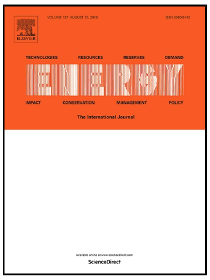


A multi-regional energy transport and structure model for China’s electricity system

Yaru Zhang, Tieju Ma, Fei Guo

PII: S0360-5442(18)31430-0

DOI: 10.1016/j.energy.2018.07.133

Reference: EGY 13398

To appear in: *Energy*

Received Date: 09 January 2018

Accepted Date: 20 July 2018

Please cite this article as: Yaru Zhang, Tieju Ma, Fei Guo, A multi-regional energy transport and structure model for China’s electricity system, *Energy* (2018), doi: 10.1016/j.energy.2018.07.133

A multi-regional energy transport and structure model for China's electricity system

Yaru Zhang[1], Tieju Ma[1,2,*] , Fei Guo[2]

[1]School of Business, East China University of Science and Technology

Meilong Road 130, Shanghai 200237, China

[2]International Institute for Applied Systems Analysis

Schlossplatz 1 - A-2361 Laxenburg, Austria

---

[*] Corresponding authors:

Tieju Ma. School of Business, East China University of Science and Technology, Meilong Road 130, Shanghai 200237, China. Tel/fax.: +86 21 64252015. E-mail addresses: tjma@ecust.edu.cn

Abstract

The imbalance between the distribution of coal resources and electricity demand makes the transport of energy a significant challenge for China's electricity system. Moreover, with China's air pollution control policies, more clean energy resources will be used to generate electricity, which will change regional power generation structures and influence the energy transport among regions. In this paper, a multi-regional model is developed to optimize the long-term generation and transmission structure of China's electricity system by minimizing the accumulative system cost and considering regional resource endowments and air pollution control polices in four key areas. Results indicate that 1) the share of power generation from clean energy will increase from 24% in 2015 to 62% in 2050, 2) the structure of power generation in each region will be influenced by local water resource availability, and the total CO_2 emission will be reduced by around 16% in 2030 owing to the air pollution control policies, and 3) by 2050, coal will be mainly transported from the North to the Central, the South, the East and the Northeast, while the electricity will be transmitted to the Central, the South and the East from the Northwest, the North, the Southwest and the Central.

Keywords: China's electricity system; energy transport; electricity transmission; Ultra-high voltage (UHV); system optimization model

1. Introduction

China's fast industrialization and urbanization have led to significant growth in electricity consumption, reaching 5919.8 TWh in 2016, approximately twenty times the consumption in 2006 [1, 2]. In terms of energy resources, China is rich in coal and poor in both oil and gas [3], which implies that coal accounts for a majority of electricity generation, nearly 67% in 2016. However, the distribution of coal resources and the demand for electricity are geographically unbalanced in China. Most of the country's coal is located in its north and northwest regions, such as Inner Mongolia, Shanxi, Shaanxi and Xinjiang, while a considerable number of coal-fired power plants are in the eastern and southern coastal regions, near demand centers and far away from coal mining areas [4]. At present, approximately 80% of inter-regional energy transport is about transporting coal and the remaining 20% is by electricity transmission [5]. However, the capacity for coal transportation by railway is limited. In addition, it is not well accepted to build new large-scale coal power plants at the demand regions because the population densities at these regions are quite high, and coal power plants could cause serious air pollution in these regions. The Chinese government is planning to build an inter-regional and smart electricity transmission grid [6]. Ultra-high voltage (UHV) is now being viewed as an emerging technology in China with the aim of meeting the need for large amounts of power transportation over long distances at lower loss and costs [7].

With the implementation of various China's air pollution control policies, more clean energy resources, such as hydro and photovoltaic (PV), are used to generate electricity [8]. This means that the power generation structure is changing, which will lead to a new challenge to energy transport between regions. In addition, China is adopting new energy transport technologies and new power generation technologies, which provides a chance to reconfigure the electricity system both technologically and spatially. Therefore, what should be the cost-effective energy transport and structure in China's electricity system have become important problems to explore.

Many studies have investigated the energy transport in China's electricity system. Mou and Li [9] studied China's coal flows by a linear programming method and considered future shifts in coal supply zones and their influence on coal transportation arteries. Zhou et al. [10] provided a comprehensive introduction to China's power transmission systems and grids, as well as some issues faced by China's power grids. Cheng et al. [11] developed a multi-regional optimization model to optimize the planning of China's power sector by minimizing the total cost of China's power sector whilst considering inter-regional power transmission and the impact of carbon policies. Chen et al. [12] performed a case study to quantify life cycle carbon emission flows concurrent with electricity coal flows and electricity flows in China. Yi et al. [13] established a multi-regional power dispatch and capacity expansion model to analyze China's future inter-regional power transmission planning and its influences on each region. Zheng et al. [14] proposed the IRSP (Integrated Resource Strategic Planning) smart grids model to study the impact of cross-region transmission on China's low carbon electricity development until 2035. Zhang et al. [15] built a novel source–grid–load coordinated planning model considering the integration of wind power generation. Zhang et al. [16] presented an integrated source-grid-load planning model for China's whole power system. The above-mentioned studies mainly focused on either a single electricity transmission system or scenario analyses from a short-term perspective but seldom focused on the alternative relationship between coal transportation and electricity transmission, as well as the energy transport among regions from a long-term perspective.

There are also many existing studies on the energy structure of China. Zhang et al. [17] presented a multi-period modelling and optimization framework for the future pathway planning of China's power sector, considering CO_2 mitigation between 2010 and 2050. Zeng et al. [18] gave an overall review of China's thermal power development based on industry data of 2014 and 2015. Guo et al. [19] proposed 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. Niu et al. [20] studied the current development status of electric power substitution in China and adopted a SWOT (Strengths, Weaknesses, Opportunities and Threats) model to analyze the electric power substitution. Zhou et al. [21] used LBNL (Lawrence Berkeley National Laboratory) China end-use energy model to assess the role of energy efficiency policies and structural change in industry for transitioning China's economy to a lower emission trajectory. Gao et al. [22] applied portfolio theory to optimize China's energy structure, considering the learning curve effect of renewable energy cost and the increasing fossil energy cost over time. In these studies, few considered the regional resource endowments and the impact of regional water resource and air pollution control policies on multi-regional energy structures.

The main difference between our research and previous studies is that we built a system optimization model to analyze long-term and multi-regional energy transport (i.e., coal transportation and UHV transmission) and electricity generation structure for each region, which has specific resource endowments and air pollution control polices. The rest of the paper is organized as follows. Section 2 presents our optimization model of China's electricity system. Section 3 introduces the data used in the model. Section 4 shows the analysis results of optimal strategies for regional energy structure and inter-regional long-distance energy transport pathways for China's electricity system. Section 5 gives conclusions of the study.

2. Methodology

2.1 Model descriptions and assumptions

China's power grid is divided into seven regions according to the State Grid Corporation of China (SGCC) and the China Southern Power Grid (CSG) [23, 24]. As shown in Fig.1, the seven regions are the Northwest (Xinjiang, Gansu, Qinghai, Ningxia, and Shaanxi), the Southwest (Sichuan, Chongqing, and Tibet), the Northeast (Liaoning, Jilin, Heilongjiang, and East inner Mongolia), the North (Beijing, Tianjin, Hebei, Shanxi, Shandong, and West inner Mongolia), the Central (Hubei, Hunan, Jiangxi, and Henan), the South (Guangdong, Guangxi, Yunnan, Guizhou, and Hainan), and the East (Shanghai, Jiangsu, Zhejiang, Fujian, and Anhui).

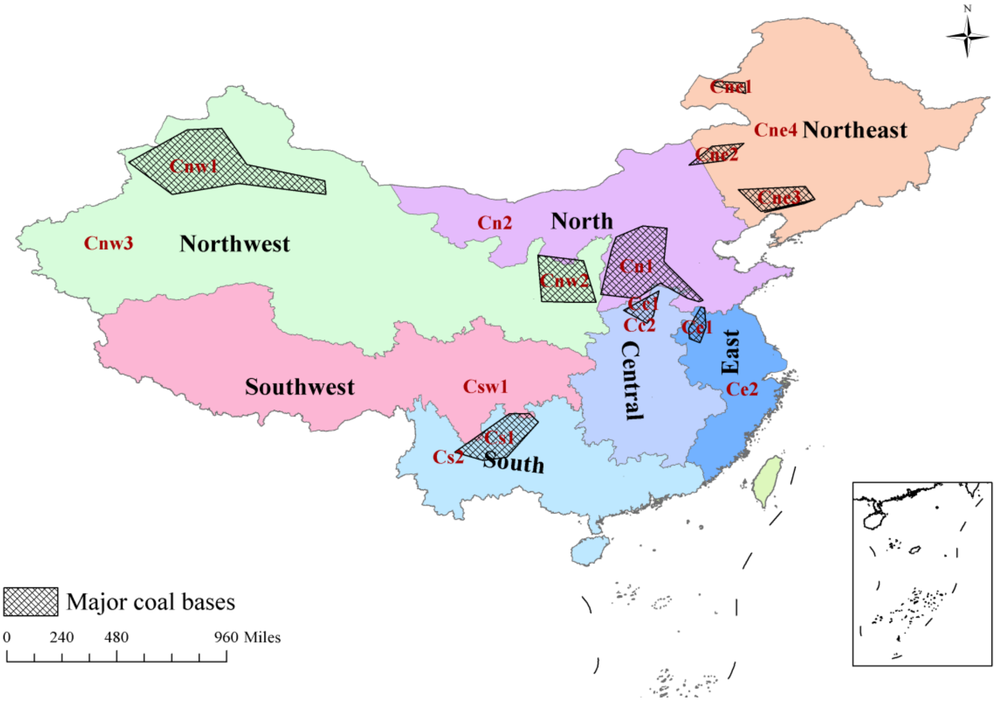


Fig.1. Model descriptions and assumptions

These seven regions differ greatly in respect to economic development level, power demand, resource endowment, and power generation structure. Even within the same region, there are also significant differences in the distribution of coal resource. There are 14 large-scale coal bases in China: Shendong, Eastern Mongolia, Eastern Ningxia, Northern Shanxi, Middle Shanxi, Eastern Shanxi, Northern Shaanxi, Huanglong, Xinjiang, Henan, Lianghuai, Western Shandong, and Yungui. These large-scale coal bases supply over 90% of China's coal consumption [25]. In this study, these 14 large-scale coal bases are grouped into 9 major coal bases: Cnw1, Cnw2, Cn1, Cne1, Cne2, Cne3, Cc1, Cs1 and Ce1 (see Fig. 1), according to their geographical location in the seven regions. Besides these 9 major coal bases, for each grid region, all the rest relatively small coal mines in it are treated as a small coal base, namely Cnw3, Csw1, Cne4, Cn2, Cc2, Cs2 and Ce2 (see Fig.1). In short, each region typically includes a small coal base and a few major coal bases (1-3 depends on regions and no major coal base for the Southwest). For example, in the Northwest, there are two major coal bases (Cnw1 and Cnw2) and one small coal base (Cnw3).

