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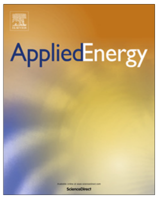

Linkage analysis for the water–energy nexus of city

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HIGHLIGHTS

- The water–energy nexus of Beijing is investigated using input–output and linkages analyses.
- The linkages analysis is used to explore the embodied water and energy flows in urban economy.
- The key sectors for water–energy nexus in Beijing are identified.

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ABSTRACT

Rapid urbanization and the expansion of metropolitan areas have resulted in severe demands on water and energy resources, which threaten the sustainability of the urban economy and environment. In this paper, an input–output model and linkage analysis are used to detect the synergetic effects of water and energy consumption and interactions among economic sectors. Beijing is chosen as a case study to investigate the water–energy nexus and the water and energy importing and exporting functions of major economic sectors. The results reveal that the agriculture and food processing sectors are major virtual water suppliers, while petroleum and natural gas processing, and electricity production sectors are major embodied energy suppliers. These energy suppliers mainly import intermediate products to satisfy the final demand of Beijing, thus transferring resources pressure to other regions. With rapid urbanization, the real estate industry sector chain has become an important water–energy nexus node and resources transfer node. The real estate sector needs large amounts of virtual water and embodied energy resource inputs to continue its production and thereby promote the growth of logistical industries. The transportation sector was also found to be important energy consumer and energy transfer node. In addition, the services sector, contributing one fourth of Beijing's total GDP, is a key water–energy nexus node because it consumes considerable amounts of both virtual water and embodied energy resources to support its production pattern.

1. Introduction

Energy and water resources are inextricably intertwined and are both important for economic development. The interdependence of water and energy resources can be translated into the concept of the "water–energy nexus" [1,2].

Currently, there is research on the requirements of water for energy production and supply issues in electricity generation [2–6], oil and gas operations [7], and total energy productions [4,8]. This research uses methods such as inventory analysis [3,4,7,8], life cycle analysis [5,6], input–output analysis [5,6], and scenario analysis [2]. Some studies have considered the correlation between the water–energy nexus and greenhouse gas emissions (GHG), i.e., water–carbon trade-offs to investigate the influences of different GHG emission reduction options on water use in energy production [5,9–11]. Water conservation and reuse issues for energy production are also taken into consideration by Dubreuil et al. [12] when implementing water allocation strategies in an energy optimization model with a dedicated water module to assess an optimal water–energy mix. Yang and Chen [13] developed a new energy–water nexus analysis framework for wind power generation systems, which includes both element and pathway nexus analyses to investigate the dominant sectors and pathways for energy–water circulation and the mutual relationships between pairwise components of the wind power generation system. Zhu et al. [14] trace the virtual water (VW) applicable to power generation in the electric power system in China. Based on this, Guo et al. [15] used ecological network analysis to identify the important grids that largely influence both the magnitude and

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diversity of the VW flows within the electric power system. The issues concerning energy for water are also under intensive investigation. These investigations explore the energy requirements for water production, treatment, end use, reclamation, disposal [16], and energy for enhanced water supply scenarios [17]. Zhou et al. [18] measured the climatic co-benefit of water conservation based on a water flow analysis to reduce energy demands and GHG emissions in an optimized water supply system. Besides energy for water supply issues, the water quality issue has also been investigated, e.g., Santana et al. [19] estimated the effect of influent water quality on the operational embodied energy (EE) of drinking water using life cycle analysis.

Several studies investigated the trade-offs between energy and water by exploring the escalating water demand for energy production and the energy needed for water treatment. Specifically, Scott et al. [20] advanced the understanding of the water–energy nexus by demonstrating how these resources are coupled at multiple scales. Bartos and Chester [1] developed a spatially explicit model of water–energy inter-dependencies and assessed the potential for co-beneficial conservation programs, by assessing source, treatment, and use and reuse periods. DeNooyer et al. [21] quantified the water withdrawal and consumption for power generation in Illinois, combining digital spatial datasets with basic engineering principles to synthesize a geographic information system (GIS) model of current and projected water demand for thermoelectric power plants. Nanduri and Saavedra-Antolínez [22] used the Markov decision process (CMDP) model to examine the electricity–water–climate change nexus, by investigating the impact of a proposed joint water and carbon tax on the operation of a transmission-constrained power network. Huang et al. [23] developed a bottom-up model to integrate China's energy system with water resources. They projected water demand in the power sector and assessed the impacts of water constraints on power generation. Scanlon et al. [24] investigated the influence of droughts on the water–energy nexus by quantifying water and electricity demand and supply for each power plant during a drought period in Texas. Other research combined the water–energy nexus with climatic variability [25,26] and considered the potential for conserving both energy and water resources by measuring the life-cycle economic efficiency of GHG reductions [27].

