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Multi-objective optimization for power generation mix focusing on reducing carbon emission and mitigating water scarcity

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Abstract— Global warming and water scarcity are two serious cases that the whole world is facing. The electric power system is a carbon-intensive and water-intensive department emitting and consuming a large amount of carbon dioxide and water respectively. Emerging renewable technology to the power generation system is a solving method and tendency for reducing carbon emissions and the water consumption but taking time to be realized. In this case, deploying an optimal power generation mix under the existing condition should be considered to mitigate those cases. In this paper, an optimal power generation redistribution model is utilized to minimize the total amount of national carbon emissions, and water consumption of arid regions. Case study for 30 provinces of China in 2015 is selected. Five power generation types, namely, thermal power, hydropower, nuclear power, wind power and solar power are discussed. The upper and lower boundary of provincial electricity generation with different energy resources are quantified to limit the adjustment range. The results show that the total carbon emissions can be reduced 1.3% after optimization; the water consumption in provinces like Shandong, Hebei, Tianjin, Beijing and Shanxi facing water scarcity is decreased, which can mitigate the water scarcity to some extent. The optimization results preliminarily revealed the optimization model is effective and could provide a new perspective to optimize the power generation of regions in China.

Keywords—carbon emissions, water consumption, mitigation, optimization, power generation mix

I. Introduction

A major current focus on dealing with global climate change is how to reduce greenhouse gas emissions (GHG), and carbon dioxide is one of the common GHG that aggravating global climate change. As the biggest carbon dioxide emitter all over the world, China should take action to reduce carbon emissions. The Chinese government aims to make carbon emissions reaching a peak in 2030, and has signed the Paris agreement in 2015 [1]. Most of carbon emissions come from the energy system in human activity, like electricity generation, which consumes much water as well. Meanwhile, water scarcity is another increasingly serious problem worldwide, and nearly 40% of the global population is under pressure from water scarcity [2]. In China, approximately, 34-38% population living in water shortage areas face water scarcity more than one month per year [3]. Thus, cutting carbon emissions and mitigating water scarcity are vital issues that we should pay attention to, and the electric power sector is selected as an angle and cut-in point to mitigate those problems in this research.

With growing interest, much research has focused on the relationship between the electric power system and water resources, or analyzing carbon emissions of electricity generation. For example, a methodology was applied to the Brazilian electricity apartment to manage the GHG with carbon sources diagram [4]. According to a detailed inventory, the study [5] analyzed and calculated carbon emissions that came from power grid projects. In addition, studies pointed out that the concept of virtual water (VW) could help to analyze the water footprint in different sectors, promote the improvement of water policies and water resources management, which is a useful tool to mitigate water shortage [6-7]. In the inter-provincial level of China, by quantitatively analyzing VW and virtual scarce water transfers embodied in electricity transmission, the feature of electricity-water nexus was pointed out [6].

It is noted that the electric power system is a carbon-intensive and water-intensive department, but much research considers carbon factor and water sector separately when investigating them within the power generation system, which does not comprehensively. Besides, although some researches had noticed both the carbon and water footprint in electricity, a specific strategy for regional power generation mix was insufficient [8-9]. Therefore, this paper aims to establish an optimization model to enhance the power generation mix, which can reach the goal of having relatively low carbon emissions and positive effect on water scarcity at the same time. The equality constraint is that the total power generation should meet the total power generation demand. What is more, the specific inequality constraint is assumed for each province with various power generation types. After optimization, carbon emissions related to power generation can be reduced 1.3% totally, and areas with heavy water scarcity tend to consume less water through redistributing the mix of power generation. The results could put forth a strategy for the government as a reference when planning future power generation tasks, which is more environmentally friendly and reasonable.

