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Multi-Regional Energy Industrial Water Withdrawal Research under Different Energy Development Scenarios: A Case Study of China

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Limited water resources are threatening the development of energy industry, especially for a country like China, with huge yet still fast increasing energy demand, geographically inverse distribution of energy resources and water resources. However, previous studies mainly focus on a nation-wide scale and merely in coal industry chain. Understanding the impact of regional differences on energy industrial water withdrawal remains a challenge. In this work, a multi-regional supply and demand analytical method is proposed, and China is divided into 17 regions for multi-regional analysis. Results indicate that water withdrawal pressure of energy industry differs greatly in different regions. An energy development path of carbon emission reduction can have a significant coordinating water-saving effect. long-distance power transmission may aggravate water shortage in water-scarce regions. Three representative coal-rich energy bases are analysed and the gap between demand of energy industrial water withdrawal and water supply is huge in a business-as-usual scenario. This gap can be reduced or eliminated only if both total amount control and intensity control strategies are jointly adopted.

1. Introduction

1.1 Water restriction in the development of energy industry

With the growth of the population and economy, the growing energy industry is impacting on the security of water resources. The energy industry is a high-water-consuming industry. It is estimated that total withdrawals for thermoelectric power accounted for 41 % of total water withdrawals in the US (Dieter et al., 2018). Energy security needs to be coordinated with water resources management (Wang et al., 2018).

The pressure of energy industrial water withdrawal in different regions ranges a lot and the conflict between energy and water is more intense in water-deficient areas. Severe drought in the Southeast of US has threatened the cooling water supplies of more than 24 of 104 nuclear power reactors (Hightower and Pierce, 2008). The inter-regional electricity transmission may further exacerbate the risk of water scarcity (Wang et al., 2019). The uneven distribution of energy and water necessitates a regional level assessment for identifying the most appropriate energy development planning.

The future development paths of the energy industry would be various (IEA, 2015). Meldrum et al. (2013) pointing out that total life cycle water use appears lowest for electricity generated by photovoltaics and wind. The promotion of renewable energy could alleviate the pressure on water greatly. Energy industrial water withdrawal assessment under different energy development scenarios is of significance.

1.2 Prominent China issues

China is confronted with tremendous water scarcity problem and China's water resources and energy resources have a typical characteristic of reverse distribution. The total reserves of coal in Inner Mongolia, Shaanxi, Xinjiang, Shanxi, and Ningxia account for 76 % of the country's total, but water resources only account for 6 % of the country (Pan et al., 2016). The demand for water withdrawal in the energy sector is increasingly becoming a major factor constraining the development of the energy industry (IEA, 2015).

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Series of studies have been conducted to analyze the regional differences of energy industrial water withdrawal. But they are mainly concentrated in coal industry and power generation industry. Pan et al. (2012) studied the whole process of China's coal industry chain, and predicted the water demand of coal industry chain under different energy scenarios. With the rapid development of other energy industries like coal chemical industry, the analysis should be extended to a wider range covering the energy production, transformation and utilization. The State Council issued the most stringent water resources management policy, namely the “Three Red Lines” policy in 2010. However, the later energy development would exceed the target (Qin et al., 2015). Only a variety of water resources management policies implemented jointly can the water stress be alleviated (Zhang et al., 2016). In addition, China has planned a number of energy bases, and their presence may intensify energy-water conflicts. Research on the scale of energy base is helpful to better formulate energy development policies.

Therefore, China is selected to conduct an integrated multi-regional case study under a series of energy development scenarios, to quantitatively measure the water shortage stress in energy industry and to evaluate the compliance of energy development with water resources.

2. Multi-regional supply and demand analytical method

Cai et al. (2014) estimate water demand in each China’s province with the amount of water used for the extraction, processing and conversion of primary energy. Qin et al. (2015) compared the water withdrawal with the industrial water targets set by the “Three Red Lines” water policies on a national scale. Continuing these methods, a multi-regional supply and demand analytical method considering both the water supply side and the water demand side in energy industry is raised to conduct a comprehensive analysis between water for energy and water policies.

