t, in region r in year t'
$ttr_{t,r}$	kWh	Total power transmitted into region r in year t
$tfc_{t,r}$	RMB	Total fuel cost in region r in year t
$tom_{t,r}$	RMB	Total O&M cost of all types of power plants in region r in year t

Appendix B. Equations imported from Guo et al.'s work

Equation for capital investment:

$$inv_{g,t,r} = \sum_{t'=t-TLT_g+1}^{t} \left(CAP_{g,t'} \cdot nbc_{g,t',r} \cdot \frac{I}{(1+I)\cdot\left(1-(1+I)^{-TLT_g}\right)} \right) \tag{B1}$$

Equation for O&M costs:

$$tom_{t,r} = \sum_g om_{g,t,r} = \sum_g \left(\mu_g \cdot ic_{g,t,r}\right) \tag{B2}$$

Equation for fuel costs:

$$tfc_{t,r} = \sum_f fc_{f,t,r} = \sum_f \left(FP_{f,t,r} \cdot fd_{f,t,r}\right) = \sum_f \left(FP_{f,t,r} \cdot \sum_g fd_{g,f,t,r}\right) = \sum_f \left(FP_{f,t,r} \cdot \sum_g \left(pg_{g,t,r} \cdot FCR_{f,g,t}\right)\right) \tag{B3}$$

Constraint for regional installed capacity of renewable:

$$ic_{g,t,r} \le IC_{g,r}^{ub} \tag{B4}$$

Constraint for construction capacity:

$$\sum_r nbc_{g,t,r} \le NB_g^{ub} \tag{B5}$$

Constraint for fuel supply:

$$\sum_r rfd_{f,t,r} \le FSC_f^{ub} \tag{B6}$$

References

[1] NBSC (National Bureau of Statistics of China). China statistical yearbook 2015. Beijing, China: China Statistics Press; 2015 [in Chinese].
[2] Hu X, Chen L, Lei H. China's low carbon development pathways by 2050, scenario analysis of energy demand and carbon emissions. Beijing, China: Science Press; 2009 [in Chinese].
[3] Mischke P, Karlsson KB. Modelling tools to evaluate China's future energy system — a review of the Chinese perspective. Energy 2014;69:132–43.
[4] Cai W, Wang C, Wang K, Zhang Y, Chen J. Scenario analysis on CO_2 emissions reduction potential in China's electricity sector. Energy Policy 2007;35(12): 6445–56.
[5] Zhu L, Fan Y. Optimization of China's generating portfolio and policy