II. METHOD

A. *Objective function*

The main objective of the optimization model is used to minimize the water consumption in water shortage areas and reduce carbon emissions by redistributing the power generation mix at the provincial level. In this case, dry area will have less burden in generating electric power while more power generation tasks are allocated to the area that has sufficient water. At the same time, in order to meet the goal of emitting less carbon dioxide, this model gives a way to redistribute the power generation mix. Here, the total amount of virtual water and carbon emissions contribute to the objective function, which is expected to be minimal.

$$\min[F = \sum_{i=1}^{30}(WSI_i \cdot W_i + C_i)] \tag{1}$$

where water stress index (WSI) is a constant; i represents the province; W_i is the total amount of virtual water volumes; C_i is the total amount of carbon emissions.

$$W_i = \sum_{j=1}^{5}(E_{i,j}^{gen} \cdot VWC^j) \tag{2}$$

$$C_i = \sum_{j=1}^{5}(E_{i,j}^{gen} \cdot CEC^j) \tag{3}$$

where j stands for different energy sources that are used in power generation, and the referring relationship is shown in Table 1; $E_{i,j}^{gen}$ represents the amount of power generation of the i^{th} province by using the j^{th} energy source after optimization. VWC^j is a constant related to the virtual water when the electricity is generated by the source *j*. CEC^j is a constant related to carbon emissions of when the electricity is generated by the source *j*.

$$\min\left\{F = \sum_{i=1}^{30}[WSI_i \cdot \sum_{j=1}^{5}(E_{i,j}^{gen} \cdot VWC^j) + \sum_{j=1}^{5}(E_{i,j}^{gen} \cdot CEC^j)]\right\} \tag{4}$$

By combining equation (2) and (3), equation (1) can be shown as equation (4).

TABLE I. THE POWER GENERATION TECHNOLOGY BY USING DIFFERENT ENERGY SOURCES

The value of j	Energy Sources
1	Coal
2	Water
3	Nuclear
4	Wind
5	Solar

B. *Constraints*

- *Power generation balance*

The constraint for power generation balance is treated as the equality constraint, which can be express as the formula (5) below:

$$C_i = \sum_{j=1}^{5}(E_{i,j}^{gen} \cdot CEC^j) \tag{5}$$

The meaning of this formula is that the amount of power generation should fully meet the power demand in provinces with 5 generation types are taken into account. E_i^{dmd} represents the total amount of power demand in province *i*.

- *Generation capacity*

The power generated by *j* technology from the *i* province is restricted by the generation capacity formula below:

$$PGC_{i,j\min} \le PGC \le PGC_{i,j,\max} \tag{6}$$

where $PGC_{i,j\min}$ and $PGC_{i,j,\max}$ mean the minimum and maximum amount of power generation by the technology *j* in the province *i* respectively.

- *Transmission line constraints*

Constraint (7) considers the transmission line loss.

$$AT_{mn}(A^T - L) - [T_{mn}A^T]^T = E_i^{dmd} - \sum_{j=1}^{5}E_{i,j}^{gen} \tag{7}$$

$$T_{mn} < TLC \tag{8}$$

where A is a 1×30 matrix, and $A=[1,1,\cdots,1]$; L represents transmission line loss; T_{mn} means power transmission amount from m province to n province; transmission line capacity (*TLC*) is the maximum capacity from one province to another.

III. Data Source

Water stress index (WSI) proposed by Pfister [11] is applied to demonstrate various water scarcity situations in thirty provinces of China that are discussed in this paper. According to the WSI value, provinces are categorized in to three classes—class 1 (extremely water-deficient areas), class 2 (general water-deficient areas) and class 3 (water sufficient areas). The detailed classification is shown in Table 2. For the data used for calculation or as a reference, such as the amount of power generation by different power generation technology in each province, generation capacity, and utilization hours, it can be found in China Electric Power Yearbook [12] and China Energy Statistical Yearbook [13].

TABLE II. Classification For Thirty Provinces

Classification	Provinces
Class 1	Beijing (BJ), Tianjin (TJ), Shanghai (SH), Shanxi (SX), Shandong (SD), Hebei (HEB), Ningxia (NX), Xinjiang (XJ), Jiangsu (JS), Gansu (GS), Shaanxi (SAX)
Class 2	Qinghai (QH), Henan (HEN), Liaoning (LN), Zhejiang (ZJ), Fujian (FJ), Inner Mongolia (IM)
Class 3	Jilin (JL), Heilongjiang (HLJ), Guangdong (GD), Sichuan (SC), Guangxi (GX), Hainan (HN), Hunan (HUN), Anhui (AH), Jiangxi (JX), Hubei (HUB), Yunnan (YN), Chongqing (CQ), Guangzhou (GZ)