On the water supply side, the red line of energy industrial water withdrawal (RLEIWW) is the policy suggested energy industrial water withdrawal supply limit, which reflects the comprehensive local water supply capacity. Eq(1) shows the calculation formula of the RLEIWW for future period in each region, which can be get according to the total water withdrawal limit from the “Three Red Lines” policies (RLIWW) and the current water use structure (ϕ_{EIWW}, the proportion of real energy industrial water withdrawal in the total industrial water withdrawal).

$$\mathrm{RLEIWW} = \mathrm{RLIWW} \times \phi_{\mathrm{EIWW}} \tag{1}$$

On the water demand side, the demand of energy industrial water withdrawal (DEIWW) can be obtained when the water withdrawal intensity of different energy technologies and local energy industry structure are given. The DEIWW is calculated by the formula Eq(2) where Y_i is the output of product i, and q_i is the water withdrawal intensity of product i (the amount of water withdrawal per unit of product i).

$$\mathrm{DEIWW} = \sum_{\mathrm{i}} (\mathrm{q_i} \times \mathrm{Y_i}) \tag{2}$$

For assessing the water withdrawal pressure, the proportion of DEIWW in total industrial water withdrawal (TIWW) reflects the uneven distribution of water supply and demand (ϕ_W), shown in Eq(3). The difference between RLEIWW and DEIWW (Δ_{EIWW}) reflects the compliance of energy development with water policies, shown in Eq(4).

$$\phi_{\mathrm{W}} = \frac{\mathrm{DEIWW}}{\mathrm{TIWW}} \tag{3}$$

$$\Delta_{\mathrm{EIWW}} = \mathrm{DEIWW} - \mathrm{RLEIWW} \tag{4}$$

Energy development scenarios (EDSs) reflect possible energy development paths. EDSs describe the future primary energy demand, power generation structure, energy industry production structure and the level of water-saving technological progress by time and region. The DEIWW and Δ_{EIWW} in each region under different EDSs are calculated to analyze the relationship between energy development and water resources.

To explore the countermeasures and energy industry transformation paths, the method is applied to the energy base scale. Based on the more detailed water supply projects, energy development planning, and environmental protection policies, the analysis mainly focus on whether there is technological progress and capacity reduction. Countermeasure analysis and policy recommendations are made by comparing the impact of different EDSs.

3. Case description

China (excluding Tibet, Hainan, Hong Kong, Macao and Taiwan) is divided into 17 regions as shown in Table 1 and it is mainly based on administrative divisions, taking into account the abundance of water resources, the degree of resource enrichment, the connection of power grids and other factors. Among them, Beijing-Tianjin-

Hebei, Jiangsu-Shanghai-Zhejiang-Fujian have centered loads. Yunnan-Guizhou and Sichuan-Chongqing are rich in hydropower. Shaanxi-Gansu-Ningxia are rich in coal (Guo et al., 2016).

EDSs considered in this paper are the current policies scenario (BAU), the new policies scenario (NDS), the 450 scenario (450S), the NPS-LDPT scenario and 450-LDPT scenario. The data of economic activities, demographic changes, energy prices and efficiency in BAU, NPS and 450S is taken from International Energy Agency (2015). BAU reflects current policies. NPS meets China's national independent contribution goals, and 450S further strengthens carbon trading mechanisms to meet the China's climate change control requirements. The LDPT scenarios are set to take into account the regional differences in energy development caused by long-distance power transmission across regions. In NPS-LDPT and 450-LDPT scenario, the regional development data of energy production are allocated according to the original NPS and 450S scenarios, while the data of power system are the sub-regional power structure optimization results through the LoMLog model (Guo et al., 2016).

Table 1: Partition list of China (excluding Tibet, Hainan, Hong Kong, Macao and Taiwan)

Number	Regions	Number	Regions	Number	Regions
1	Inner Mongolia (NM)	7	Beijing, Tianjin, Hebei (BJ-TJ-HE)	13	Shanghai, Jiangsu, Zhejiang, Fujian (SH-JS-ZJ-FJ)
2	Xinjiang (XJ)	8	Shandong (SD)	14	Anhui (AH)
3	Shanxi (SX)	9	Shaanxi, Gansu, Ningxia (SN-GS-NX)	15	Yunnan, Guizhou (YN-GZ)
4	Sichuan, Chongqing (SC-CQ)	10	Qinghai (QH)	16	Guangxi (GX)
5	Hubei (HB)	11	Henan (HA)	17	Guangdong (GD)
6	Heilongjiang, Jilin, Liaoning (HL-JL-LN)	12	Hunan, Jiangxi (HN-JX)		

The estimated RLEIWW in each region is shown in Table 2. Following energy technologies are included for analysis: coal mining, coal washing, onshore oil exploration, crude oil processing, onshore natural gas extraction, coal power, natural gas cycle power, biomass power, nuclear power, solar photovoltaic, coal to oil, coal to natural gas, coal to olefins, coal to synthetic ammonia, and coal to coke.

