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A Grid-Structure Based Multi-Region Optimisation Model for the Development of Power Generation Sector in China

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Power demand in China has increased over years and is expected to further expand in the future. The disparity of resources distribution and load dispatch for regions requires regional analyses rather than taking China as a single entity. Meanwhile subsidy policies for clean energy and power prices will largely affect the development of the power sector in a long-term. In this paper, a multi-region model based on grid structures is built aiming for maximising profits gained by China's power generation sector from 2013 to 2050. A case study is performed demonstrating deployment trends for technologies and the utility of transmission capacity. The results indicate different developing strategies for regions and the importance of energy subsidies. In addition, power transmission utility is analysed and discussed.

1. Introduction

China has experienced a rapid economic growth as well as sharp increase in power demand, from 1,347.3 TWh in 2000 to 4,976.8 TWh in 2012 (NBSC, 2014). Electricity demand was expected to further increase in the future (Hu et al., 2009) and pathways for the development of power capacity are worth studying.
Many studies focus on analysing China's power sector by taking the whole country as a single entity. Cai et al. (2007) analysed the development of China's power sector in various policy scenarios by the Long-range Energy Alternatives Planning System (LEAP) and gave CO_2 reduction potential. Zhu and Fan (2010) adapted portfolio theory to optimise China's power sector in three scenarios. Zhang et al. (2012) developed a model optimising costs for China's power sector while considering carbon markets and CCS technologies. However, these studies do not distinguish regional natural resources and power demand differences.
Gnansounou and Dong (2004) considered power transmission between two provinces in China and integrate their electricity markets. Wang and Nakata (2009) divided China into coastal and inland areas and discussed the development of clean coal technologies concerning different environmental policies. Notably, these simplified divisions cannot reflect the actual situation of China's power sector. Cheng et al. (2015) divided China into 10 parts based on physical grid structures and minimised total costs with the consideration of electricity transmission. Nevertheless, this work does not consider transmission capacity and cross-region transmission. Though studies for India (Parikh and Chattopadhyay, 1996) and Greece (Koltsaklis et al., 2014) took regional variations and electricity transmission into account, electricity markets and policies in these countries are much different from China. Thus, this paper established a multi-region model, considering actual grid structures and capacity, resource distribution and energy subsidy policies, in order to give an insight into the long-term development of China's power generation sector.

2. Methodology

2.1 Model structures and assumptions

Based on the current physical structure of grids, China is divided into seven regions: Northeast, North, Central, East, South, Northwest and Tibet (Zhou et al., 2010). Among these grids, Tibet grid, as well as Hainan, Hong Kong, Macau and Taiwan, are relatively independent ones and their load are insignificant compared to the others, thus they are not considered in this model. In addition, natural resource

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endowment are important. According to the Ultra-high Voltage (UHV) transmission projects proposed by the State Grid Corporation of China (SGCC, 2014), Inner Mongolia and Xinjiang will become main electricity exporting provinces due to their abundant coal reserves and developable renewable resources. Owing to these considerations, China is modelled as 8 regions reflecting physical grid structures as well as natural resources. As shown in Figure 1, 8 regions are as follows: Northeast (Heilongjiang, Jilin and Liaoning), North (Beijing, Tianjin, Hebei, Shanxi and Shandong), Inner Mongolia, Central (Jiangxi, Hubei, Hunan, Henan, Sichuan and Chongqing), East (Shanghai, Jiangsu, Zhejiang, Anhui and Fujian), South (Yunnan, Guizhou, Guangxi and Guangdong), Northwest (Shaanxi, Gansu, Ningxia and Qinghai), and Xinjiang.

Figure 1: Regional division of China based on grid structures and natural resources

In terms of power generation technologies, 7 types are considered: pulverised coal (PC), ultra-supercritical coal (USC), natural gas combined cycle (NGCC), nuclear (NU), hydroelectric (HD), wind power (WD) and photovoltaic (PV). These technologies have the potential to be largely deployed across the country (The State Council, 2013). Based on their different feed-in tariff policies, they are divided into two categories. The first one includes PC, USC, NGCC and HD, whose on-grid prices are regulated by the government at any time. The second category includes NU, WD and PV, whose on-grid prices are either a strike price or a feed-in tariff decided by the time when the plant is put into operation. Due to the lack of CCS experiences and current governmental policies nationwide, CCS equipment is not considered in this model.
In order to introduce power transmission between regions, this model considers currently built extra-high and ultra-high voltage power transmission lines, proposed ultra-high voltage power transmission lines and their transmission losses. International transmission is neglect due to its relatively low amount compared to national power demand (NBSC, 2012).