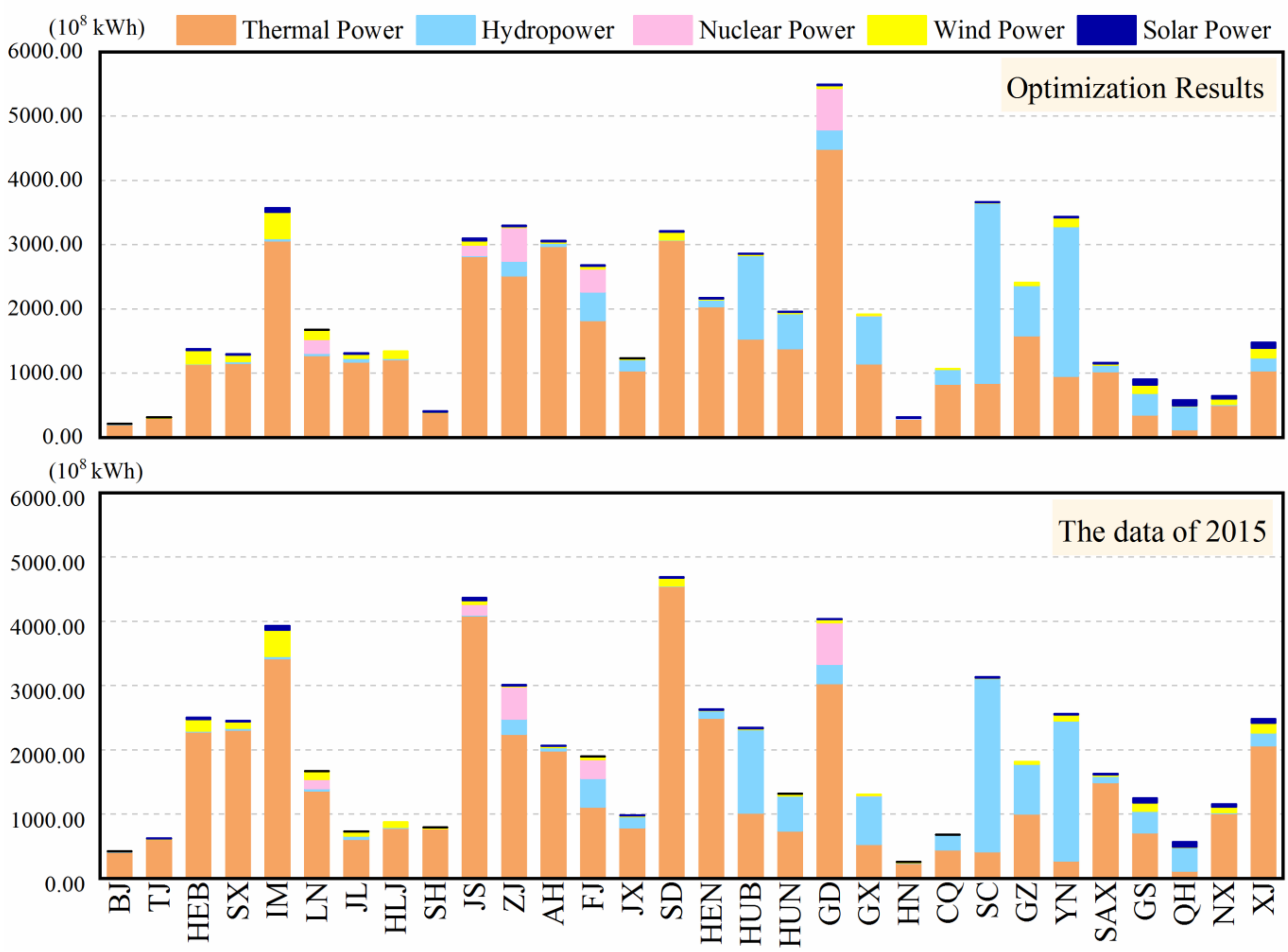

Fig. 1. Power generation mix with five major generation types in thirty provinces