implications based on portfolio theory. Energy 2010;35(3):1391–402.
[6] Chen Q, Kang C, Xia Q, Guan D. Preliminary exploration on low-carbon technology roadmap of China's power sector. Energy 2011;36(3):1500–12.
[7] Zhang D, Liu P, Ma L, Li Z, Ni W. A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation. Comput Chem Eng 2012;37:227–47.
[8] Gnansounou E, Dong J. Opportunity for inter-regional integration of electricity markets: the case of Shandong and Shanghai in East China. Energy Policy 2004;32(15):1737–51.
[9] Wang H, Nakata T. Analysis of the market penetration of clean coal technologies and its impacts in China's electricity sector. Energy Policy 2009;37(1): 338–51.
[10] Cheng R, Xu Z, Liu P, Wang Z, Li Z, Jones I. A multi-region optimization planning model for China's power sector. Appl Energy 2015;137:413–26.
[11] Parikh J, Chattopadhyay D. A multi-area linear programming approach for analysis of economic operation of the Indian power system. IEEE Trans Power Syst 1996;11(1):52–8.
[12] Koltsaklis NE, Dagoumas AS, Kopanos GM, Pistikopoulos EN, Georgiadis MC. A spatial multi-period long-term energy planning model: a case study of the Greek power system. Appl Energy 2014;115:456–82.
[13] Zhou X, Yi J, Song R, Yang X, Li Y, Tang H. An overview of power transmission systems in China. Energy 2010;35(11):4302–12.
[14] NBSC. China statistical yearbook 2012. Beijing, China: China Statistics Press; 2012 [in Chinese].
[15] SGCC (State Grid Corporation of China), Projects, SGCC, Beijing, China. <www.sgcc.com.cn/ywlm/projects/index.shtml>accessed 14.12.2015.
[16] The State Council. The action plan for the control of air pollution. Beijing, China: The State Council; 2013 [in Chinese].
[17] The State Council. The 12th five-year plan for energy development. Beijing, China: The State Council; 2013 [in Chinese].
[18] NDRC (National Development and Reform Commission). China's national plan on climate changes (2014-2020). Beijing, China: NDRC; 2014 [in Chinese].
[19] Guo Z, Liu P, Ma L, Li Z. A grid-structure based multi-region optimisation model for the development of power generation sector in China. Chem Eng Trans 2015:439–44.
[20] OECD (Organization for Economic Co-operation and Development). Projected costs of generating electricity. Paris, France: OECD; 2010.
[21] China's Chemical Products Web, Coal prices for cities [in Chinese] <www.chemcp.com/news/201501/529762.asp>accessed 20.04.2015.
[22] OECD/IAEA. Uranium 2014: resources, production and demand. Paris, France: OECD Publishing; 2014. http://dx.doi.org/10.1787/uranium-2014-en.
[23] NDRC. Notice on further adjusting environmental protection electricity prices. Beijing, China: NDRC; 2014 [in Chinese].
[24] NDRC. Notice on regulating on-grid prices for gas power plants. Beijing, China: NDRC; 2014 [in Chinese].
[25] NDRC. Notice on properly adjusting wind power feed-in tariff. Beijing, China: NDRC; 2014 [in Chinese].
[26] NDRC. Notice on the use of price leverage to promote the healthy development of solar PV industry. Beijing, China: NDRC; 2013 [in Chinese].
[27] NDRC. Notice on improving the mechanism for nuclear power's on-grid price. Beijing, China: NDRC; 2013 [in Chinese].
[28] The State Council. The energy development strategy action plan (2014-2020). Beijing, China: The State Council; 2014 [in Chinese].
[29] China Electricity Council. Collection of statistics information on China's power industry in 2008. Beijing: China Electricity Council; 2009 [in Chinese].
[30] EBCEPY (Editorial Board of China Electric Power Yearbook). China electric power yearbook 2010. Beijing, China: China Electric Power Press; 2010 [in Chinese].
[31] EBCEPY. China electric power yearbook 2011. Beijing, China: China Electric Power Press; 2011 [in Chinese].
[32] EBCEPY. China electric power yearbook 2012. Beijing, China: China Electric Power Press; 2012 [in Chinese].
[33] EBCEPY. China electric power yearbook 2013. Beijing, China: China Electric Power Press; 2013 [in Chinese].
[34] SERC (State Electricity Regulatory Commission). Annual report on electricity regulation (2011). Beijing, China: SERC; 2011 [in Chinese].
[35] Huber M, Weissbart C. On the optimal mix of wind and solar generation in the future Chinese power system. Energy 2015;90(Part 1):235–43.
[36] Zhao B, Shi XF, Sun K, Zheng Y, Zhang HY. Economic analysis of the instance for UHV AC transmission. Proc CSEE 2009;29(22):8–11.
[37] CAE (Renewable energy development strategy research group of Chinese Academic of Engineering). Books of China's renewable energy development strategy research-comprehensive volume. Beijing, China: China Electric Power Press; 2010 [in Chinese].
[38] Guo Z, Liu P, Ma L, Li Z. Effects of low-carbon technologies and end-use electrification on energy-related greenhouse gases mitigation in China by 2050. Energies 2015;8(7):7161–84.
[39] NBSC. China energy statistical yearbook 2014. Beijing, China: China Statistics Press; 2014 [in Chinese].

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