Recently, UHV lines (over 1000 kV UHVAC and ±800 kV UHVDC) have been adopted in China to significantly increase the electricity transmission capability [26]. A previous study [20] found that the UHV would surpass other power transmission ways in terms of cost-effectiveness when the transmission capacity exceeds the 2400MW and the transmission distance exceeds 800km. According to the plans released by the SGCC [23] and CSG [24], 28 UHV lines are planned to be constructed by 2020. As shown in Table 1, 18 of them are inter-regional transmission lines, while the rest 10 are intra-regional lines. In our study, a region's energy consumption is supplied by energy generated inside this region and the energy transported to it from other regions. Like some previous modeling practices (including some non-bottom-up system optimization model, i.e., Ref. [27]), we treated the energy transport inside each region in an accumulative way to make the scale of the optimization model suitable for solving and analysis. Of course, it will be more credible to consider more details of the intra-region energy supply, which will be considered in our future work with this study as a starting point. The UHV planning by 2020 shown in Table 1 is treated as the initial status for our analysis of building suitable potential UHV grids by 2050 with the model.

Table 1 The UHV lines by 2020

No.	UHV lines	Year	Linked regions	No.	UHV lines	Year	Linked regions
1	Jindongnan–Nanyang–Jingmen	2009	North–Central	15	Shanxi–Jiangsu	2017	North–East
2	Yunnan–Guangdong	2009	South	16	Shanghaimiao–Shandong	2017	North
3	Xiangjiaba–Shanghai	2010	Southwest–East	17	Ximeng–Taizhou	2017	North–East
4	Jinping–Sunan	2012	Southwest–East	18	Dianxibei–Guangdong	2017	South
5	Nuozhadu–Guangdong	2013	South	19	Jiuquan–Hunan	2017	Northwest–Central
6	Huainan–Zhejiang–Shanghai	2013	East	20	Zhundong–Wannan	2018	Northwest–East
7	Zhebei–Fuzhou	2014	East	21	Yaan–Wuhan	2018	Southwest–Central
8	Xiluodu–Zhejiang	2014	Southwest–East	22	Zhundong–Chengdu	2018	Northwest–Southwest
9	Hami–Zhengzhou	2014	Northwest–Central	23	Mengxi–Changsha	2020	North–Central
10	Ximeng–Jinan	2016	North	24	Zhangbei–Nanchang	2020	North–Central
11	Mengxi–Tianjinnan	2016	North	25	Longbin–Lianyungang	2020	Northwest–East
12	Huainan–Nanjing–Shanghai	2016	East	26	Humeng–Shandong	2020	North
13	Ningdong–Zhejiang	2016	Northwest–East	27	Mengxi–Hubei	2020	North–Central
14	Yuheng–Weifang	2017	Northwest–North	28	Shaanbei–Nanchang	2020	Northwest–Central

Note: Nos. 1–13 lines are currently in operation (by 2016); Nos. 14–20 are under-construction; Nos. 21–28 are planned to be constructed.

In China, the inter-regional coal transportation is mainly by railways and waterways [13]. Therefore, it is assumed that there are only two ways to transport coal between regions in our model. Given the geographical conditions, coal would be transported from the North to the East and from the North to the South by waterways, while all the others by railways.

In addition, we assume that all coal bases are able to supply intra-regional coal demand and inter-regional coal transportation, and power can be transmitted by UHV among regions. Theoretically, the model would allow any location being the potential site for power plants, and then the optimization process would find the optimal locations. However, in this sense, the number of potential locations will be infinite and the optimization model will become extremely difficult to solve. Therefore, we made a reasonable constraint to the model: considering the economy-of-scale, the new built coal power plants which generate electricity for the UHV lines are assumed to be close to the major coal bases thus it saves the cost of transporting coal to them.

2.2 Modeling China's electricity system based on the MESSAGE platform

The model of China's electricity system in this paper builds on the MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impacts) integrated assessment modeling framework. MESSAGE is a linear programming engineering optimization model for long-term energy system planning and policy analysis [28].

China's electricity system is structured into energy network including three levels, resources (coal, hydro, wind, solar, and uranium, etc.), regions (i.e., Northwest, Southwest, Northeast, North, Central, South and East), and demands. As shown in Fig. 2, these levels are linked by different technologies, such as power generation, coal transportation, and electricity transmission. By default, MESSAGE minimizes the accumulative total system costs as a criterion for optimization [29]. In this paper, the cost of China's electricity system is mainly made up of three parts, investment cost, operation and maintenance (O&M) cost, and fuel cost. MESSAGE determines how the available technologies and resources are used to satisfy each region's demand. The system's optimal solutions include the strategies of coal transportation and inter-regional UHV transmission, as well as the power generation structure of each region. The detailed model formulation of China's electricity system is shown in Appendix. In this paper, a discount rate of 5% is used [30].

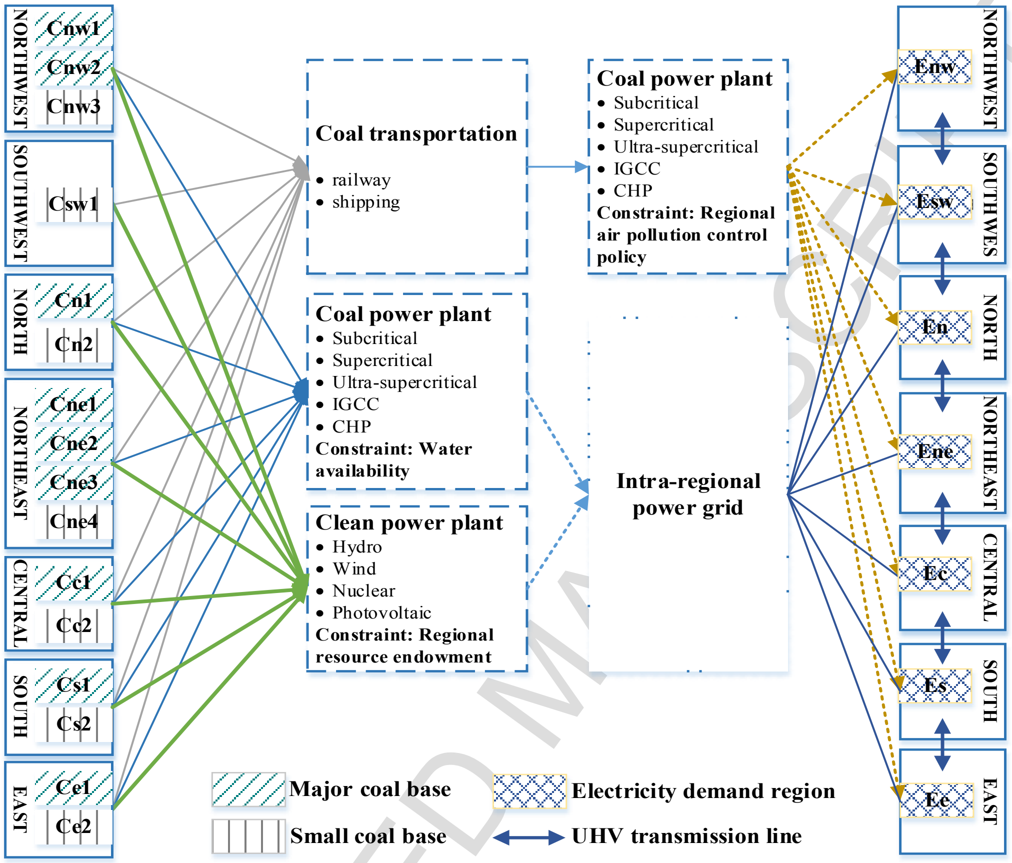


Fig.2. MESSAGE model structure of China's electricity system

3. Data

The data inputs for MESSAGE model include (i) time horizon, (ii) electricity demand, (iii) historical installed capacity, (iv) O&M and investment costs of the technologies, and (v) various constraints on power plant technologies.

3.1 Time horizon

The time horizon in this study is from 2015 to 2050, with a time step of 5 years. The base year is 2014, and the year of 2015 represents the starting year in the optimization process.

3.2 Electricity demand

Regional electricity demand is influenced by population growth, economic prosperity, government policy, as well as many other factors. The detailed prediction of the demand is not the focus of this paper. For the model, this future regional electricity demand is exogenous, referring to the various published projections. We collected projections on China's future power demand from Ref. [11, 19, 31-34]. China's NEA (National Energy Administration) [35] also provides the projection of China's future power demand, and its projection covers an area (see Fig.A.1 in Appendix). Among all these existing projections, we adopt the growth rate in the projections of SGERI (State Grid Energy Research Institute) from its publication called "China Energy and Electricity Outlook 2017". SGERI's projection is about in the middle of all these projections (see Fig.A.1 in Appendix). With the power demand growth rate in the SGERI's projection, we projected China's regional electricity demand, as shown in Table 2. In addition, we used MWyr as a unified unit in our model.

Table 2 Regional electricity demand in the future (unit: MWyr)

Region	2020	2025	2030	2035	2040	2045	2050
Northwest	85602	100690	116727	126369	135466	142376	147429
Southwest	41375	48667	56419	61079	65476	68816	71258
Northeast	57438	63417	66651	72157	77351	81297	84182
North	191940	225771	255439	268469	282163	293632	304054
Central	100718	118470	137340	148684	159388	167518	173464
South	135580	164614	236497	246110	256113	266523	275982
East	192993	227009	263165	284903	305413	320992	332385

3.3 Power generation technologies

There are five types of coal power generation technologies in the model, namely subcritical plants, supercritical plants, ultra-supercritical plants, integrated gasification combined cycle (IGCC) plants, and combined heat and power (CHP) plants. In addition, four kinds of clean power generation technologies are also covered in the model, i.e., hydro, wind, nuclear, and PV.

The detailed parameters for these power generation technologies are shown in Table 3 and Table 4.

Table 3 Parameters of power generation technologies

Technology	Efficiency (%)[36]	Variable cost (yuan/kWyr) [37]	Fixed cost (yuan/kW/yr) [13]	Plant life (year) [17]
Subcritical	35	307	133	35
Supercritical	41	245	117	35
Ultra supercritical plant	45	245	106	35
IGCC	48	272	269	35
CHP	35*	245	117	35
Hydro power plant	100▲	0	105	70
Wind power plant	100▲	0	310	20
Nuclear power plant	100▲	245	600	60
Photovoltaic	100▲	0	216	20

*For CHP, we only consider its power generation efficiency rather than its thermal efficiency.

