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Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: A case study of the Beijing–Tianjin–Hebei region

Saige Wang, Bin Chen *

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, PR China

HIGHLIGHTS

- The multi-regional network model for energy-water nexus is proposed.
- The water-related energy and energy-related water are systemically inventoried.
- System properties and dynamics are altered by the urban agglomeration nexus.

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ABSTRACT

The nexus between energy and water introduces cross-sectoral vulnerabilities, which provides cross-cutting opportunities to mitigate urban energy and water demand pressure. The existing nexus research has generally been limited to inventorying energy-related water and water-related energy. In this study, we propose a hybrid framework to study the interwoven connections of energy consumption and water use for urban agglomerations. The energy-related water and water-related energy are also systematically inventoried with the multi-regional input–output method. Then, a multi-regional nexus network is established, based on ecological network analysis, to explore the structural properties and sectoral interactions between sectors within urban agglomerations. A case study of the Beijing–Tianjin–Hebei region shows the differences of direct energy/water and embodied energy/water consumption between sectors and regions. There are significant changes of control/dependence relationships between sectors and regions after considering the urban agglomeration nexus. Also, the effect of the nexus on water networks is smaller than energy networks. The nexus effect on energy and water networks for Beijing is bigger than those of Tianjin and Hebei. The recycling rates in water networks are around 20–23%, which are lower than those of energy networks (28–30%). The recycling rates of Tianjin and Beijing are higher than that of Hebei. According to the results of energy and water flows between regions, Beijing and Tianjin are dependent on Hebei for water and energy resources, while Hebei is more self-sufficient. The multi-regional network approach presents great potential for bridging nexus analysis with sustainable planning for urban agglomerations by simultaneously mitigating the energy and water burden.

1. Introduction

With rapid urbanization and industrialization, adjacent cities with similar scales and resource sharing have become increasingly reliant on each other. Particularly, water and energy have become major restraints to urban development; a large amount of water is consumed for energy supply (such as coal mining, power generation), and energy is needed for water provision, water use, and wastewater withdrawal [1].

The tracking of energy and water flows between regions, and the quantification of their interdependencies, are fundamental for the balance of energy and water [2]. The concept of 'energy–water nexus' can be introduced as a useful metaphor to investigate the mutual dependency of energy and water in terms of coupled mechanisms being interlinked and conversion processes embedded in intertwined multi-disciplinary chains at multiple scales [3]. There have been many studies exploring the energy–water nexus. Currently, quantitative analyses of the energy–water nexus are

* Corresponding author at: State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, No. 19 Xinjiekouwai Street, Beijing 100875, PR China.

E-mail address: chenb@bnu.edu.cn (B. Chen).

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focusing on their parallel relationship: how much water is used for energy supply and what is the energy consumption for water use [4–6]. In these studies, material/substance flow analysis and life cycle assessment were commonly used to identify the leverage points of the concerned systems by evaluating the pathways and requirements of a substance or commodity by using the complete supply chain of both energy and water [7–10]. Several studies have been conducted to simulate the complex interactions and dynamics of the energy–water nexus in urban systems [11–17]. For example, Kenway et al. systematically reviewed the diverse links between water management and energy use within cities and showed that, on average, water-related energy accounts for 13% of the total electricity and 18% of the natural gas used by the population [13]. Chen et al. built an urban, system-oriented, energy–water nexus network and analyzed its structural properties and sectoral dynamics based on ecological network and input–output analyses [11]. By integrating the urban nexus in the metabolism framework, researchers made important progress toward more practical and sustainable urban planning and management.

Input–output analysis can assess indirect flows besides the direct one, to account the amount required for producing goods and services based on sectoral interactions and exchanges in a complex system [18,19]. Considering regional characteristics as well as sectoral disparities, multi-regional input–output (MRIO) analysis has been further introduced to study regional disparities, which allows for a distinction between domestic and foreign production technologies [18–20]. MRIO accounting relies on the regional economic input–output tables and inter-regional trade matrices that can trace the flows of resources derived from consumption activities in one region and supported by outputs from specific production sectors in other regions, and has been frequently applied to urban energy and water systems, focusing on single element, such as virtual water [21], energy [22], or carbon footprint [23]. Very few studies have explored the interwoven relations among various elements. For example, Okadera et al. evaluated the water footprint of the energy supply using an input–output framework [24]. Ewing et al. integrated the ecological footprint and water footprint using an environmentally extended MRIO model [25].