2.2 Mathematical equations
Mathematical equations of the model are presented in this section. These equations can be classified into two groups. The first group includes objective function and expressions of its relative variables. The second group indicates physical constrains. Four sets, t, r, g and f, stand for time, region, power generation type and fuel type, respectively. Meanwhile, t and t', r and r' share the same set in the equations.

2.2.1 Objective function
The objective function of this model is to maximise accumulated profits gained by power sector from 2013 to 2050. As expressed in Eq(1), the sum of regional profits is leveraged to 2013 and totted up.

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

Profits equals to revenues less costs. Costs consist of three parts: capital costs for constructing new capacity, operation and maintenance costs, and fuel costs, and can be calculated by Eq(2).

$$rc_{t,r} = tinv_{t,r} + tom_{t,r} + tfc_{t,r} \tag{2}$$

2.2.1.1 Regional revenues
For the first and second groups of technologies, revenues can be calculated by Eq(3) and Eq(4). Operating hours are referred to statistical materials (SERC, 2011) and their on-grid prices consider

governmental documents, including the latest feed-in tariff policies for wind (NDRC, 2014b) and solar PV (NDRC, 2013). On-grid prices for the first group are decided by the time when new capacity is added. Those for the second group are regulated by the government at any time.

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

$$rreve_{t,r,g} = ic_{g,t,r} \cdot OH_{r,g} \cdot OGP_{g,r,t} \quad (4)$$

2.2.1.2 Regional costs

Three parts of costs can be calculated by Eqs(5) to (7), respectively. Capital costs referring to OECD's report (OECD, 2010) are leveraged to annum. Total lifetimes (TLT) are referred to IEA's report (OECD, 2010). O&M costs are assumed to be part of capital costs. Fuel costs are decided by Fuel Price (FP), Fuel Consumption Rate (FCR) and the power generated.

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

$$tom_{t,r} = \sum_{g} om_{g,t,r} = \sum_{g} \left(\mu_g \cdot ic_{g,t,r} \right) \quad (5)$$

$$tfc_{t,r} = \sum_{f} fc_{f,t,r} = \sum_{f} \left(FP_{f,t,r} \cdot rfd_{f,t,r} \right) = \sum_{f} \left(FP_{f,t,r} \cdot \sum_{g} fd_{g,f,t,r} \right) = \sum_{f} \left(FP_{f,t,r} \cdot \sum_{g} \left(pg_{g,t,r} \cdot FCR_{f,g,t} \right) \right) \quad (7)$$

2.2.2 Physical constrains

2.2.2.1 Power demand and supply

Regional Power Demand (PD) is met by electricity generated in its own region and transmitted in or out (losses are included). Ideal transmission power from r' to r equals to the negative value of that from r' to r, and is limited by transmission capacity(SGCC, 2014). These expressions can be written as Eqs(8) to (11).

$$PD_{t,r} = \sum_{g} pg_{g,t,r} + ttr_{t,r} = \sum_{g} ic_{g,t,r} \cdot OH_{r,g} + ttr_{t,r} \quad (8)$$

$$ttr_{t,r,r'} = \begin{cases} itr_{t,r,r'} & (r \text{ is the exporting region}) \\ [1-TRLOSS_{r,r'}] \times itr_{t,r,r'} & (r \text{ is the importing region}) \end{cases} \quad (9)$$

$$itr_{t,r,r'} = -itr_{t,r',r} \quad (10)$$

$$itr_{t,r,r'} \le TRLIMIT_{r,r',t} \quad (11)$$

Regional power demand in year t is extrapolated based on historical power demand (NBSC, 2012) as well as governmental projections (Hu et al., 2009). Transmission loss rates between regions are calculated referring studies on UHV transmission (Zhao et al., 2009) and actual distances.