▲As renewables their efficiencies are treated as 100% especially in comparison with fossil fuels, and this is widely used in many energy models.

Table 4 Investment costs of power generation technologies (unit: yuan/kW)

Investment cost	2015	2020	2025	2030	2035	2040	2045	2050
Subcritical[19]	4541	4450	4408	4367	4367	4367	4367	4367
Supercritical[19]	4073	3950	3950	3950	3950	3950	3950	3950
Ultra supercritical[19]	4121	3950	3950	3950	3950	3950	3950	3950
IGCC[19]	15476	14350	12567	11005	10337	9710	9270	8850
CHP[19]	4347	4200	4200	4200	4200	4200	4200	4200
Hydro [38]	6000	5706	5426	5160	4907	4667	4438	4221
Wind[39]	8200	7500	7349	7200	7149	7099	7049	7000
Nuclear[38]	17000	16167	15374	14621	13904	13223	12575	11959
Photovoltaic[39]	8500	8000	7746	7500	7372	7246	7122	7000

The operation factor (i.e., the percentage of annual operation time) of power plants is calculated based on the China Electric Power Yearbook [40], as shown in Table 5.

Table 5 The annual operation time percentage of power plants in different regions

Technology	Northwest	Southwest	Northeast	North	Central	South	East
Coal power plant	48.25%	32.38%	49.43%	57.37%	49.61%	48.19%	53.28%
Hydro power plant	34.02%	41.62%	23.72%	8.95%	35.13%	38.63%	21.07%
Wind power plant	21.34%	21.45%	19.99%	22.21%	21.91%	21.76%	23.92%
Nuclear power plant	0.00%	0.00%	66.38%	0.00%	0.00%	80.31%	89.11%
Photovoltaic	13.16%	14.27%	8.68%	8.67%	4.74%	6.93%	5.90%

3.4 Energy transport technologies

As mentioned before, coal in China is mainly transported (by railways and waterways) from coal resource regions to electricity demand regions where coal power plants are established. The existing facilities of China's railways and waterways are already well developed. Therefore, we do not consider their investment costs, only their O&M costs. We assume that the O&M cost of railway transportation of coal is related to the distance. The railway line distance is obtained from Ref. [41], and the O&M costs of railways and waterways are recalculated with reference to Ref.[13], as shown in Table 6. The loss of coal transportation by railway and waterway are 1.2% and 1.5%, respectively [42].

With UHV transmission lines built in China, the electricity can be generated in resource regions and then to be transmitted to demand regions. Five UHV lines have been constructed by 2015 (i.e., the starting year of this study), and the detailed parameters of them are listed in Table 7. The investment costs and O&M costs of UHV transmission lines are related to the distance between power grids. They are calculated referring to Ref. [13], as shown in Table 8. The UHV transmission loss is about to 0.004% per km [43]. The loss ratios of UHV transmission lines between regions are listed in Table 9.

Table 6 The O&M costs of coal transportation (unit: yuan/kWyr)

	Cnw2	**Cnw3**	**Csw1**	**Cne1**	**Cne2**	**Cne3**	**Cne4**	**Cn1**	**Cn2**	**Cc1**	**Cc2**	**Cs1**	**Cs2**	**Ce1**	**Ce2**
Cnw1	386	252	457	769	528	675	693	410	527	459	583	618	649	503	557
Cnw2	—	187	247	434	167	169	304	88	131	142	262	381	360	187	306
Cnw3	—	—	229	565	325	510	452	292	323	227	364	374	404	276	330
Csw1	—	—	—	636	368	503	476	309	287	265	278	185	363	273	344
Cne1	—	—	—	—	201	210	192	316	320	387	521	716	704	423	432
Cne2	—	—	—	—	—	176	137	197	155	271	404	520	622	252	333
Cne3	—	—	—	—	—	—	95	191	79	270	403	598	588	298	312
Cne4	—	—	—	—	—	—	—	246	188	338	244	701	354	278	276
Cn1	—	—	—	—	—	—	—	—	67	85	217	412	131*	98	110*
Cn2	—	—	—	—	—	—	—	—	—	127	260	447	131*	128	110*
Cc1	—	—	—	—	—	—	—	—	—	—	157	383	296	78	127
Cc2	—	—	—	—	—	—	—	—	—	—	—	259	163	180	154
Cs1	—	—	—	—	—	—	—	—	—	—	—	—	111	411	421
Cs2	—	—	—	—	—	—	—	—	—	—	—	—	—	351	272
Ce1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	105

* Coal is transported by waterways.

Table 7 Parameters for existing UHV transmission lines in 2015

No.	**Line name**	**Operation time (year)**	**Length (km)**	**Capacity (MW)**	**Linked regions**
1	Jindongnan–Nanyang–Jingmen	2009	654	5000	North–Central
2	Xiangjiaba–Shanghai	2010	1907	6400	Southwest–East
3	Jinping–Sunan	2012	2059	7200	Southwest–East
4	Xiluodu–Zhejiang	2014	1680	8000	Southwest–East
5	Hami–Zhengzhou	2014	2210	8000	Northwest–Central

Table 8 The investment costs and O&M costs of UHV transmission lines between regions (unit: yuan/kW)

Investment cost **O&M cost**	**Northwest**	**Southwest**	**Northeast**	**North**	**Central**	**South**	**East**
Northwest	—	2139	3719	2846	3212	3196	3594
Southwest	64	—	4006	3036	3091	2787	3480
Northeast	112	120	—	2488	3106	3762	2946
North	85	91	75	—	2367	2878	2488
Central	96	93	93	71	—	2187	1890
South	96	84	113	86	66	—	2543
East	108	104	88	75	57	76	—

Table 9 The loss ratios of UHV transmission lines between regions

Region	Southwest	Northeast	North	Central	South	East
Northwest	3.30%	11.34%	6.90%	8.76%	8.68%	10.70%
Southwest	—	12.80%	7.86%	8.14%	6.60%	10.12%
Northeast	—	—	5.08%	8.22%	11.56%	7.40%
North	—	—	—	4.46%	7.06%	5.08%
Central	—	—	—	—	3.54%	2.03%
South	—	—	—	—	—	5.36%

3.5 Fuel supply

Historical coal supply is referring to Ref. [44], and the coal price of each region is obtained from Ref. [45], as shown in Table 10. The uranium 235 used in China's nuclear power plants mainly relies on imports. The price of uranium 235 is set at 40 US$/pound in 2015 [46], approximately 574 yuan/kg.

Table 10 Coal supply and price in 2015

	Cnw1	Cnw2	Cnw3	Csw1	Cne1	Cne2	Cne3	Cne4	Cn1	Cn2	Cc1	Cc2	Cs1	Cs2	Ce1	Ce2
Coal supply (10MWyr)	5543	19181	4813	3650	2188	3647	3319	2261	60288	9580	4959	2480	6272	2042	4886	1276
Coal price (yuan)	287	635	508	739	367	367	668	543	452	584	671	742	639	756	783	773

3.6 Constraints

3.6.1 Regional power demand

Regional power demand must be met by its own regional electricity generation and by inter-regional power transmission.

3.6.2 Regional water availability

As coal power plants need large quantities of water for cooling, the establishment of coal power plants close to the major coal bases depends strongly on local water resources. Technologies in cooling systems of coal-fired power plants in China mainly include closed-cycle cooling, once-through cooling, air cooling, and seawater cooling, and 84% of water consumption by coal power plants are used for closed-cycle cooling [47]. Therefore, we just consider the closed-cycle cooling technology with the largest water consumption in this paper. Furthermore, water used by a new coal power plant cannot exceed the water availability. The data of water supply are based on Ref. [48], while the water withdrawal factor for electricity generation technologies is from Ref. [49]. After calculating, the water availability of the Cne2 area (Huolinhe major coal base), which belongs to the Eastern Mongolia large-scale coal bases, is negative in Table 11. It means that the Cne2 region is facing a serious water shortage, as shown in Fig.3. Therefore, the capacity of coal power plants in Cne2 will be limited by water availability.

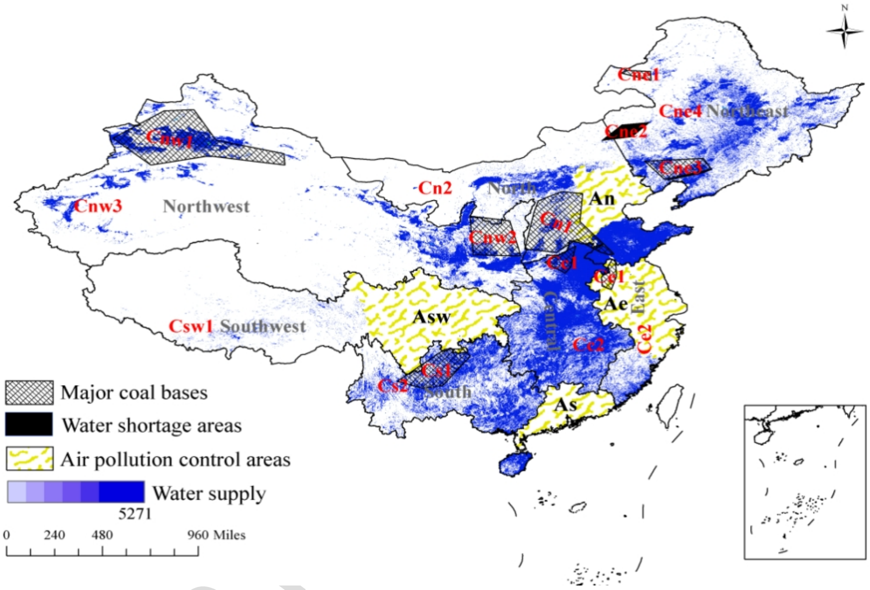


Fig.3. Water shortage areas and key air pollution control areas

Table 11 Regional water supply and water withdrawal of current power plants (unit: 100million m^3)

	Cnw1	Cnw2	Cnw3	Csw1	Cne1	Cne2	Cne3	Cne4	Cn1	Cn2	Cc1	Cc2	Cs1	Cs2	Ce1	Ce2
Water Supply	340.85	20.81	530.71	328.69	0.95	0.61	47.29	609.50	116.37	645.47	66.89	1060.32	51.20	1056.01	22.75	1204.58
Water withdrawal	5.00	4.36	6.18	0.02	0.28	1.25	3.27	4.40	23.40	2.59	7.83	7.66	3.61	4.21	5.15	2.98
Water availability	335.85	16.44	524.53	328.67	0.67	-0.64	44.03	605.10	92.96	642.87	59.06	1052.66	47.59	1051.80	17.59	1201.60

3.6.3 Regional air pollution control policies

In recent years, Chinese government has been actively responding to environmental and climate challenges. Significant policies, such as the 12th Five-Year Plan on air pollution prevention and control in key regions (2012), the Action Plan on the Prevention and Control of Atmospheric Pollution (2013), and the Law of the People's Republic of China on Air Pollution Prevention and Control (2015), were issued to improve the country's air quality. These national environmental policies restricted the new establishment of coal power plants in certain key areas, namely the Jing-Jin-Ji (An), the Yangtze River Delta (Ae), the Pearl River Delta (As) and the Sichuan-Chongqing (Asw), as shown in Fig.3. According to these environmental policies, the new coal power plants built in these four key control areas have to be CHP.

