Virtual Water Flows of the Energy Sector among Chinese Provinces: A Multiregional Input–Output Approach

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Abstract The energy industry of China consumes the largest amount of direct water withdrawal and consumption in industry. However, there is a critical spatial mismatch between water demand of energy production and water availability. We used a multiregional input–output model to investigate the virtual water flows embedded in energy-related production among provinces in China. The results reveal that at the national level close to 1/5 of the virtual water use is traded as virtual water embedded in the inter-provincial energy trade, specifically 15.5% of the total water withdrawal and 18.9% of the total water consumption. The virtual water flows of the energy industry present an unsustainable water use pattern that is virtual water flows from the water scare north China to the water abundant south China, which does not match virtual water trade strategy. The more-developed coastal regions are supported by water withdrawal and consumption of the energy industry in the less-developed regions where water scarcity is severe. This study has proved the great importance and urgent need of water-energy nexus studies and also provided an approach to integrating water use management into energy industry planning and management.

Keywords: water use for energy sector, virtual water flow, multiregional input–output analysis

1. Introduction

In China, the energy industry which is consisted of mining and washing of coal, extraction of petroleum and natural gas, processing of petroleum, as well as generation and supply of electricity, is the second largest freshwater withdrawer, being only smaller than agriculture and the largest withdrawer among industries. Besides the large quantities of water withdrawal, the spatial mismatch between water demand for energy and water availability also poses huge difficulties on energy security and development in China. Regions of energy production and consumption are separated to some extent. A spatial mismatch between the producers and the consumers of energy resources requires large-scale inter-provincial energy flows. Another spatial mismatch exists in energy resources and water resources. The amount of coal, crude oil, and electricity produced in northern China accounts for more than 60% of the national total, whereas the amount of water resources in that region only accounts for approximately 10% of the national total.

Virtual water flow is a useful accounting tool for tracking the movement of embedded water around the country and understanding the potential driving forces behind domestic water use. In this study, we used a multiregional input–output method to calculate the water withdrawal and consumption of the energy sector at the provincial level from a consumption-based perspective. Virtual water flows embedded in intranational energy flows were evaluated and analyzed. This study aims to provide insights to policymakers for a comprehensive understanding of the structural and spatial features of the water-energy nexus in China.

2. Methods

This study quantified the interregional virtual energy-water flows at the provincial level in China, using a mixed-unit multiregional input-output (MRIO) model. The MRIO model can not only calculate water use by sector, but also trace its sources from other regions. The MRIO model is helpful for understanding the driving forces behind local water use.

For a given region, the virtual water amount of its domestic final demand is expressed as follows

$$W = CF = D(I\text{-}A)^{-1}F \qquad \text{(Eq. 1)}$$

where, $D = [d_1, d_2, \ldots, d_i, \ldots, d_n]^T$ is the direct water use efficiency vector of all n sectors, and represents the amount of water used directly when one unit product is generated. C represents the complete water use efficiency vector, which is calculated by multiplying the direct water use efficiency (D) by the inverse matrix of (I-A). A represents the direct consumption coefficient matrix, consisting of the direct consumption coefficient (a_{ij}) which is also known as the input coefficient, and means the directly consumed quantity of i product when a unit j product is produced. F is the final demand, which consists of household consumption and capital formation. W represents the amount of total water use driven by the final demand F, that is, the virtual water driven by the final demand of a given region.

In one region, there are exports and imports of goods and services of sector i, accompanied by a virtual water flow export and import of this sector. The net virtual water export of sector i from region r is expressed as follows

$$\text{Net VWEx}_i^r = \text{VWEx}_i^r - \text{VWIm}_i^r = \sum_{p=1}^{R} C_i^r \times F_i^{rp} - \sum_{p=1}^{R} C_i^p \times F_i^{pr} \quad \text{(Eq. 2)}$$

where, VWExir = [VWExr1, VWExr2,…, VWExrR]T is the virtual water flow vector exported from region r to other regions, VWImr = [VWIm1r, VWIm2r,…, VWImRr]T is the virtual water flow vector imported from other regions to region r, R is the number of regions, and i is the index of the sector.