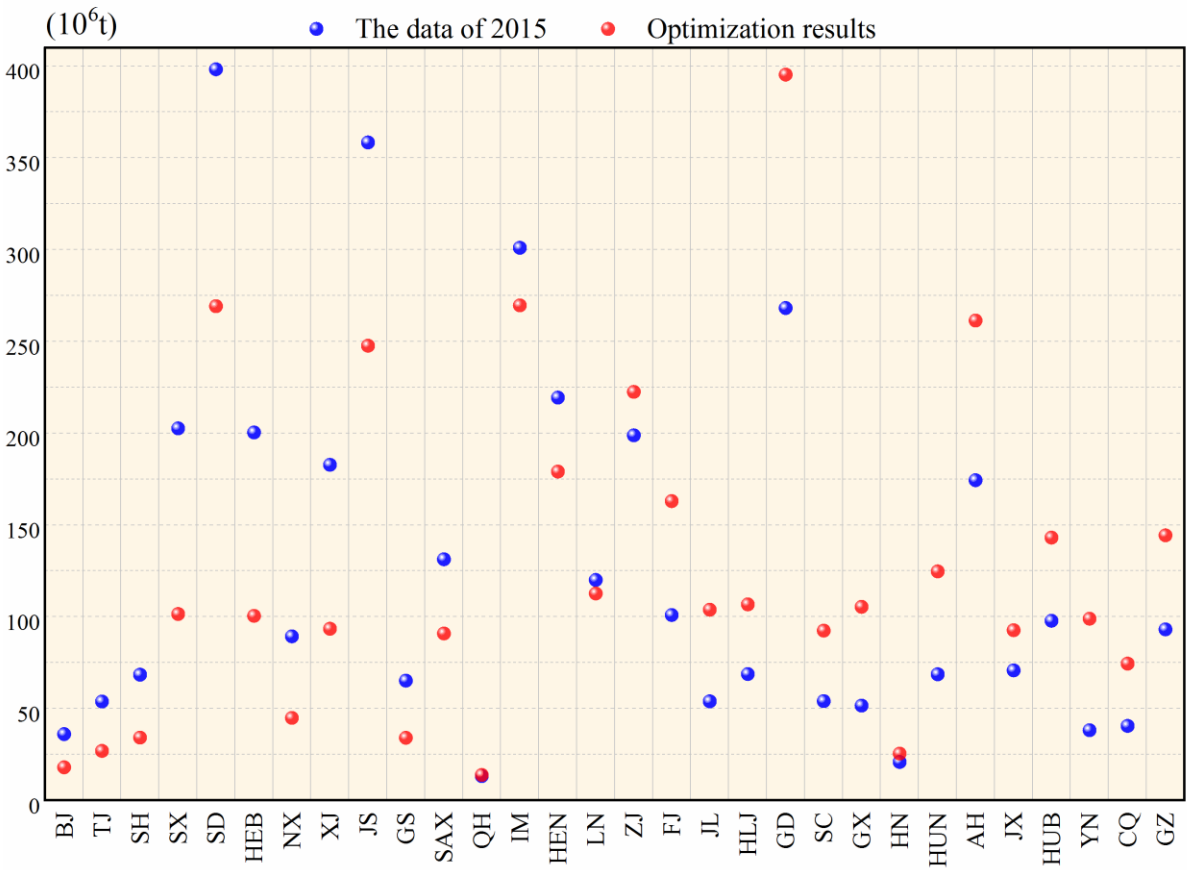

Fig. 2. Changes of carbon emissions before and after optimization in thirty provinces

IV. RESULTS AND DISCUSSIONS

According to results by using this optimization model, the total amount of carbon emissions can be reduced by 3.8×10^8t which decreased 1.3% from that of its actual value in 2015. Before optimization, the top three provinces with the highest amount of carbon emissions are Shandong, Jiangsu and Inner Mongolia (4.0×10^8t, 3.6×10^8t, and 3.0×10^8t respectively). By observing Fig. 1, it can be found that those three provinces also have the most power generated from thermal power, which matches the previous concept that thermal power is the main factor which leads to the most carbon emissions among those five types of power generation technology [10]. Fig. 2 presents changes in the amount of carbon emissions before and after optimization. In this case, reducing the power generated from thermal power is an effective way to cut carbon emissions to some extent—by doing this, the amount of carbon emissions from Shandong, Jiangsu and Inner Mongolia is possible to low down to 2.7×10^8t, 2.5×10^8t, and 2.7×10^8t respectively, with generation capacity in other ways remains basically unchanged. From the national aspect, the total amount of power generation from thermal power in this optimal model is decreased from 4.3×10^{12} kWh to 4.2×10^{12} kWh, when that from hydropower, nuclear power, wind power, and solar power are increased (from 1.10×10^{12} kWh to 1.12×10^{12} kWh, from 1.8×10^{12} kWh to 1.9×10^{12} kWh, from 1.8×10^{11} kWh to 2.0×10^{11} kWh and from 3.9×10^{10} kWh to 4.4×10^{10} kWh respectively).

