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Multiregional input–output and ecological network analyses for regional energy–water nexus within China

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HIGHLIGHTS

- The nexus network model for regional energy-water nexus is proposed.
- Regional water-related energy and energy-related water within China are systemically inventoried.
- System properties are altered by the regional nexus due to the nexus impact.

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ABSTRACT

Water use and energy consumption are strongly interwoven in networks of economic activity. Tracking energy and water flows among regions and quantifying their interdependencies are fundamental for synergetic management of these two essential resources. In this work, we built an accounting framework to assess the performance of energy–water nexus networks within China. Water consumption for various energy types and energy consumption in all stages of water use were inventoried for different regions. Then, direct and indirect energy and water embodied in monetary flows among regions were calculated via multiregional input–output analysis to build an embodied energy network, embodied water-related energy network, embodied water network, and embodied energy-related water network. Finally, a set of ecological network analysis indices were used to analyze the properties and connection of these four networks. The results show disparities of water-related energy/total energy ratios among regions and the nexus impact on regional energy and water systems. Beijing and Shanghai have large ratios of final demand consumption because of their large population and rapid economic development. Embodied water and energy consumption in capital stock in Hainan, Ningxia represented 15% of total consumption by booming investments. We found that embodied water was transferred from western to eastern regions and northern to southern regions. Major energy export–import pairs were Xinjiang–Shanghai, Hebei–Beijing, Xinjiang–Zhejiang, and Jiangsu–Shanghai. Regions with controller/relier roles in the network were identified in the context of nexus impact, for which Beijing and Shanghai have a strong control and dependence relationship with other regions. The proposed nexus network approach may help bridge the gap between nexus modeling and regional resource management.

1. Introduction

Water and energy are recognized as indispensable inputs to economic activities, which are strongly interwoven in regional development. A large amount of energy and water flows embodied in economic activities are transferred via trade of products and services, which shape energy and water that are intrinsically interconnected [1–3]. Energy inputs are needed at various stages of the water system value chain, including extraction from lakes, rivers and aquifers, desalination, water treatment, construction of dams, reservoirs and pipelines, pumping for distribution to consumers, and wastewater treatment [4–6]. It is estimated that total annual energy production is responsible for 61.4 billion m^3 of water withdrawals, 10.8 billion m^3 of water consumption, and 5.0 billion m^3 of wastewater discharge in China, equivalent to 12.3%, 4.1%, and 8.3% of national totals for each water category, respectively [7,8]. Moreover, water is essential for the extraction and processing of fossil fuels and hydropower generation and cooling in thermal power plants [9]. For example, approximately 40% of freshwater withdrawal in the United States is used for cooling thermoelectric power plants, which has constrained regional water resource

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use [10–12]. The interaction between water and energy resources is particularly important in China, where an uneven resource distribution of energy and water have already exposed great challenges to regional sustainable development.

Most recent research on the energy–water nexus has explored the energy or water sector alone or impacts of specific technologies on sectors with energy minimization and water use options [12–15]. Such studies attempt to find synergies between energy and water systems to integrate the benefits of new technology, which is fundamental in nexus issues [16–18]. However, nexus research for the overall macroeconomic system is more pressing for regional resource management, especially in China because of its rapid industrialization and urbanization. The geographic distribution of China's water resources is uneven, which affects energy development choices. For example, 83% of the country's water resources are concentrated in southern regions around the Yangtze River, providing rich potential for hydropower generation. North China, in contrast, is an arid region where 17% of the country's water supply is overexploited to support 41% of its population, 56% of its cultivated land, and a majority of national coal bases [19–23]. Such a situation poses great challenges to economic transition and trade structure adjustment for guaranteeing energy and water security when coordinating multiregional resource management [24]. Recently, nexus studies have been conducted from socioeconomic perspectives at city, urban agglomeration, national, and even global scales [25–28]. In those studies, linkage analysis, input–output analysis (IOA) and ecological network analysis (ENA) have been used to explore nexus properties among sectors and regions [29,30].