The capacity mixes of coal power generation technologies for different areas in each region are very different. The historical installed capacity of coal power plants in different coal bases is obtained from the China Electricity Council [36] and Ref. [50], as shown in Table 12. The historical installed capacity for clean power plants for each region is based on Ref. [36] (see Table 13).

Table 12 Installed capacity of coal power plants in each coal base in 2014 (unit: 10MW)

Technology	**Northwest**			**Southwest**		**Northeast**				**North**			**Central**		**South**			**East**		
	Cnw1	**Cnw2**	**Cnw3**	**Csw1**	**Asw**	**Cne1**	**Cne2**	**Cne3**	**Cne4**	**Cn1**	**Cn2**	**An**	**Cc1**	**Cc2**	**Cs1**	**Cs2**	**As**	**Ce1**	**Ce2**	**Ae**
Subcritical	1223	1402	1851	1408	1344	10	426	765	1767	7434	3902	3076	2711	2930	1687	3740	2671	1070	5646	5038
Supercritical	876	792	823	610	610	183	180	424	468	2935	895	569	1290	1262	744	1852	720	1132	2737	1645
Ultra	110	246	398	132	132	0	120	612	56	1215	335	200	930	1080	0	2903	1783	1120	5679	5547
IGCC	0	0	0	0	0	0	0	0	0	0	25	25	0	0	0	0	0	0	0	0
CHP	1261	261	895	232	214	40	60	1041	1616	3977	2598	2156	955	624	30	2228	1670	528	3404	2749

Based on Ref. [31, 33, 51, 52] and the current technology development level, the upper limits for installed capacities of power plants in each period are assumed to be as shown in Table 14.

Table 13 Installed capacity of clean power plants for each region in 2014 (unit: 10MW)

Technology	Northwest	Southwest	Northeast	North	Central	South	East
Hydro power plant	2826	7032	809	770	6017	10348	2685
Wind power plant	2316	40	1974	3680	228	767	653
Nuclear power plant	0	0	200	0	0	721	1088
Photovoltaic	1461	18	83	411	54	98	363

Table 14 Upper limits for installed capacities of different power plant technologies in the future (unit: GW)

Technology	2020	2025	2030	2035	2040	2045	2050
Subcritical coal power plant	367	336	260	183	109	62	12
Supercritical coal power plant	202	221	224	220	196	175	167
ultra	341	403	397	415	368	311	291
IGCC	0.6	1.2	2.1	3.9	6.2	9.6	15
CHP	210	328	466	517	521	522	554
Nuclear power plant	72	89	120	158	199	210	220
Hydro power plant	348	446	466	560	613	662	690
Wind power plant	232	300	480	708	872	996	1130
Photovoltaic	213	334	412	541	869	1278	1370

3.6.4 Coal consumption

The upper limits for annual coal extraction are listed in Table 15, referring to Ref. [53].

Table 15 Upper limits for coal extraction (unit: GWyr)

Year	Cnw1	Cnw2	Cnw3	Csw1	Cne1	Cne2	Cne3	Cne4	Cn1	Cn2	Cc1	Cc2	Cs1	Cs2	Ce1	Ce2
2020	73.46	254.22	63.80	48.12	72.43	48.12	48.12	29.84	795.59	120.41	65.45	32.72	82.77	26.95	64.48	15.40
2025	82.71	286.23	71.83	53.13	77.44	53.13	53.13	32.94	878.40	129.61	72.26	36.13	91.38	29.75	71.19	16.20
2030	87.36	302.32	75.87	53.77	78.08	53.77	53.77	33.34	888.99	130.78	73.13	36.56	92.49	30.11	72.05	16.30
2035	88.95	307.80	77.24	51.65	75.96	51.65	51.65	32.03	853.99	126.90	70.25	35.12	88.84	28.93	69.22	15.96
2040	88.06	304.74	76.47	48.63	72.94	48.63	48.63	30.15	803.97	121.34	66.13	33.07	83.64	27.23	65.16	15.48
2045	85.45	295.70	74.21	44.86	69.17	44.86	44.86	27.81	741.68	114.42	61.01	30.51	77.16	25.12	60.11	14.88
2050	82.09	284.06	71.29	40.55	64.86	40.55	40.55	25.14	670.42	106.50	55.15	27.57	69.75	22.71	54.34	14.19

4. Results

With the MESSAGE model presented in Section 2 and the data described in Section 3, the optimal development strategies of China's electricity system are obtained, including power generation structure, inter-regional coal transportation, and inter-regional electricity transmission.

4.1 Regional power generation structure

The power generation structures for China and the seven sub-regions are shown in Fig. 4. From Fig. 4a, we can see that the electricity from existing subcritical and supercritical coal power plants with low efficiency will gradually decrease, which means that these two technologies will be replaced by other power generation technologies. The clean power generation will dominate the entire electricity system in 2050, accounting for 62% of the total power generation.

For coal-fired power plant technologies, ultra-supercritical coal power plants will develop steadily until 2050 due to their better economic performances. Due to the high initial investment costs, our results show that the capacity of IGCC plants will not be increased in this period. CHP will grow rapidly because it is supported by national air pollution control policies, reaching 553GW in 2050 (see Fig.5). In general, coal power technologies with ultra-supercritical and CHP will become major options in the future, especially for the Central (see Fig.4d), the North (see Fig. 4e), the Northeast (see Fig. 4f) and the Northwest (see Fig.4h). The total capacity of coal power technologies will peak around 2030, up to 1235GW, while the proportion of coal power technologies in the power generation structure will decrease from 67% in 2015 to 24% in 2050 (see Fig.5), the ratio is lower in the air pollution control areas. This means that clean energy power generation technologies, such as hydro, wind, PV, and nuclear, will play an important role in future power generation.

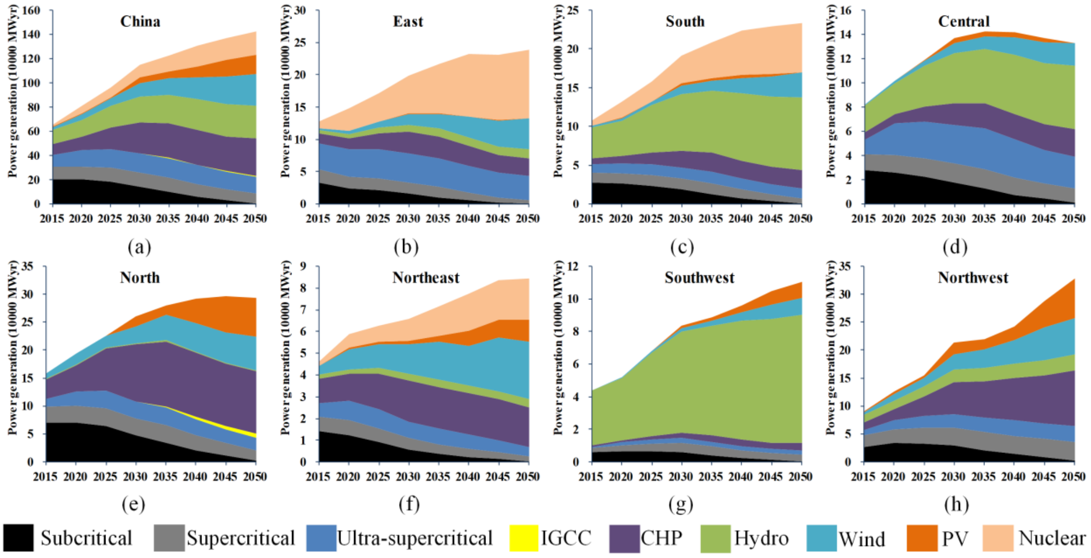


Fig.4. Power generation structure of the different regions

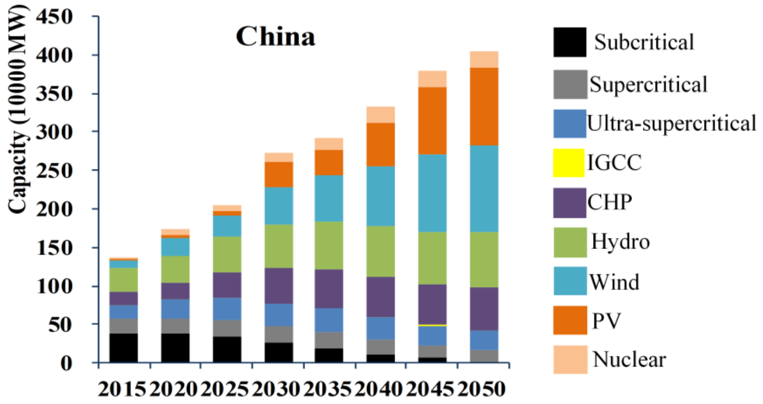


Fig.5. The total installed capacity of power plants for China

In the country level, the capacity of hydropower will only increase at a small rate from 319GW in 2015 to 709GW in 2050. However, regions with abundant hydropower reserves, such as the South (see Fig. 4c) and the Southwest (see Fig. 4g), will largely develop hydropower, and it will become the main source for local electricity supply and power exporting.

Regarding wind power, due to the fast development in recent years and China’s wind resource endowments, its installed capacity will increase rapidly between 2015 and 2050, especially in the North, the Northwest, and the Northeast, reaching 1129 GW by 2050 and taking a share of 27.89% in China’s total power capacity. However, due to the seasonal and geographical constraints, the operation of wind power is intermittent and unstable. As a result, wind power takes only a share of 18.32% in China's total power generation in 2050.

Although nuclear power technology has a high initial investment cost, it is very economical because of its long lifetime, lower fuel prices, and reduced greenhouse gas (GHG) emissions. The proportion of nuclear power generation will grow from 2.74% in 2015 to 13.30% in 2050, especially in the East, the South and the Northeast (see Fig. 4b, Fig. 4c and Fig. 4f).The total capacity of nuclear power will increase to 221GW by 2050, accounting for 5.54% in the total power capacity.