However, most of the research on the water–energy nexus focuses on specific production processes, such as electricity production, water treatment or agricultural production, while very little research considers urban economic systems. Because the physical flows of water and energy resources are hidden in economic commercial trade, it makes sense to use "virtual water" and "embodied energy" to explore the water and energy utilization within an economic system from a comprehensive perspective. VW, as first put forward by Allan [28], is the amount of water consumption during the production process of a specific agricultural product. The VW trade strategy has already been shown to be an important measure to alleviate water scarcity and inequitable water distribution [29–34]. There are two main methodologies to calculate VW and EE. One is the bottom-up approach using specific calculations of the resources consumption during each production period. However, it is difficult to trace the VW flows through the supply chain [32,35] using this approach. The other methodology is the top-down approach, which is less precise than the bottom-up approach, and uses input–output models to calculate resource consumption. These models include both direct and indirect processes, and describe the supply chain effects to distinguish the responsibility of final users [29,33,36–38].

The input–output model has been proven to be an effective tool to investigate the economic pressure on resources and the environment, and can reveal both direct and indirect resource consumption during production periods [36,37], explore the resources pressure transfer through economic trade networks [29,33,38], and detect the driving force of resources consumption from an economic structure perspective [39,40]. Moreover, the model can be used to investigate the supply chain effect on the consumption of resources in an economic trade network by analyzing the linkages between sectors [41,42]. The linkage analysis derived from input–output analysis is an effective approach to detect the role of each sector in the economy, such as resource suppliers or resource consumers. Duarte et al. [41] further developed traditional linkage analysis with the components being described as the internal effect, mixed linkage, net or external backward linkage, and net or external forward linkage to detect key sectors from a consumption perspective. Currently, water–energy nexus research mainly focuses on a specific production process, while few studies explore this issue from an economic network perspective. The contribution of this research is that it applies linkage analysis to a particular case of the water–energy nexus in an urban system, in order to explore the production and consumption structure of both water and energy resources, as well as the interconnected relationship between two essential resources. Specifically, linkage analysis is used to illustrate the total impact of economic activities on resources, and detect the intersectoral resource flows within the economic structure. The linkage analysis examines upstream and downstream resource flows in the economic network and depicts the water–energy nexus structure from a coherent linkage perspective. Based on this, the key sectors as well as important linkages among economic sectors are identified, thus facilitating more efficient resources management.

This paper uses linkage analysis to interpret the water–energy nexus issue in an urban system to evaluate the role of each sector in the urban system and to identify the key sectors of the water–energy nexus. The remainder of the paper is organized as follows: Section 2 describes the material and methods, including linkage analysis and data collection; Section 3 illustrates the results of the Beijing case study; Sections 4 and 5 provide a discussion and conclusions.

2. Material and methods

2.1. Linkage analysis

Linkage analysis, derived from input–output analysis, can detect the direct and indirect consumption of resources as well as the role of each economic sector [41,42]. Here we conducted the linkage analysis for the VW and EE between urban economic sectors. The linkage analysis has been modified to a Hypothetical Extraction Method (HEM), which divides the components of the impacts into four parts: an internal effect (IE), a mixed effect (ME), net or external backward linkage (NBL), and net or external forward linkage (NFL). The main equations and implications are now presented:

$$q_j = \frac{w_j}{x_j} \tag{1}$$

where w_j is the direct water or energy consumption of sector j; x_j is the total output of sector j; and q_j is the direct water or energy coefficient of sector j.

$$A = \begin{pmatrix} A_{s,s} & A_{s,-s} \\ A_{-s,s} & A_{-s,-s} \end{pmatrix} \tag{2}$$

$$(I - A)^{-1} = \begin{pmatrix} \Delta_{s,s} & \Delta_{s,-s} \\ \Delta_{-s,s} & \Delta_{-s,-s} \end{pmatrix} \tag{3}$$

where A is the direct consumption coefficient matrix; $(I - A)^{-1}$ is the Leontief inverse matrix; s is the block of similar sectors of the

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