Table 2: RLEIWW in different regions (unit: 100 Mm^3)

Number	2015	2020	2030	Number	2015	2020	2030	Number	2015	2020	2030
1	9.05	9.62	10.18	7	7.98	8.69	9.17	13	9.47	9.90	10.03
2	3.63	3.63	3.67	8	14.31	15.80	16.52	14	4.55	4.50	4.55
3	7.37	8.98	9.27	9	9.74	9.94	10.54	15	7.62	8.78	9.05
4	4.22	4.92	5.07	10	0.60	0.62	0.70	16	0.82	0.84	0.84
5	2.07	2.40	2.41	11	7.95	8.63	8.94	17	2.91	2.90	2.88
6	12.11	12.87	13.20	12	3.14	3.28	3.29				

The data of the intensity of energy industrial water withdrawal in each region is from the latest industrial water quota documents for the whole country and each region and the thermal power energy efficiency benchmark data. The water withdrawal quota of thermal power with once-through water cooling is set to its water consumption quota since most of the water withdrawal is returned to the original environment. Nuclear power plants all adopt seawater once-through cooling, so the water withdrawal intensity of nuclear power is the withdrawal of fresh water. Assume that the thermal power unit with CCS has twice the water withdrawal intensity of a unit without CCS (US DoE, 2014).

Table 3: EDS settings for energy base analysis

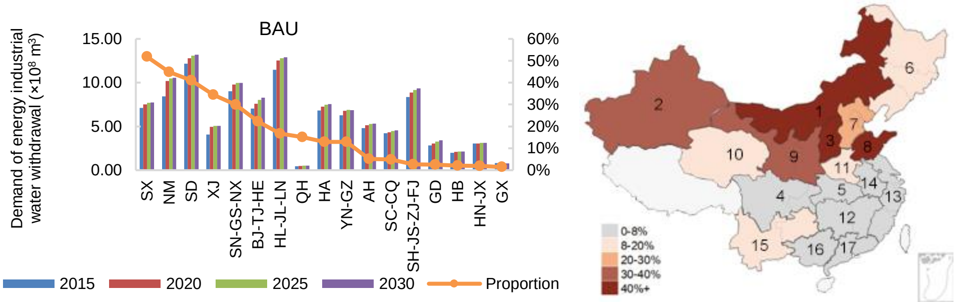
Scenario	Setting
a1	There is no technological progress, and keep the current water withdrawal intensity unchanged.
a2	There is technological progress, and the intensity of water withdrawal decreases with time (20 % from 2015 to 2020, 15 % from 2020 to 2025, and 10 % from 2025 to 2030).
b1	Keep current project planning.
b2	Implement the capacity reduction of coal, close small thermal power plants, and set the utilization rate of coal chemical capacity at 50 %.

For energy bases analysis, Yulin, Shaanxi, Ningdong, Ningxia and Ordos, Inner Mongolia are selected since they are located in areas where water shortage is severe and demand of energy industrial water is high. Considering technological progress and industry development, four scenarios are set as shown in Table 3.

4. Results and discussion

4.1 Regional analysis

Figure 1a shows the DEIWW under the BAU scenario and Figure 1b shows the proportion of DEIWW in TIWW in 2015. The national average proportion of DEIWW in TIWW is 8 %, but Shanxi (52 %), Inner Mongolia (45 %), Shandong (41 %), Xinjiang (34 %) and Shaanxi-Gansu-Ningxia (30 %) account for higher. These regions are where large energy bases locate, and the energy industry is an important component of their industry. The areas such as Shanghai - Jiangsu - Zhejiang - Fujian, even though the DEIWW is high, it accounts for only 3 % of the TIWW, since its water resources are abundant.