Photovoltaic power generation will start to grow rapidly after 2030, especially in the North (see Fig. 4e) and the Northwest (see Fig. 4h), where the daylight and sunshine time are very long. By 2050, the capacity of PV will reach 1010GW, accounting for a share of approximately 25% in the total power capacity.

Coal power plants require significant quantities of water for cooling. The capacity of coal power plants in the Cne2 region will be restricted due to local water resource shortages (see section 3.6.2). From Fig. 6, we can see that the total installed capacity of coal power plants in the Cne2 region will decrease from 2015 to 2050. Clean energy will gradually replace coal, and dominate the power generation structure in 2050.

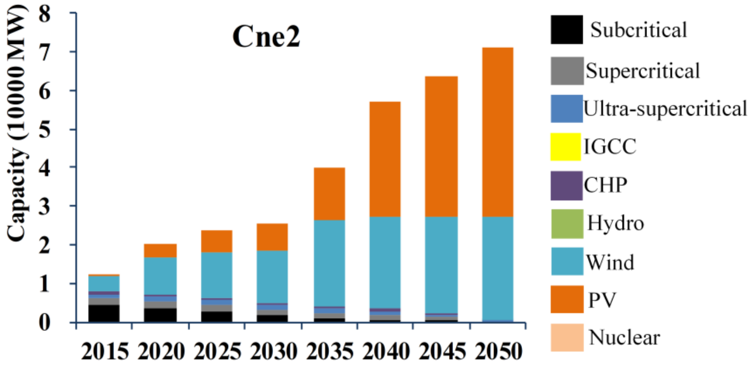
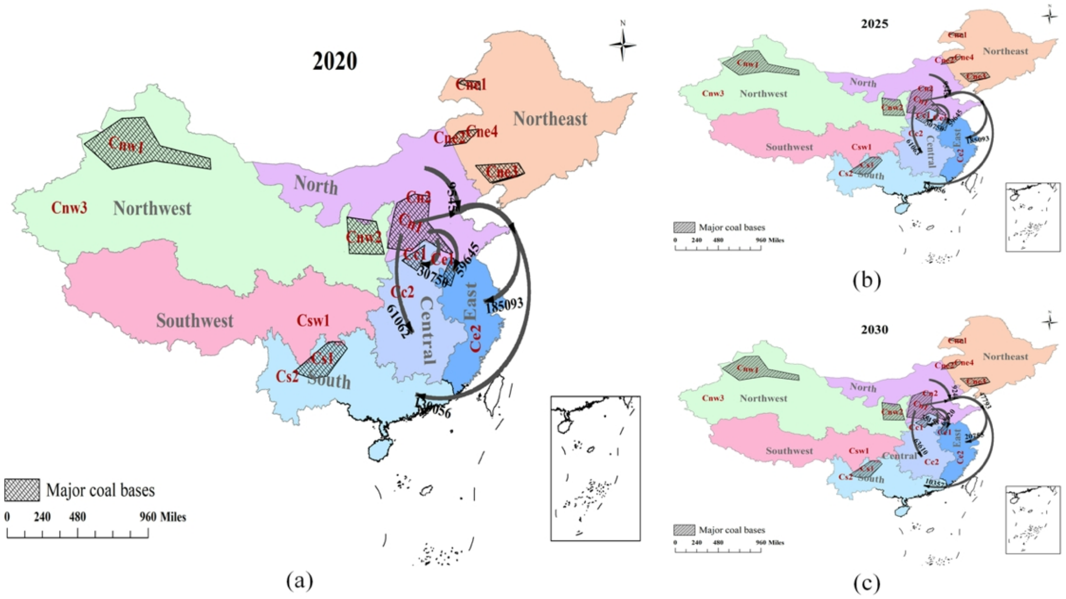


Fig. 6. Installed capacity of power plants in water shortage areas

4.2 Inter-regional coal transportation

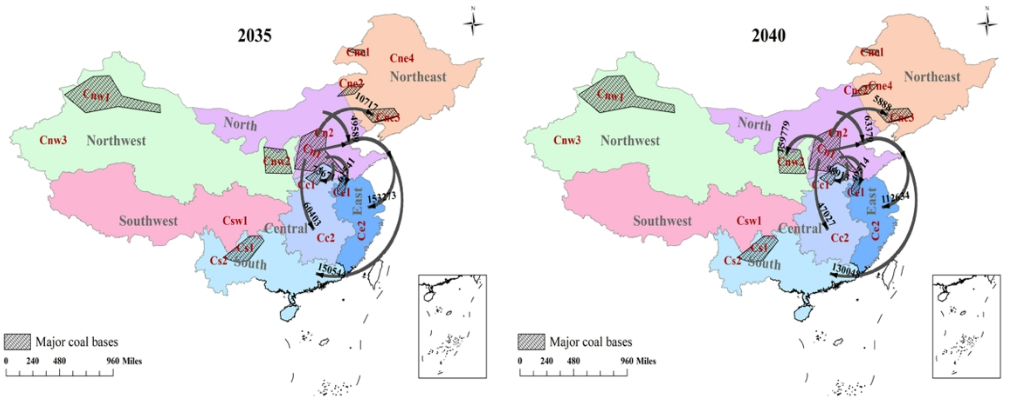
The model results show that most of electricity demand is satisfied by intra-regional power generation. However, a large amount of coal for producing electricity must be continuously transported to the South and the East, far away from the coal centers in the Northwest and the North, forming strong coal transportation flows across the country. Fig. 7 shows that, from 2020 to 2030, these coal transportation pathways will not change much, while the amount of transported coal will increase 12% in 2030 from 476154MWyr in 2020, specifically, coal transported from the North to the Central, the East, and the South will increase 8%, 11%, and 16%, respectively (see Fig.7a, b, and c). Moreover, the inter-regional coal transportation between the North and the Central will primarily depend on railways, while the South and the East will primarily rely on waterways.



(a) (b) (c)

Fig.7. Inter-regional coal transportation from 2020 to 2030

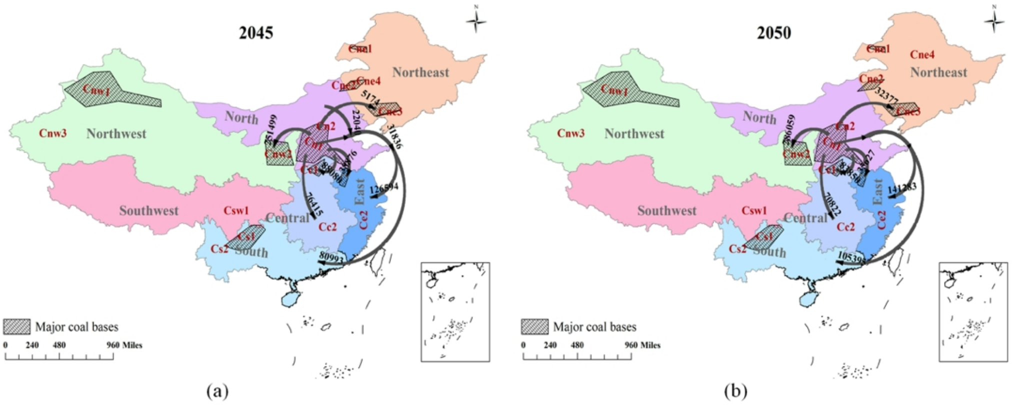
Fig. 8 shows that, in 2035 and 2040, coal will be transported from the North to the Northeast and the Northwest, which is not observed in 2030 in Fig.7c.



(a) (b)

Fig. 8. Inter-regional coal transportation from 2035 to 2040

In 2045, the coal transportation pathways are similar with those in 2040, while the amount of transported coal is different (see Fig.9a). Fig. 9b shows that coal will not be export from Cn2 region in 2050.



(a) (b)

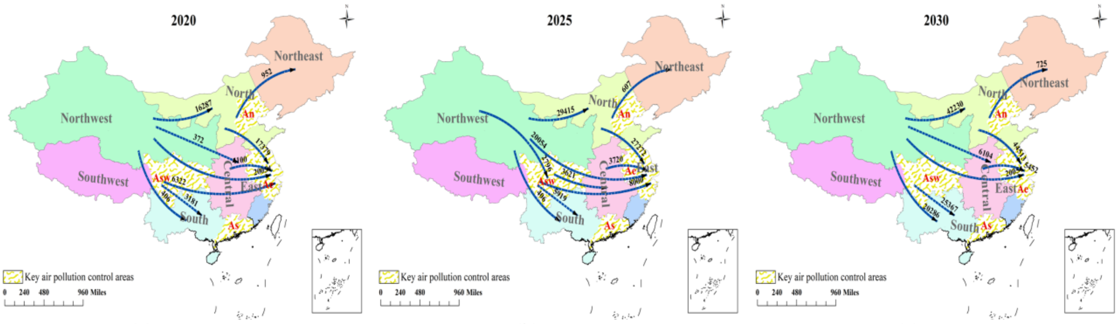
Fig.9. Inter-regional coal transportation from 2045 to 2050

In summary, the main coal exporting regions are the North, while the main coal importing regions include the East, the Central, and the South. The Southwest will not transport coal from other regions. This is because that the regional resource endowment is different, for instance, the North is rich in coal resource, while the Southwest is rich in hydropower. The direction of the coal flows in our results are almost identical to those in Ref [9, 12], although a different regional division is adopted.

4.3 Inter-regional electricity transmission

Compared to transporting coal, electricity transmission has received much more attention in recent years. With the maturity of UHV transmission technology, large-capacity and long-distance electricity transmission is becoming feasible with much less loss. Moreover, another advantage of UHV is that it can promote the uses of electricity generated from clean energy (e.g., wind and hydro) in remote areas and accordingly reduce the air pollutant emissions during transporting coals by trains, trucks, or ships.

From a medium-term perspective (by 2030), existing UHV transmission lines (see Table 7) cannot satisfy the inter-regional electricity transmission demand. New UHV transmission pathways should be developed in the future. Furthermore, the UHV transmission pathways from the Northwest, the North and the Central to the East, from the Northwest to the North, from the North to the Northeast, and from the Northwest and the Southwest to the South should be built by 2020 (see Fig. 10a), the pathways from the Northwest to the Southwest, from the Southwest to the Central should be adopted by 2025 (see Fig. 10b), and our results suggest there will be no need to build extra new UHV transmission lines in 2030 (see Fig. 10c).