Fig. 3 shows the data of virtual water consumption in various provinces. Arrange the abscissa according to the number of WSI that is illustrated in Table 1, provinces are in order from left to right with the value of WSI from the largest to the smallest. Beijing, Tianjin, Shanghai, Shanxi, Shandong, Hebei, and Ningxia are provinces with the most urgent water scarcity issue, after optimization, water consumption in those provinces all decreases by observing Fig. 3—decreases are 3.4×10^{11} m^3, 5.1×10^{11} m^3, 6.5×10^{11} m^3, 1.9×10^{11} m^3, 2.4×10^{11} m^3, 1.9×10^{11} m^3, and 8.4×10^{11} m^3, respectively. Compared to Fig. 1, it can be seen that the amount of power generated from provinces with extremely serious water scarcity is reduced, when that generated from provinces with slight water stress issue is increased, with more or less degree. Obviously, Sichuan and Yunnan are provinces with highest water consumption and light water scarcity, and the water consumption in those two provinces are raised from $4.4\times10^{13}$$m^3$ to $4.6\times10^{13}$$m^3$, and from 3.5×10^{13} m^3 to $3.9\times10^{13}$$m^3$ respectively.

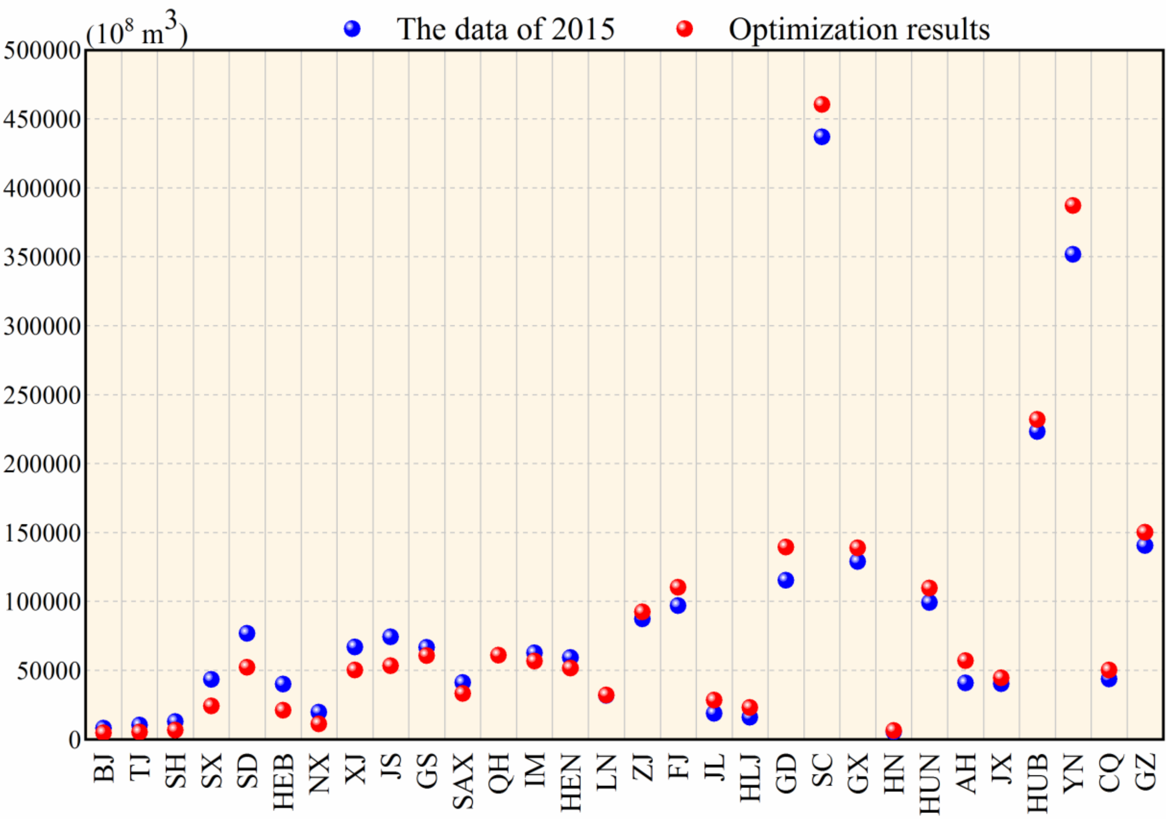

Fig. 3. Changes of the water consumption before and after optimization in thirty provinces