IOA is a useful tool to comprehensively clarify interwoven economic linkages among sectors, which facilitates tracking of resources to their origin or to where they are utilized in a complex economic network. Such analysis can assess the embodied energy consumption (both direct and indirect) required to produce goods and services in a region based on sectoral interactions and exchanges with other economies [31–34]. For a certain sector, indirect energy or water use embodied in economic activities can be calculated from intermediate exchanges with other economic sectors, based on the sector–sector Leontief inverse. Sectoral disparities can be investigated via the sector–sector input–output table, whereas regional disparities can be studied by multiregional input–output (MRIO) analysis [35–38]. In addition to regional economic input–output tables, MRIO relies on inter-regional trade matrices, which can account for primary and final energy or water expended outside the regional boundary that is needed to provide goods or services to local residents and governments. It has been widely used to trace resource flows that result from consumption activities in one region and are supported by outputs from specific production sectors in other regions [39]. MRIO has frequently been used to assess urban energy and water issues, such as virtual water, embodied energy, and the energy and water footprint [40]. Few studies have explored the interwoven relations among various elements for a complex system using the MRIO model. Particularly, Okadera et al. evaluated the water footprint of the energy supply using an input–output framework [41]. Ewing et al. integrated the ecological and water footprints using an environmentally extended MRIO model [42]. Galli et al. developed an environmentally extended MRIO model to group the footprint family under a common framework and combine indicators in the family [43]. Steen et al. took the European Union as a case to identify its three interconnected and mutually influencing environmental pressures, including carbon emissions, appropriation of productive land and freshwater use, as caused by consumption based on an MRIO model [44]. It is evident that there remains a lack of investigation into the energy–water nexus in the economic system under an MRIO accounting framework.

ENA, a system-based approach, has its unique strength in examining the structure and function of systems from a system perspective [45]. The control and dependence analysis of ENA may also provide insights into the interwoven relationship among nodes owing to direct and indirect flows, which can be used to identify regulating pathways in the system. Recently, it has been applied to the economic system at various levels, especially to energy and water systems in cities, because of its advantages of probing the structure and function of urban systems [45–47]. For example, Chen et al. pointed out that the "control strength" of ENA is potentially useful in identifying which sector has a dominant role in urban energy consumption and water use [46]. Very few attempts have been made to analyze the urban energy–water nexus from a network perspective, e.g., Wang et al. built an accounting framework for an urban agglomeration energy–water nexus and investigated properties of the hybrid nexus network based on MRIO and ENA [28]. However, there are still challenges in quantifying the potential nexus impact and guiding the energy–water nexus management accordingly at regional level.

Given the above, in the present study, we set up energy–water nexus networks based on MRIO and ENA to explore regulation pathways for both energy and water conservation among 30 regions in China. The remainder of the paper is organized as follows. Section 2 describes the methodology of MRIO and ENA analyses for the construction of nexus networks. Section 3 presents results and discussion of the case study of China in the context of intrinsic energy–water nexus impacts. Finally, conclusions are provided in Section 4 to characterize the nexus networks of China.

2. Methodology

2.1. Inventory analysis for energy–water nexus

Direct energy consumption and water use in various regions were first inventoried. Using the China Energy Statistical Yearbook and standard coal-equivalent (tce) coefficients for each energy source, the energy consumption of each region was converted into a physical quantity. Direct energy inflow to the ith region (f_i^{ene}) was calculated from the sum of nine energy types (coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas and electricity) as shown in Eq. (1). Direct water inflow to the ith region (f_i^{wat}) was calculated from the sum of all water types (surface water, groundwater, desalinated water, and reclaimed water) as shown in Eq. (2) [48–50].

$$f_i^{ene} = \sum_{m=1} e_i^m \tag{1}$$

$$f_i^{wat} = \sum_{m=1} w_i^m \tag{2}$$

where e_i^m is energy consumption for the mth type and w_i^m is water consumption for the mth type.

Then, water-related energy and energy-related water were calculated to investigate the energy–water nexus. Adapted from Ref. [50], the energy for water consumption was grouped by characteristic categories, including the: (i) provision of water (wp), (ii) use of water (wu), and (iii) wastewater disposal (wr), which were calculated by Eqs. (3)–(5), respectively.

$$f_i^{wp-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wp} \tag{3}$$

$$f_i^{wu-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wu} \tag{4}$$

$$f_i^{wr-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wr} \tag{5}$$

Based on different energy types, the energy-related water (e-water) was divided into nine categories, namely, water for coal, coke, crude oil, gasoline, kerosene, diesel oil, fuel oil, natural gas, and electricity production. Similarly, the amount of regional energy-related water (f_i^{n-wat}) was computed based on regional direct energy consumption of the mth type and corresponding water use intensity ($\overline{w}^n$):