In contrast to MRIO, ecological network analysis (ENA) can utilize the integral flows to quantify not only the direct and indirect flows in the transformation process but also the relationships between economic sectors from a systems perspective [26,27]. By analyzing the indirect paths implied in the direct flows among sectors, ENA can trace energy consumption or water use processes backwards to account for the total consumption or use involved, and reveal the characteristics of the system's structure and function [28]. ENA has been widely used to explore urban energy consumption [26] and water use [29]. Particularly, Chen and Chen (2016) pointed out that the "control strength" of ENA is potentially useful in identifying which sectors play a more dominant role in urban energy consumption and water use [26].

Moreover, MRIO and ENA have been combined to investigate the energy flows or water flows for a single city. For example, Yang and Chen used this method to examine mutual interactions and control situations within the wind power generation system in a pathway nexus analysis [30]. Fang et al. employed this hybrid method to set up an input–output model and a virtual water network to reflect the virtual water exchanges in an urban system [29].

In this study, we systemically quantified the energy for water and water for energy and built a network model for urban agglomeration energy–water nexus based on MRIO and ENA. Taking Beij ing–Tianjin–Hebei (Jing-Jin-Ji) as a case study, we inventoried the sectoral energy-related water and water-related energy. Then, the embodied energy consumption and water consumption were calculated using MRIO. By combining direct energy consumption with water-related energy, we developed a nexus network to analyze the direct and indirect interactions, while the system properties and sectoral dynamics were addressed by a set of ENA indices. Using a similar approach, we merged the water directly consumed by the city and energy-related water. Finally, we analyzed the energy and water utilization characteristics of the Jing-Jin-Ji region to reflect the current situation of regional disparity. By doing this, we aim to build a multi-regional assessment of the energy–water nexus to modify the future integrated development of the urban agglomeration, thus providing insights for sustainable regional planning.

The remainder of this paper is organized as follows. Section 2 describes the study site, framework and structure, energy–water flows accounting, energy–water nexus modeling and data sources. Section 3 presents the results of the Jing-Jin-Ji region case study, and discussions about the characteristics and disparities between sectors and regions for energy and water utilization. Section 4 provides conclusions about the properties and dynamics of the energy–water nexus network for urban agglomeration.

2. Materials and methods

2.1. Study site

Jing-Jin-Ji is the national capital region of China, and includes an economic region surrounding Beijing, Tianjin, and Hebei, along the coast of the Bohai Sea (Fig. 1). Jing-Jin-Ji is an urban agglomeration with an area of 2.167×10^7 ha and a population of 9.196×10^7. The overall strategies for the sustainable development of energy and the environment in this linked metropolitan system are expected to set an example for urbanization throughout China [31]. Each region plays different ecological roles on the regional energy and water utilization [18]. Currently, the administrative system constraints, environmental pollution, and imbalanced development have seriously impeded the integration and cooperation of the Jing-Jin-Ji region [32].

2.2. Framework and structure

We grouped the oriented 42 sectors from input–output tables into seven sectors for the Jing-Jin-Ji region (Table 1). From a consumption perspective, we calculated the direct energy and embodied energy consumption for urban household, capital formation and change in stock and export based on MRIO. The direct water and embodied water consumption for these three categories were also calculated by MRIO [32]. The sectoral energy, direct energy, and water-related energy were calculated, and combined as hybrid energy to build the nexus network model [11]. A similar process was applied to the direct water and energy-related water, to calculate the hybrid water for the nexus network model. By converting sectoral consumptions of energy and water into equivalent inflows, we established a multiregional nexus network (MRNN) that describes the relationships among the seven sectors and three regions, in which sectors function as nodes. The nexus point is built to form the energy and water flows in the same nexus network.

In Fig. 2, the nodes in the network models are the sectors of Beijing, Hebei and Tianjin, and the paths are the energy and water flows between any two regions or sectors. Adapted from [13], the energy for water consumption was defined and grouped by characteristic categories, including: (i) the provision (Ep) of water; (ii) the use of water (Eu); and (iii) the resources of wastewater (Er). Ep is the energy related to the supplying of water that includes energy use for treating and transporting water and wastewater via centrally managed facilities; energy for the transfer of raw water; energy to deliver decentralized (household and cluster-scale) supplies such as rainwater tanks; energy for additional pressure