(a) (b)

Figure1: DEIWW and its proportion in industrial water withdrawal in 2015

Figure 1a and Figure 2 show that the DEIWW is different under different EDSs. Under the NPS, 450S and two LDPT scenarios, the national DEIWW is significantly lower than the BAU scenario, which means the coordinating water saving effects have been achieved. The water saving effect of 450S is more obvious than that of NPS. The main reason is that the constraint of carbon emission reduction reduces the consumption of fossil energy such as coal, and increases the permeability of low water withdrawal intensity technologies, like photovoltaic, wind power and nuclear power. In the NPS-LDPT and 450-LDPT scenarios, due to the implementation of long-distance power transmission optimization, in some regions, such as Inner Mongolia, the pressure of the future energy industrial water withdrawal has increased significantly. In some eastern regions, such as Shandong, water withdrawal pressure is reduced accordingly.

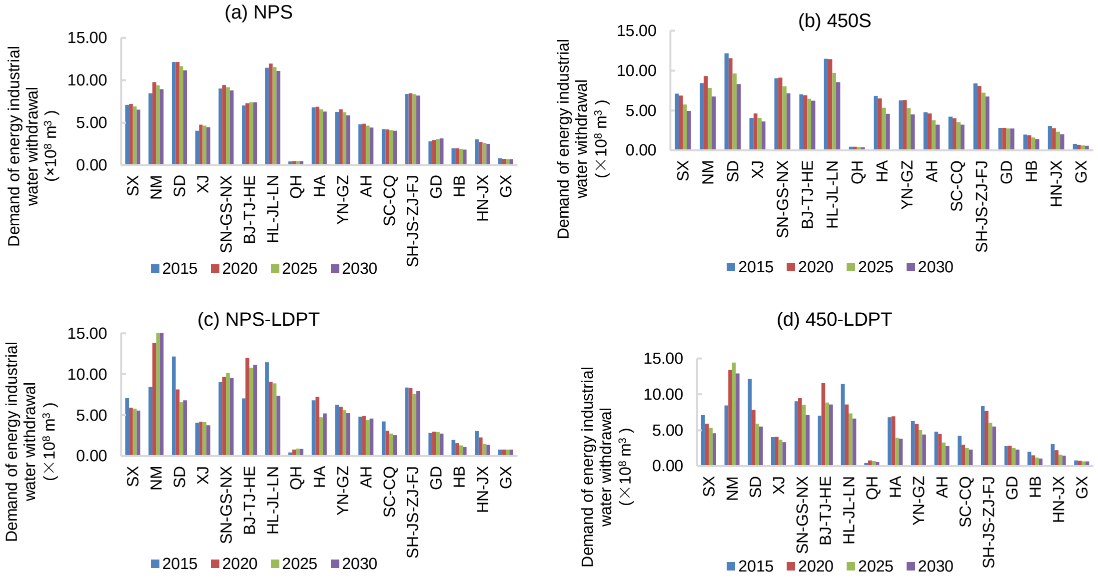


Figure 2: Changes in DEIWW under different EDSs between 2015 - 2030

Table 4: The differences between the RLEIWW and DEIWW (unit: 100 Mm^3)