2.2.2.2 Installed capacity

This model assumes that all types of technologies will be decommissioned at the end of their lifespan. Thus the installed capacity of type g in region r in year t can be expressed as Eq(12).

$$ic_{g,t,r} = \sum_{t'=t-TLT_g+1}^{t} nbc_{g,t',r} \quad (12)$$

Installed capacity for existing plants refer to statistical books (China Electricity Council, 2009) and annual reports (EBCEPY, 2013). Considering resource endowment, maximum regional installed capacity for renewable (CAE, 2010) limits their deployment, as shown in Eq(13). New built capacity is constrained by construction practicality, referring to historical experiences (EIA, 2011), as noted in Eq(14). In addition, targets for clean energy (NDRC, 2014a) are included. Furthermore, it is assumed no nuclear plants will be added in Northwest, Xinjiang and Inner Mongolia due to its abundant coal reserves.

$$ic_{g,t,r} \le IC_{g,r}^{ub} \quad (13)$$

$$\sum_{r} nbc_{g,t,r} \leq NB_{g}^{ub} \quad (14)$$

2.2.2.3 Fuel supply

Annual total fuel demand must not exceed Fuel Supply Capacity (FSC), as expressed in Eq(15). The capacity is both limited by domestic productivity (NBSC, 2013) and international availability (IAEA, 2009).

$$\sum_{r} tfd_{f,t} \leq FSC_{f}^{ub} \quad (15)$$

2.2.2.4 Assumptions for economical parameters

Capital costs for technologies are expected to decline gradually through to 2050 with different rates. The model assumes that on-gird prices for coal-fired plants will remain stable, and those for others will be regulated by policies (The State Council, 2014). Fuel prices take the current coal and gas prices (China's Chemical Products Web, 2015) and are set to be flat. Discount rate is assumed to be at 7 %.

3. Results and discussions

The Linear Programming Solver of the General Algebraic Modelling System (GAMS) was used in this paper for modelling and optimisation.

3.1 Installed capacity for technologies in regions

Installed capacity in North, East, Central and South regions will share some similarities as shown in Figure 2. Hydroelectric power will be exploited, notably in Central and South. Solar and wind will not be well deployed due to insufficient subsidy policies. In order to meet increasing power demand, thermal power plants will remain the majority and USC plants will gradually replace PC plants through to 2050. NGCC will not be deployed in these areas concerning high gas prices. Nuclear power will have the priority to develop in the East to fulfil the national clean energy targets as well as meet its demand by 2050.

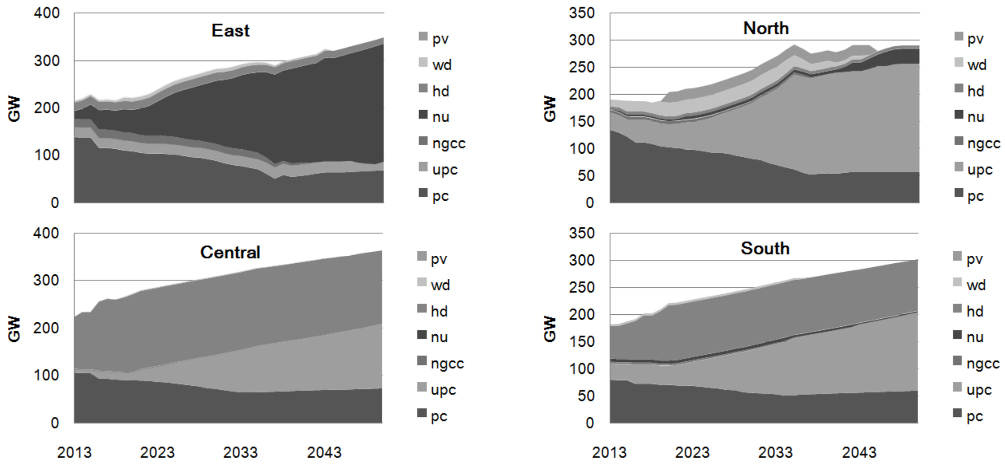

Figure 2: Installed capacity for technologies in East, North, Central and South

In terms of regions with abundant wind and solar sources, wind power will develop rapidly by 2020 in Northeast and Northwest because of the national clean energy targets as well as the cease of feed-in tariff for wind by 2020, and though to 2050 in Xinjiang owing to declining capital costs (shown in Figure 3). PV will experience rapid development by 2020 in Xinjiang and Inner Mongolia, but no new addition in Northeast and Northwest due to insufficient subsidies. These indicate the importance of subsidies for wind and solar power as well as the strong national targets. PC will remain popular in Northwest, Xinjiang and Inner Mongolia until 2035 owing to low coal prices. NGCC will expand in the three areas because of low gas prices and subsidies for gas plants.