V. Conclusion

In this paper, a multi-objective optimization model was proposed to reduce carbon emissions and the water consumption of power generation by redistributing power generation mix within provinces. For the objective of reducing carbon emissions, thermal power generation in some carbon high-emitted provinces is cut down, and carbon emissions are decreased to some extent; considering the exited technology and generation capacity, the optimal result shows that the power generated from thermal power plants decreases 6.0×10^{10} kWh, when that generated from hydropower, nuclear power, wind power, and solar power increases 2.5×10^{10} kWh, 1.5×10^{10} kWh, and 1.4×10^{10} kWh respectively. For mitigating water scarcity, the result shows a transferring process—when provinces in water-sufficient areas tend to consume relatively more water and undertake increasing power generation tasks, provinces in water-deficient areas have the decreasing water consumption and take on less power generation tasks. To sum up, the power generation mix can be optimized to reach the goal of cutting carbon emissions and mitigating water scarcity at the same time by utilizing this model. Meaningfully, by using this framework, it is able to analyze the power generation mix if is optimal enough and makes a reasonable plan for redistributing to make the electric power sector more environmentally friendly. The data discussed in this research is at the provincial level, for the next stage, high-resolution data can be applied for detailed analyzing at a specific power plant level.

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References

[1] Q. Weng and H. Xu, "A review of China's carbon trading market," Renewable and Sustainable Energy Reviews. 2018, pp.613–9.

[2] M. Larsen and M. Drews, "Water use in electricity generation for water-energy nexus analyses: The European case," Science of The Total Environment. 2019, 651:2044–58.

[3] C. Wang, R. Wang, E. Hertwich, Y. Liu and F. Tong, "Water scarcity risks mitigated or aggravated by the inter-regional electricity transmission across China," Applied Energy. 2019, 238:413–22.

[4] A.C. Lira Quaresma, F.S. Francisco, F.L. Pessoa and EM. Queiroz, "Carbon emission reduction in the Brazilian electricity sector using Carbon Sources Diagram," Energy. 2018,159:134–50.

[5] W. Wei, X. Wang, H. Zhu, J. Li, S. Zhou, Z. Zou, et al. "Carbon emissions of urban power grid in Jing-Jin-Ji region: Characteristics and influential factors," Journal of Cleaner Production. 2017, 168:428–40.

[6] C. Zhang, L. Zhong, S. Liang, K.T. Sanders, J. Wang and M. Xu, "Virtual scarce water embodied in inter-provincial electricity transmission in China," Applied Energy. 2017, 187:438–48.

[7] X. Liao, X. Zhao, J.W. Hall and D. Guan, "Categorising virtual water transfers through China's electric power sector," Applied Energy. 2018, 226:252–60.

[8] M.M. Mekonnen, P.W. Gerbens-Leenes and A.Y. Hoekstra, "Future electricity: The challenge of reducing both carbon and water footprint," Science of The Total Environment. 2016, 569–570:1282–8.

[9] J.D. Ogland-Hand, J.M. Bielicki, Y. Wang, B.M. Adams, T.A. Buscheck and M.O. Saar, "The value of bulk energy storage for reducing CO2 emissions and water requirements from regional

electricity systems," Energy Conversion and Management. 2019, 181:674–85.

[10] Y. Cheng, N. Zhang and C. Kang, "Carbon emission flow: from electricity network to multiple energy systems," Global Energy Interconnection. 2018, 1:500–6.

[11] S. Pfister, A. Koehler and S. Hellweg, "Assessing the environmental impacts of freshwater consumption in LCA," Environmental science & technology. 2009, 43(11): 4098-4104.

[12] National Energy Administration. China Energy Statistical Yearbook 2016. China Statistics Press; 2016 [in Chinese].

[13] National Energy Administration. China Electric Power Yearbook. China Statistics Press; 2016 [in Chinese].