Number	Year 2015					Year 2020					Year 2025					Year 2030				
	BAU	NPS	450S	NPS-LDPT	450-LDPT	BAU	NPS	450S	NPS-LDPT	450-LDPT	BAU	NPS	450S	NPS-LDPT	450-LDPT	BAU	NPS	450S	NPS-LDPT	450-LDPT
1	0.6	0.6	0.6	0.6	0.6	-0.58	-0.16	0.29	-4.22	-3.79	-0.59	0.52	2.05	-6.79	-4.51	-0.38	1.24	3.44	-5.61	-2.74
2	-0.43	-0.43	-0.43	-0.43	-0.43	-1.31	-1.14	-0.97	-0.56	-0.44	-1.41	-0.99	-0.4	-0.52	-0.02	-1.4	-0.79	0.04	-0.1	0.35
3	0.27	0.27	0.27	0.27	0.27	1.45	1.75	2.09	3.08	3.05	1.41	2.23	3.36	3.32	3.76	1.53	2.72	4.33	3.72	4.67
4	-0.01	-0.01	-0.01	-0.01	-0.01	0.59	0.72	0.92	1.82	1.93	0.51	0.86	1.47	2.23	2.45	0.51	1.03	1.86	2.53	2.75
5	0.09	0.09	0.09	0.09	0.09	0.32	0.42	0.51	0.81	0.89	0.27	0.49	0.81	1.12	1.23	0.25	0.57	1	1.32	1.37
6	0.64	0.64	0.64	0.64	0.64	0.35	0.91	1.44	3.79	4.29	0.23	1.5	3.31	4.17	5.68	0.3	2.11	4.64	5.86	6.59
7	0.94	0.94	0.94	0.94	0.94	1.1	1.39	1.78	-3.32	-2.89	0.92	1.53	2.48	-1.87	0.06	0.89	1.76	2.96	-1.99	0.57
8	2.16	2.16	2.16	2.16	2.16	3.01	3.65	4.22	7.64	7.97	3.08	4.49	6.54	9.59	10.26	3.34	5.36	8.22	9.7	11
9	0.71	0.71	0.71	0.71	0.71	0.17	0.5	0.83	0.26	0.47	0.27	1.08	2.21	0.07	1.72	0.58	1.75	3.38	1	3.4
10	0.17	0.17	0.17	0.17	0.17	0.13	0.16	0.18	-0.18	-0.17	0.14	0.19	0.25	-0.27	-0.06	0.16	0.23	0.31	-0.17	0.13
11	1.14	1.14	1.14	1.14	1.14	1.37	1.76	2.12	1.4	1.7	1.32	2.19	3.44	4.06	4.83	1.39	2.63	4.34	3.74	5.11
12	0.1	0.1	0.1	0.1	0.1	0.23	0.55	0.5	1	1.04	0.17	0.66	0.95	1.8	1.71	0.15	0.78	1.25	1.92	1.82
13	1.1	1.1	1.1	1.1	1.1	1.03	1.42	1.81	1.6	2.19	0.79	1.61	2.73	2.36	3.93	0.68	1.84	3.3	2.08	4.51
14	-0.25	-0.25	-0.25	-0.25	-0.25	-0.64	-0.37	-0.13	-0.39	0	-0.75	-0.13	0.74	0.12	1.26	-0.76	0.13	1.34	-0.03	1.74
15	1.36	1.36	1.36	1.36	1.36	1.98	2.22	2.49	2.73	2.89	2.01	2.69	3.62	3.3	3.9	2.2	3.19	4.53	3.82	4.65
16	0.01	0.01	0.01	0.01	0.01	0.08	0.11	0.14	0.03	0.08	0.07	0.13	0.21	0.04	0.17	0.07	0.16	0.27	0.07	0.18
17	0.09	0.09	0.09	0.09	0.09	-0.16	-0.07	0.08	-0.1	0.07	-0.39	-0.18	0.15	-0.04	0.34	-0.55	-0.25	0.15	0.12	0.59
Total	8.68	8.68	8.68	8.68	8.68	9.12	13.84	18.31	15.39	19.28	8.06	18.87	33.91	22.7	36.72	8.98	24.45	45.35	27.95	46.66

Focus on the future structure of DEIWW in several typical areas under different EDSs, as shown in Figure 3, in the northwest regions, such as Inner Mongolia and Shaanxi-Gansu, the demand mainly comes from the coal industry chain, including raw coal mining and washing, thermal power (mainly coal-fired power), and coal chemical industry. In the eastern and southern regions, such as Anhui, Jiangsu-Shanghai-Zhejiang-Fujian, thermal power dominates the water demand. In coastal areas, the proportion of nuclear power continues to increase, but until 2030, the freshwater withdrawal of nuclear power still cannot be compared with the thermal power. It is noted that under the two LDPT scenarios, the scale of thermal power in certain regions such as Inner Mongolia increases significantly, which exacerbates the scarcity of water withdrawal.