(a) (b) (c)

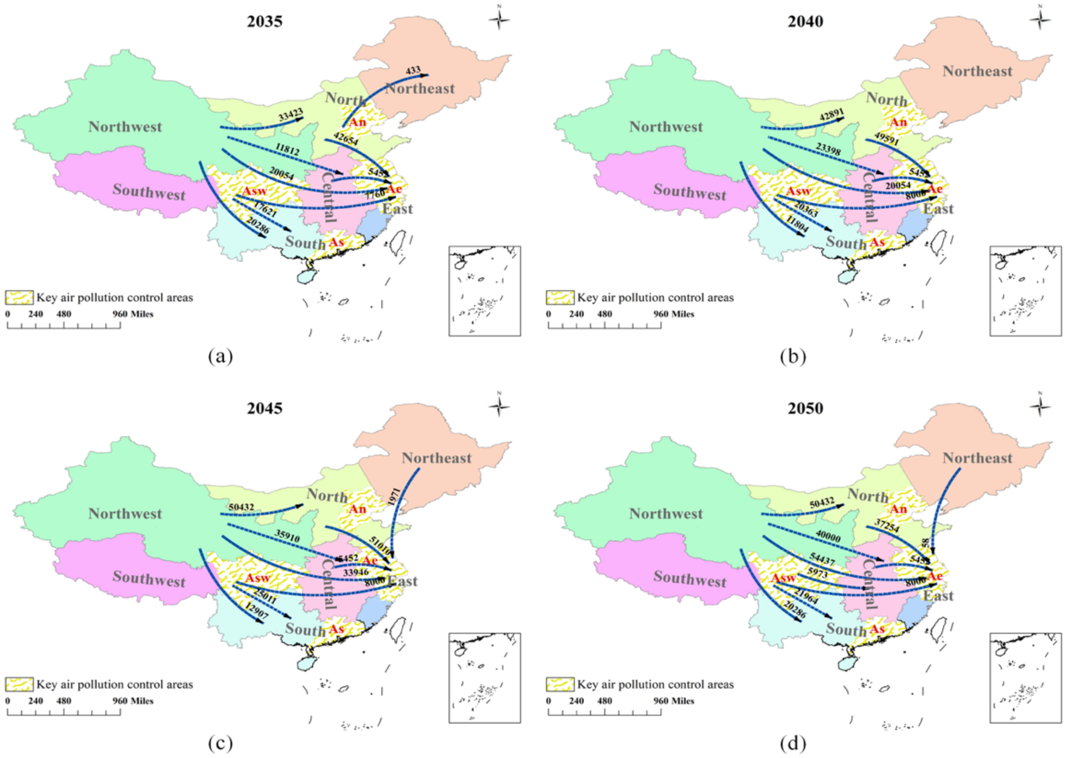
Fig. 10. Inter-regional electricity transmission from 2020 to 2030

It should be noted that some regions both transmit electricity out to and accept electricity in from other regions, which means that these regions function as regional electricity hubs. For example, the electricity transmitted from the Northwest is used to satisfy the intra-regional electricity demand of the Central, while electricity generated in the Central is transmitted to the East by UHV transmission lines. In addition, our results from a medium-term perspective also supported the view from Ref.[19] that the development of UHV grids would enable inter-regional power transmission, especially from the North and the Northwest to the East.

From a long-term perspective (2035–2050), we can see that, by comparing Fig.11a and Fig.11b, the electricity will not be transmitted from the North to the Northeast. From Fig.11c and Fig.11d, we can see that the electricity generated in the North, the Northwest, the Southwest and the Central will mainly be transmitted to the East and the South. Moreover, by drawing comparisons with the pathways adopted in the medium-term, we found that there would be need to build an extra new UHV transmission line from the Northeast to the East in 2045.

We compared our results in 2050 with those of existing studies Ref.[11, 54], and found that the direction of power flow in our results is quite similar to that of these existing studies, for instance, the power will be mainly transmitted from the Northwest, the Southwest and the Northeast to the East, the South, the North and the Central. However, we also found some differences, such as the power would be transmitted from the Northeast to the East instead of to the North in 2050, and the amount of electricity delivered is different to that of these existing studies due to we adopted a different region-division. Comparing with these two existing studies Ref.[11, 54], our research considered the coal transportation as an alternative way of energy transport, regional resource endowments and air pollution control policies, which was not considered in these two existing studies. Moreover, our study conducted a time-interval analysis from

2015 to 2050, which could suggest more comprehensive strategies for decision-makers in different period, such as 2035, 2040, 2045 and 2050.



(a) (b) (c) (d)

Fig. 11. Inter-regional electricity transmission from 2035 to 2050

4.4 Sensitivity analysis on the load rate of UHV lines

In the above, we assumed that the UHV lines were fully loaded at all times. This is an ideal situation to minimize the total cost of the system. However, in real world, most of time, transmission lines are not fully loaded (i.e., a load rate less than 1). Actually, in the initial period of UHV construction, UHV's load is low before the formation of the main grid. To enhance the reliability of our results, sensitivity analysis on load rate of UHV transmission lines is carried out in our study. We run the model with UHV's load rate as 50% and 80%, and analyze how the optimal results are influenced by different load rate.

Fig.12 presents the new installed capacity of UHV lines in different periods with different load rate of UHV lines. Not surprisingly, we can see the new installed capacity of UHV increases as the load rate decreases from 100% to 50%. In addition, the total system cost increases 0.13% and 0.58% when the load is 80% and 50% respectively. The sensitivity analysis also shows that, with different load rate, the main structure of the UHV as the transmission backbone do not change significantly in our results.

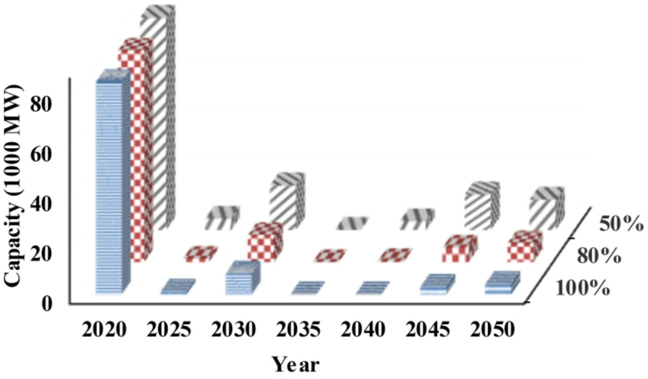
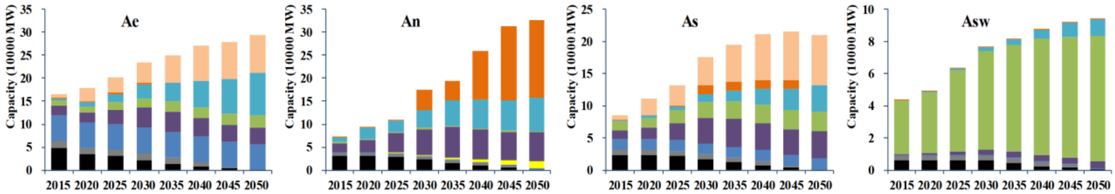


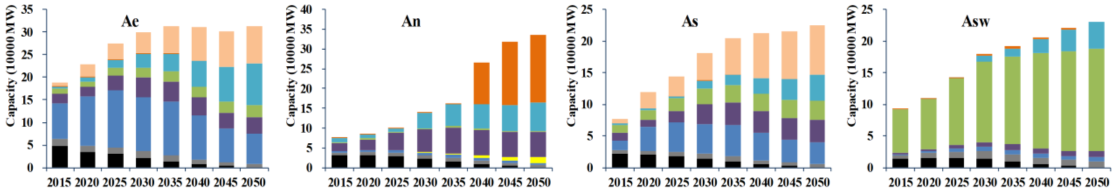
Fig.12. The new installed capacity of UHV transmission with different load rate

4.5 Effects of air pollution control policies

As mentioned in section 3.6.3, the Chinese government has developed various environmental policies to control the pollutant emissions and improve the air quality in the four key air pollution control areas. In order to explore how these air pollution control policies influence the regional installed capacity, we compared the electricity generation structure in the four key areas with (Fig. 13a) and without (Fig. 13b) the air pollution control polices (i.e., the new coal power plants in these areas must be CHP). From Fig. 13 we can see that the air pollution control polices not only raise the proportion of CHP coal power plant in these areas (especially in area An and As), but also raise the share of clean energy generation, especially in the North, more than half of electricity generation would be from PV in 2050. The policies make small difference in the Southwest because this region mainly depends on hydropower.



（a） with air pollution control policy

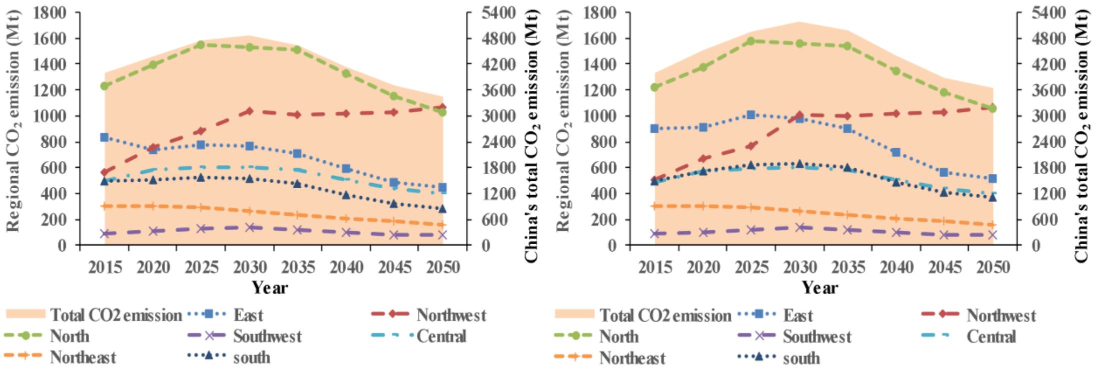


（b） without air pollution control policy

■ Subcritical ■ Supercritical ■ Ultra-supercritical ■ IGCC ■ CHP ■ Hydro ■ Wind ■ PV ■ Nuclear

Fig. 13. Installed capacity of power plants in the four key air pollution control areas

We also analyze how the air pollution control policies influence the CO_2 emissions by using the CO_2 emission factors of different power plants from Ref. [55]. Fig.14a shows the total CO_2 emission for different regions with air pollution control policies, and Fig.14b shows that without air pollution control policies. We can see that, in both Fig. 14a and Fig.14b, CO_2 emissions from most regions increase at first and then drop down over time, and all of them will experience a decrease from 2030 to 2050 except the Northwest. In addition, the highest CO_2 emissions is in the North, while the lowest is in the Southwest. Comparing Fig. 14a with Fig. 14b, we can see that the air pollution control policies will reduce the CO_2 emission in the East and the South quite a lot. Our results also show that the total amount of CO_2 emission of power generation in China will peak around 2030 (in both Fig. 14a and Fig.14b), and with the air pollution control policies, the total amount of CO_2 emission will be 4855Mt in 2030, around 16% less than that without the air pollution control policies.