Uncertainties for fuel prices and capital costs may largely affect the results. For instance, if gas price could drop significantly in the future, install capacity for NGCC would increase notably compared to the case performed above. On the other hand, if capital costs for wind and solar could decline faster than the rate set in the case, more capacity would be installed. However, the paper aims at performing a case study based on reasonable assumptions and giving insights into the power sector rather than predicts the future.

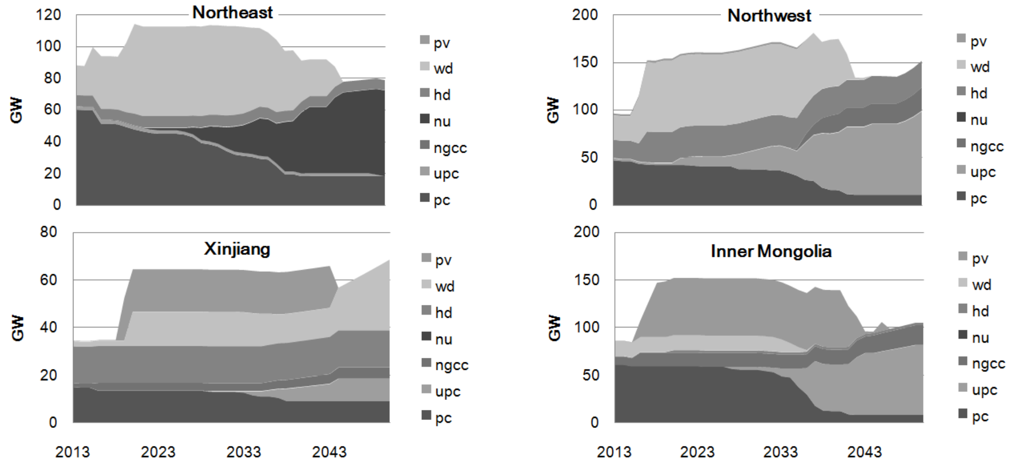

Figure 3: Installed capacity for technologies in Northeast, Northwest, Xinjiang and Inner Mongolia

3.2 Power transmission

Actual transmitted power is compared to theoretical transmission capacity to examine the utility of proposed UHV lines. By analysing the results between 2040 and 2050, some transmission lines will reach its maximum capacity. These are from North to East, Central to East and South, Northwest to East and North, and Inner Mongolia to Northeast (black arrows in Figure 4). The rest is unused, from Xinjiang to the other regions, North to Central, Northwest to Central, Northeast to North, and Inner Mongolia to East and Central. East is load centred, and will receive power from other regions due to its high fuel prices. Central area tends to export power rather than import due to its abundant hydropower. For the three resource-rich regions, Northwest is the only one exporting large amount of power. Xinjiang and Inner Mongolia lacks the momentum to export power due to relatively low on-grid prices and long-distance transmission losses.

Figure 4: Power transmission schematics between 2040 and 2050

4. Conclusions

In this study, a model reflecting natural resource endowment and grid structures is built aiming for maximising profits for power generation sector in China. Various energy subsidy policies are considered in order to deliver pathways for the development from 2013 to 2050.

For thermal power, USC will gradually replace PC, but relatively late in Northwest, Xinjiang and Inner Mongolia where coal is relatively cheap, and NGCC will only develop in these three regions due to low-cost gas. With respect to clean energy, hydropower will be fully exploited. Energy subsidies and national targets are important to the deployment of wind and PV both in the short term and long term. Nuclear will be competitive in the East and Northeast due to high regional prices for fossil fuel.

Utility of transmission lines between regions varies significantly. For load-centred regions with high fuel prices, such as East, transmission capacity will be fully used. Regions with abundant hydropower like Central will tend to dispatch its regional power rather than importing power. With respect to resource-rich regions, subsidies for renewable and incentives for coal plants are required to stimulate power exporting.

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