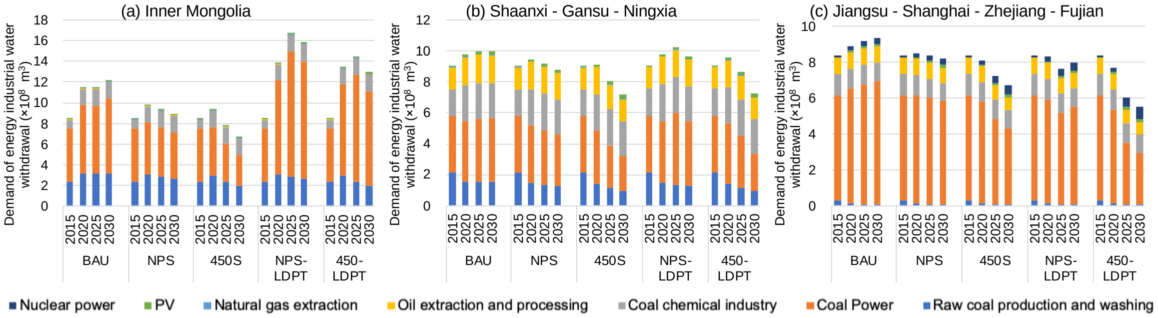


Figure 3: Structure of DEIWW under different EDSs in different regions

4.2 Energy bases analysis

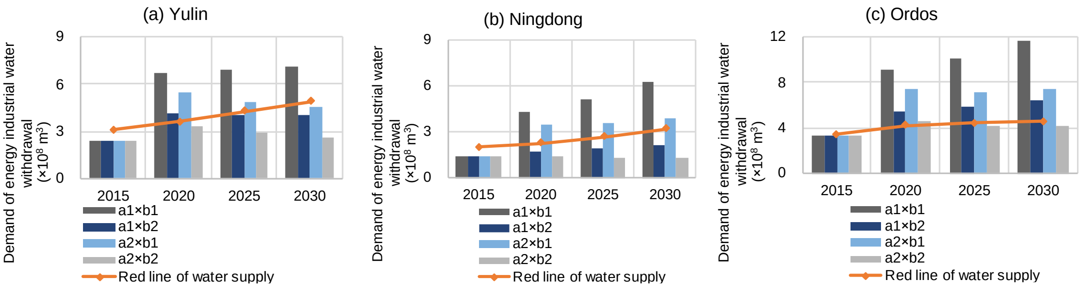


Figure 4: Analysis of supply and demand of energy industrial water withdrawal in typical energy bases

Figure 4 compares the supply and the demand of future energy industrial water withdrawal in Yulin, Ningdong and Ordos under different scenarios. According to the existing planning scenario, the future energy industrial water withdrawal in these regions increases sharply and exceeds the red line significantly. When considering only the water saving effects brought about by technological progress or the cut of excessive industrial capacity, there is still a gap in energy industrial water withdrawal. Only when the two measures are jointly adopted can these energy bases achieve better sustainable development.

5. Conclusions

A multi-regional case study of China is conducted with the multi-regional supply and demand analytical method. The DEIWW and RLEIWW are calculated by regions and EDSs. And the pressure of energy industrial water withdrawal and the compliance of energy development with water policies is compared.

The pressure of energy industrial water withdrawal between different regions ranges a lot. The regions with high proportion of DEIWW in TIWW are Shanxi (52 %), Inner Mongolia (45 %), Shandong (41 %), while Shanghai - Jiangsu - Zhejiang – Fujian only accounts for a low proportion (3 %). Different energy development paths would bring different impacts to the water demand of the energy industry. The 450S EDS is more effective than the NPS and it proves that carbon emission reduction constraints can bring synergistic water saving effects. The long-distance power transmission could lead to more concentrated water withdrawal in Inner Mongolia, and less in Jiangsu-Shanghai-Zhejiang-Fujian. On the scale of energy bases, Yulin, Ningdong and Ordos are likely to face considerable water withdrawal pressure in the future due to the overcapacity of coal chemical industry.

The corresponding policy suggestions to alleviate the pressure of water withdrawal on energy industry are put forward. It is recommended firstly to control the production of raw coal in the northwest areas and accelerate the exit of backward production capacity with high water withdrawal and pollution. The coal-fired thermal power generation and the coal chemical industry should be more orderly developed. Increase the permeability of renewable energy such as wind power and photovoltaics in the water-short regions to achieve synergistic water saving effects on the water supply side.

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