(a) with air pollution control policies (b) without air pollution control policies

Fig.14. CO$_2$ emission of different regions

5. Conclusions

This paper developed a multi-regional optimization model to analyze China's electricity system, mainly focusing on electricity transmission and coal transport among regions and power generation structure in different regions from 2015 to 2050, taking into account regional resource endowments and the air pollution control polices in four key areas. The model minimizes the accumulative total cost of China's electricity system.

In the optimal results of our model, clean energy generation technologies will dominate China's power generation by 2050, even without the air pollution control polices as well as other emission constraints. This implies that from a long-term perspective, developing clean energy generation technologies would be an economic choice for China, in addition to being environmental-friendly.

The results of our model also show that the optimal structure of power generation in each region will be greatly influenced by regional resource endowments, for example, in the Cne2 (Huolinhe major coal bases), capacity expansion of coal power plants will be constrained by water shortage, and thus adopting more (and earlier) clean power generation technologies would be a good choice for this area. Our results show the air pollution control policies (i.e., new built coal power plants must be CHP) in the four key areas would reduce peak CO_2 emission (which will be in 2030) quite a lot (by around 16%), which implies such policies will not only improve air quality but also is very effective in reducing CO_2 emission, and the Chinese government would be encouraged to implement such policies gradually in other areas.

Our results show that both coal transportation and electricity transmission through UHV are important to balance power demand and supply among regions from a long-term perspective. For the construction of UHV transmission lines, our results suggest that, before 2020, high priority should be given to lines of Shanxi–Jiangsu (North–East), Ximeng–Taizhou (North-East), Jiuquan–hunan (Northwest–Central), Zhundong–Wannan (Northwest–East), and Longbin–Lianyungang (Northwest–East), and one more UHV line should be built from the Northeast to the East in around 2045.

The optimal pathways of energy transport will differ greatly under different policy objectives, and the development of inter-regional energy transport needs to be closely integrated with the macro energy policies and environmental goals. In addition, there could be uncertainties both in future electricity demands and in cost dynamics of new technologies. We would remind the readers of this paper that the optimal results presented in this paper would be subjected to additional factors and uncertainties, which have not been embodied in the model. Researchers (including us of course) should review China's electricity system continuously, especially when new technologies or social-economic problems emerge.

Acknowledgments

This work is supported by IIASA's Young Scientists Summer Program (YSSP) and sponsored by the National Natural Science Foundation of China (NSFC) [grant No. 71571069]. We appreciate the discussions with Prof. Krey Volker, Prof. Arnulf Grubler, and Dr. Makowski Marek during this research.

Appendix. Model formulation of China's electricity system

The objective function of the MESSAGE model of China's electricity system includes activity and capacity of technologies. The activity specifies input and output energy, efficiency, and variable O&M costs. Capacity includes the historical installed capacity, investment cost, fixed O&M cost, annual operation hours, lifetime, and the imposed limits on the installed capacity, as shown in Eq. (A.1).

$$\begin{aligned}
&\min \sum_{t}^{T}\sum_{k}^{K}\sum_{i}^{I}\sum_{n}^{N}\left(\frac{1}{1+\sigma}\right)^{t}[Vom_{kni}^{t}x_{kni}^{t}+Fom_{kni}^{t}(\sum_{t\ \tau_{kni}}^{t}y_{kni}^{t\ \tau_{kni}}+hc_{kni}^{0})+CF_{kni}^{t}y_{kni}^{t}] \\
&+\sum_{t}^{T}\sum_{s}^{S}\sum_{k}^{K}\sum_{m}^{M}\sum_{n}^{N}\left(\frac{1}{1+\sigma}\right)^{t}Com_{smkn}^{t}T_{smkn}^{t}+\sum_{t}^{T}\sum_{s}^{S}\sum_{k}^{K}\left(\frac{1}{1+\sigma}\right)^{t}(Com_{sk}^{t}+CF_{sk}^{t})\ T_{sk}^{t} \\
&+\sum_{t}^{T}\sum_{k}^{K}\sum_{n}^{N}\left(\frac{1}{1+\sigma}\right)^{t}p_{kn}^{t}r_{kn}^{t} \qquad \text{(A.1)}
\end{aligned}$$

The objective function is subject to several sets of constraints. The continuous decision variables x_{kni}^{t}, y_{kni}^{t}, T_{smkn}^{t}, and T_{sk}^{t} are non-negative, which yields:

$$x_{kni}^{t} \geq 0 \qquad \text{(A.2)}$$

$$y_{kni}^{t} \geq 0 \qquad \text{(A.3)}$$

$$T_{smkn}^{t} \geq 0 \qquad \text{(A.4)}$$

$$T_{sk}^{t} \geq 0 \qquad \text{(A.5)}$$

Let η_{kni}^{t} be the efficiency for the *i*th power generation technology at time *t* in the *n*th coal base covered by regional grid *k*. Coal extraction and imported coal should satisfy the demand of regional power generation.

$$r_{k}^{t}+\sum_{s}^{S}\sum_{m}^{M}\sum_{n}^{N}T_{smkn}^{t} \geq \sum_{n}^{N}\sum_{i}^{I}\frac{x_{kni}^{t}}{\eta_{kni}^{t}} \qquad \text{(A.6)}$$

Let f_{kni}^{t} be annual operation time percentage for the *i*th power generation technology at time *t* in the *n*th coal base covered by regional grid *k*. The installed capacity should satisfy the production of each power generation technology.

$$f_{kni}^{t} \times (\sum_{t\ \tau_{kni}}^{t} y_{kni}^{t\ \tau_{kni}} + hc_{kni}^{0}) = x_{kni}^{t} \tag{A.7}$$

Let Y_{kni}^{t} represent the upper limit of the installed capacity of coal power technology *i* at time *t* in the *n*th coal base covered by regional grid *k*. Let Y_{i}^{t} be the upper limit of total installed capacity of power technology *i* at time *t*. These two constraints can be described as follows:

$$y_{kni}^{t} \leqslant Y_{kni}^{t} \tag{A.8}$$

$$\sum_{k}^{K}\sum_{n}^{N} y_{kni}^{t} \leqslant Y_{i}^{t} \tag{A.9}$$

Electricity demand in each regional grid must be satisfied by regional power generation and electricity importing from other regional grids.

$$\sum_{n}^{N}\sum_{i}^{I} x_{kni}^{t} + \sum_{s}^{S} T_{sk}^{t} \geq D_{k}^{t} \tag{A.10}$$

Table A. Symbols for describing the model

Symbols	Symbols' meaning
t	Time period. year=*t*×5+2015, t=1, 2,..., 7.
s, k	Regional grids, including Northwest, North, Southwest, Central, Northeast, East, South. s=1, 2,…, 7*,* k=1,2,...,7*,* $s \neq k$.
i	Power generation technologies, including subcritical, supercritical, ultra-supercritical, IGCC, CHP, hydro power, wind power, nuclear power, and solar power. *i*=1, 2,...,9.
j	Energy transport technology, *j*=1, 2. (when j=1 presents coal transportation, when *j*=2 is UHV transmission)

m, n	Coal bases covered by the regional grids. m=1, 2,..., 5, n=1, 2 ,..., 5.
σ	Discount rates
τ_{kni}	Plant life of power generation technology i in the nth coal base covered by regional grid k
x_{kni}^{t}	Output of power generation technology i at time t in the nth coal base covered by regional grid k
y_{kni}^{t}	New installed capacity of power generation technology i at time t in the nth coal base covered by regional grid k
T_{smkn}^{t}	Output of coal transportation technology at time t from the mth coal base covered by regional grid s to the nth coal base covered by regional grid k
T_{sk}^{t}	Output of UHV transmission technology at time t from the regional grid s to the regional grid k
Vom_{kni}^{t}	Variable O&M cost of power generation technology i at time t in the nth coal base covered by regional grid k
Fom_{kni}^{t}	Fix O&M cost of power generation technology i at time t in the nth coal base covered by regional grid k
hc_{kni}^{0}	Historical capacity of power generation technology i at year 2014 in the nth coal base covered by regional grid k
CF_{kni}^{t}	Investment cost of power generation technology i at time t in the nth coal base covered by regional grid k
Com_{smkn}^{t}	O&M cost of coal transport technology at time t from the mth coal base covered by regional grid s *to* the nth coal base covered by regional grid k
Com_{sk}^{t}	O&M cost of UHV transmission technology at time t from regional grid s to regional grid k
CF_{sk}^{t}	Investment cost of UHV transmission technology at time t from regional grid s to regional grid k
p_{kn}^{t}	Fuel price at time t in the nth coal base covered by regional grid k
r_{kn}^{t}	Extraction of coal resource at time t in the nth coal base covered by regional grid k

Fig. A. 1 gives the projections on China's electricity demand from different references.

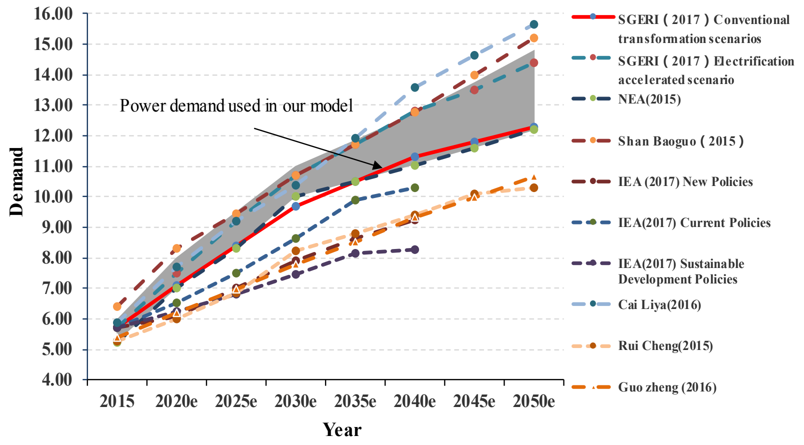


Fig. A.1. Projections on China’s electricity demand from different references

References

[1] NBSC. Statistical communique of the people's republic of China on the 2006. National economic and social development. 2007.

[2] NBSC. Statistical Communique of the People's Republic of China on the 2016. National Economic and Social Development. 2017.

[3] Xu J, Zhou M, Li H. The drag effect of coal consumption on economic growth in China during 1953–2013. Resources Conservation & Recycling. 2016.

[4] Wei W, Wu X, Wu X, Xi Q, Ji X, Li G. Regional study on investment for transmission infrastructure in China based on the State Grid data. Frontiers of Earth Science. 2017;11(1):162-83.

[5] Chen Q, Kang C, Ming H, Wang Z, Xia Q, Xu G. Assessing the low-carbon effects of inter-regional energy delivery in China's electricity sector. Renewable and Sustainable Energy Reviews. 2014;32:671-83.