3. Results

The thirty provinces in China were grouped into eight regions according to traditional economic zoning and their regional characteristics of water and energy resources. Tibet, Taiwan, Hong Kong and Macau were not included in this study because of data availability. The MIRO model was applied to compute the regional water use of the energy industry, as well as the virtual water withdrawl flows and consumption flows among regions in the country. Sensitivity analysis was conducted to validate the computation results at the regional level. It was found that the economic output of the energy sector accounted for approximately 15% of the total industries. However, the energy sector represented 64.0% of the water withdrawal and 36.1% of the water consumption, which was responsible for the largest direct water user among industries. The study results indicated that more than one third of the virtual water embedded in energy was used by final consumption outside of the province where it was used, representing 34.8% of the virtual water withdrawal and 43.5% of the virtual water consumption.

Figure 1(a) shows the interregional net virtual water withdrawal flows of the energy sector. The East Coastal, Southwest, Shanxi-InnerM, and Central regions were net exporters of virtual water withdrawal. The East Coastal region was the largest exporter, with 2.4 billion m3 of the net virtual water withdrawal mainly outflowing to the North region (28.5%), Central region (16.0%), South Coastal region (15.5%), and Northwest region (13.3%).

Figure **1**(b) illustrates the energy-related virtual water consumption flows among the eight regions. The regions indicated in yellow (the Southwest, South Coastal, North, and East Coastal regions) were net importers of virtual water consumption. The East Coastal region, which has abundant water resources and is located downstream of the Yangtze River, was the largest net importer of virtual water consumption. This region has net virtual water consumption inflows from all other regions, and 29.9% of its net virtual water consumption is imported from the Shanxi-InnerM region, where water resources are already scarce. The regions indicated in green (the Northeast, Northwest, and Shanxi-InnerM regions) were net exporters of virtual water consumption. The Shanxi-InnerM region was the largest net exporter of virtual water consumption; 487.1 million m^3 of consumptive water use in the Shanxi-InnerM region resulted from the final consumption of the energy sector in other regions, leading to 425.6 million m^3 of net virtual water consumption outflows.

4. Conclusions

This study evaluated the virtual water use of the energy sector in Chinese provinces, and the interregional virtual energy-water flows at a provincial level in China, using a mixed-unit multiregional input-output (MRIO) model which was validated through sensitivity analysis for the eight study regions. The domestic interregional energy-related trade in China resulted in substantial virtual water being used outside of the province where it was produced, including 34.8% of the virtual water withdrawal and 43.5% of the virtual water consumption. The virtual energy-water flows present an unsustainable water use pattern. This pattern does not match the virtual water trade strategy which suggests importing water-intensive products into water-scarce regions, instead of producing them domestically to alleviate regional water scarcity.

This study found that the virtual water consumption of the energy sector generally represented a north-to-south flow. However, the virtual water withdrawal of the energy sector flows in a contrary direction; that was, the virtual water withdrawal flowed from the East Coastal region to the Shanxi-InnerM, North, and Northwest regions which water resources are scarce.

This study revealed that the highly developed coastal provinces imported large quantities of water-intensive energy products from less developed provinces in the northwest, northeast, and southwest regions. The hihg energy consumption in the developed regions was supported by water withdrawal and water consumption in the less developed regions where water scarcity was severe.

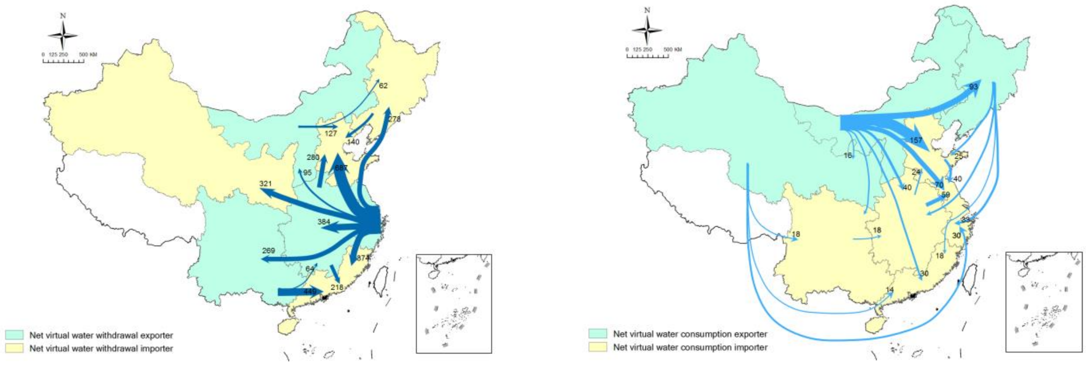

Figure 1. Inter-regional net virtual water withdrawal (left) and water consumption (right) flows of energy sectors (million m^3)

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