[6] Li Y, Lukszo Z, Weijnen M. The impact of inter-regional transmission grid expansion on China’s power sector decarbonization. Applied Energy. 2016;183:853-73.

[7] Huang D, Shu Y, Ruan J, Hu Y. Ultra high voltage transmission in China: developments, current status and future pospects. Proceedings of the IEEE.

2009;97(3):555-83.

[8] Lo K. A critical review of China's rapidly developing renewable energy and energy efficiency policies. Renewable and Sustainable Energy Reviews. 2014;29:508-16.

[9] Mou D, Li Z. A spatial analysis of China's coal flow. Energy Policy. 2012;48:358-68.

[10] 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.

[11] Cheng R, Xu Z, Liu P, Wang Z, Li Z, Jones I. A multi-region optimization planning model for China’s power sector. Applied Energy. 2015;137:413-26.

[12] Chen G, Chen B, Zhou H, Dai P. Life cycle carbon emission flow analysis for electricity supply system: A case study of China. Energy Policy. 2013;61:1276-84.

[13] Yi B, Xu J, Fan Y. Inter-regional power grid planning up to 2030 in China considering renewable energy development and regional pollutant control: A multi-region bottom-up optimization model. Applied Energy. 2016;184:641-58.

[14] Zheng Y, Hu Z, Wang J, Wen Q. IRSP (integrated resource strategic planning) with interconnected smart grids in integrating renewable energy and implementing DSM (demand side management) in China. Energy. 2014;76:863-74.

[15] Zhang N, Hu Z, Shen B, Dang S, Zhang J, Zhou Y. A source–grid–load coordinated power planning model considering the integration of wind power generation. Applied Energy. 2016;168:13-24.

[16] Zhang N, Hu Z, Shen B, He G, Zheng Y. An integrated source-grid-load planning model at the macro level: Case study for China's power sector. Energy. 2017;126:231-46.

[17] 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. Computers & Chemical Engineering. 2012;37:227-47.

[18] Ming Z, Xiaohu Z, Ping Z, Jun D. Overall review of China′s thermal power development with emphatic analysis on thermal powers' cost and benefit. Renewable and Sustainable Energy Reviews. 2016;63:152-7.

[19] Guo Z, Ma L, Liu P, Jones I, Li Z. A multi-regional modelling and optimization approach to China's power generation and transmission planning. Energy. 2016;116:1348-59.

[20] Niu D, Song Z, Xiao X. Electric power substitution for coal in China: Status quo and SWOT analysis. Renewable and Sustainable Energy Reviews. 2017;70:610-22.

[21] Zhou N, Fridley D, Khanna NZ, Ke J, McNeil M, Levine M. China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model. Energy Policy. 2013;53:51-62.

[22] Gao C, Sun M, Shen B, Li R, Tian L. Optimization of China's energy structure based on portfolio theory. Energy. 2014;77:890-7.

[23] SGCC. State Grid Corporation of China. <http://www.sgcc.com.cn/ywlm/projects/list/index.shtml> accessed 2016.

[24] CSG. China Southern Power Grid. <http://eng.csg.cn/Science_Innovation/UHVDC/201512/t20151209_109562.html>accessed 2015.

[25] Shang Y, Lu S, Li X, Hei P, Lei X, Gong J, et al. Balancing development of major coal bases with available water resources in China through 2020. Applied Energy. 2017;194:735-50.

[26] Wu D, Zhang N, Kang C, Ge Y, Xie Z, Huang J. Techno-economic analysis of contingency reserve allocation scheme for combined UHV DC and AC receiving-end power system. CSEE Journal of Power and Energy Systems. 2016;2(2):62-70.

[27] Lin B, Yao X. Power industry location optimization and integrative energy transportation system. Economic Research Journal. 2009;6:105-15.

[28] Hainoun A, Seif Aldin M, Almoustafa S. Formulating an optimal long-term energy supply strategy for Syria using MESSAGE model. Energy Policy. 2010;38(4):1701-14.

[29] Messner S, Golodnikov A, Gritsevskii A. A stochastic version of the dynamic linear programming model MESSAGE III. Energy. 1996;21(9):775-84.

[30] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews. 2011;15(1):150-68.

[31] Cai L, Wang S, Liu F. Research on future nuclear power development space in China. Energy of China. 2016;38:25-31.

[32] Shan B, Han X, Tan X. Research on electricity demand of China during the 13 (th) Five-Year Plan and med-term-&long-term periods. Electric Power. 2015;48(1):6-10.

[33] SGERI. China Energy and Electricity Outlook 2017. Beijing: China electric power press. 2017.

[34] IEA. World Energy Outlook 2017: Organisation for Economic Co-operation and Development, OECD. 2017.

[35] NEA. Medium and long term power generation capability and electricity demand forecast in China. Beijing. 2013.

[36] CEC. State power industry statistics data. Beijing: China Electricity Council. 2015.

[37] Chang Z, Wu H, Pan K, Zhu H, Chen J. Clean production pathways for regional power-generation system under emission constraints: A case study of Shanghai, China. Journal of Cleaner Production. 2017;143:989-1000.

[38] Dai H, Xie X, Xie Y, Liu J, Masui T. Green growth: The economic impacts of large-scale renewable energy development in China. Applied energy. 2016;162:435-49.

[39] CNREC. China renewable energy technology catalogue. 2014.

[40] China electric power yearbook 2014. Beijing: China Electric Power Press; China Electric Power Year book Editorial Committee. 2015.

[41] HUOCHEPIAO. Railway mileage inquiries. <http://www.huochepiao.com/licheng/>2016.

[42] Yu S, Wei YM, Guo H, Ding L. Carbon emission coefficient measurement of the coal-to-power energy chain in China. Applied Energy. 2014;114(2):290-300.

[43] Ding W, Hu Z. The research on the economy comparison of ultra high voltage. Power System Technology. 2006;30(19):7-13.

[44] NBSC. National Bureau of Statistics of China. <http://data.stats.gov.cn/>accessed 2016.

[45] IMCEC. National and Provincial Coal Price Index. Inner Mongolia Coal Exchange Center. 2015.

[46] Kim S, Ko W, Nam H, Kim C, Chung Y, Bang S. Statistical model for forecasting uranium prices to estimate the nuclear fuel cycle cost. Nuclear Engineering and Technology. 2017;49(5):1063-70.

[47] Zhang X, Liu J, Tang Y, Zhao X, Yang H, Gerbens-Leenes PW, et al. China's coal-fired power plants impose pressure on water resources. Journal of Cleaner Production. 2017;161:1171-9.

[48] Jiang D. China 1km grid water resourceds data set. National earth system science data sharing platform. 2007.

[49] Macknick J, Newmark R, Heath G, Hallett KC. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environmental Research Letters. 2012;7(4):189-90.

[50] Coalswarm. Global coal plant tracker. <https://endcoal.org/tracker/2015>.

[51] Hu ZT, Xiandong; Xu, Zhaoyuan. 2050 China's economic development and the exploration of electricity demand - based on the power supply and demand research laboratory (ILE4) simulation experiment. Beijing: China Electric Power. 2011.

[52] Shan B, Han X, Tan X, Wang y, Zheng y. Research on electricity demand of China during the 13th Five-Year Plan and med-term and long-term periods. Electric Power. 2015;48(1):6-11.

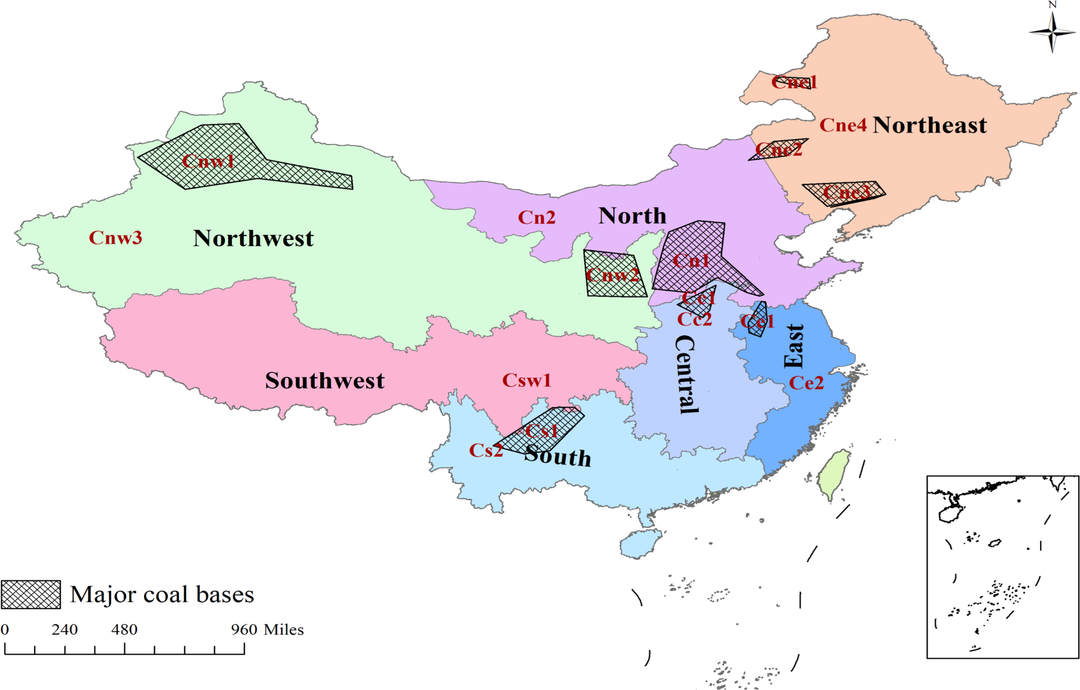
[53] Wu J. China electric power industry 2010-2050 low carbon development strategy research. Beijing: China Water and Hydropower Press. 2012.

[54] Hui J, Cai W, Wang C, Ye M. Analyzing the penetration barriers of clean generation technologies in China's power sector using a multi-region optimization model. Applied Energy. 2017;185:1809-20.

[55] Ma Z. Comparative evaluation and research for the emission coefficients of several main energy greenhouse gases in China: China Institute of Atomic Energy. 2002.

Highlights

- A multi-regional optimization model of China's electricity system is developed.
- The share of clean energy generation will increase from 24% in 2015 to 62% in 2050.
- Resource endowment and environmental policy will affect regional energy structure.
- The energy transport between regions are mapped from 2020 to 2050.


N
Cne1
Cne4
Northeast
Cne2
Cne3
Cnw1
Cn2
North
Cnw3
Northwest
Cn1
Cnw2
Cc1
Cc2
Ce1
East
Central
Southwest
Csw1
Ce2
Cs1
Cs2
South
▨ Major coal bases
0
240
480
960 Miles