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Urban energy–water nexus based on modified input–output analysis

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HIGHLIGHTS

- The modified input-output model for energy-water nexus is proposed.
- The water-related energy and energy-related water flows are analyzed.
- The critical sectors and pathways have been identified for urban nexus management.

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ABSTRACT

The energy–water nexus in urban activities poses challenges for coordinating urban energy and water management. A difficulty in such nexus issue is the lack of a unified base for energy and water flows analysis, which hinders sustainable energy and water resource utilization. Given that, we proposed a modified input–output analysis to provide a unified framework to balance urban energy and water use, by using the case of China's capital city–Beijing. First, we inventoried the energy–related water consumption and water–related energy consumption with emergy metric. The hybrid water flow, as the sum of the direct water flow and energy–related water flow, is combined with the hybrid energy flow to build the hybrid network. Then the complex interactions between economic sectors and the nexus impacts were explored via input–output analysis. The results show that Manufacture (Ma) provides the largest outflow of hybrid energy, and Agriculture (Ag) is the largest receiver. The major export–import pairs of hybrid water are Ag–Ma, Ma–Co (Construction), Service(Se)–Transportation and Mailing (Tr), Ma–Se, and Tr–Ma. These major export–import pairs (Ma–Ag) as well as Ma itself are the critical points for energy and water nexus management. The results of the nexus impacts showed that Ag, Tr, and Co are the most important sectors. This study may help identify the leverage points and regulating pathways of urban energy–water system and provide a better way for mitigating the urban energy and water pressures.

1. Introduction

Many cities worldwide are facing great challenges and opportunities in maintaining a secure and sustainable supply of energy and water, which are essential for sustaining life and development [1]. More than 70% of the global energy consumption occurs in urban areas [2], with a significant amount of water being directly and indirectly required in the extraction, processing, and conversion of energy in almost all of its forms [3]. Moreover, energy is directly input into water production, distribution, and disposal, and indirectly consumed by domestic heating or cooling, household pumping, and laundry [4]. For example, in the urban water cycle, 10% of the total energy is used for the pumping and treatment of water utilities, and more than 80% for households, industrial and commercial sectors [5]. Thus, understanding the linkage between water and energy is necessary for identifying synergies and shared goals of integrated urban system management [6–8].

The idea of energy–water nexus is a useful metaphor to describe the mutual dependence of energy and water in terms of coupled, interlinked mechanisms and conversion processes embodied in intertwined, multi–disciplinary chains at multiple scales [6,9]. This concept considers the energy embodied in economic activities (defined as the sum of direct and indirect energy) in water systems and vice versa [10,11]. Actually, nexus will lead to an interesting phenomenon; one policy target on one resource inevitably has effects on another one. For example, water conservation policy can influence not only household or industrial water use but also utility energy use, as the change of water use may induce the variation of energy consumption [12].

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So far, there have been many studies exploring the physical and quantifiable metrics of the nexus to inventory and evaluate the energy and water consumption [12–16]. Almost all of the energy–water nexus literature concurs with the point that the integration is necessary for decision making. Progress in integration by combining energy–related water with direct water and water–related energy with direct energy was also made in several studies [17–20]. For example, Wang and Chen [19] systemically inventoried urban sectoral energy–related water, water–related energy, embodied energy consumption, and water consumption and merged them into hybrid energy and hybrid water to develop the nexus network in Beijing–Tianjin–Hebei region. In the work of Yang and Chen [20], water consumption was measured by Joules instead of tons to reveal how much energy was demanded to provide a certain amount of water. As the energy and water flows are normalized in the same unit, the energy and water flows can be aggregated and accounted, which enables the decision–makers to gain a holistic view when seeking solutions for coordinating energy and water issues.

Meanwhile, as one of the life–cycle oriented methods, emergy analysis has been widely applied to resource accounting by converting the energy required for production into equivalent units of one form of energy, i.e., solar energy [21–23]. Based on the emergy metric, the energy quality and environmental supports, which are often ignored in the traditional energy analysis, are incorporated into the energy and water resource accounting for socio–economic activities to reflect the hierarchical level of various ecosystem services including precipitation, pollination, carbon sequestration, and pollution abatement [24–29]. The energy and water resources can then be integrated into the same accounting framework considering the ecosystem service to economy and tradeoff them with the same measuring standard. The co–existence of and competition between energy and water can be processed into a unified assessment framework, and both direct flows and indirect flows embodied in intertwined chains of production and consumption can be analyzed. Also, input–output (IO) analysis has been developed to track the resource and environmental emissions flows and their interactions among sectors within economy [30–39], especially the energy consumption and environmental emissions in urban areas, while few studies have been conducted to combine emergy and IO analyses to provide reasonable estimates for economic goods and services [40–44]. Among others, Ukidwe and Bakshi [43] obtained sector–specific emergy to money ratios to evaluate the environmental burdens of sectoral activities. Chen et al. [27] analyzed the environmental burdens of different sectors by considering emissions, industrial waste, natural resources, exergy, emergy, and cosmic emergy.

This study aims to provide a holistic picture of urban energy–water nexus by modified IO analyses. The remainder of this paper is organized as follows. Section 2 describes the model framework and structure, energy–water flows accounting, hybrid emergy modeling and data sources. Section 3 presents a case study of Beijing, and discussions about the characteristics and disparities between sectors for energy and water utilization. Section 4 provides conclusions about the properties and dynamics of the energy–water nexus network in Beijing.

2. Materials and methods

2.1. Model framework and structure

Fig. 1 shows the technical framework of modeling the urban energy–water nexus by recognizing the network structure of the integrated urban system based on the emergy––IO analyses. The integrated urban system includes both the economy and the supporting environment. The economy includes eight aggregated economic sectors, based on 42 sectors from IO tables. These eight sectors are Agriculture (Ag), Mining (Mi), Manufacturing (Ma), Electricity supply (El), Water supply (Wa), Construction (Co), Transportation and mailing (Tr), and Services (Se). Main sources of renewable energy (e.g., solar radiation, tidal energy, and geothermal energy, biomass), and nonrenewable energy (coal, oil, and natural gas), are utilized to meet the urban energy demand. There is a need of energy for water extraction, conveyance, treatment, disposal, and heating and cooling. Also, water is used in energy supply chain in various ways, e g., the extraction, transport, power generation, processing of biomass and fossil fuels. Thus, the water and energy are intertwined from the suppliers to end users as a hybrid life cycle to drive the urban economic system.

The sectoral direct energy and the embodied energy consumption for urban households, capital formation and changes in stock, and exports based on IO analysis were systemically inventoried. The direct water and embodied water consumption for these three categories were also calculated by IO analysis. The sectoral energy flows and water–related energy flows were calculated and combined as hybrid energy flows. A similar process was applied to the direct water flows and the energy–related water flows to calculate the hybrid water flows. Then, the hybrid energy flows and the hybrid water flows were unified into the urban hybrid energy–water nexus (UHEN) by converting the sectoral consumptions of energy and water into equivalent inflows via emergy analysis. The specific emergy to money ratios were used to assess the contributions of ecological products and services to urban energy and water consumption.

2.2. Energy–water flows accounting

We first accounted for direct energy consumption and water use by economic sectors. The direct energy or water inflow to the ith sector, $\left(f_i^{ene} \text{ or } f_i^{wat}\right)$ was calculated as the sum of all types of energy (coal, gasoline, diesel, natural gas, electricity, etc.) or the sum of all types of water (surface water, groundwater, desalinated water, reclaimed water, etc.), respectively, as shown in Eqs. (1) and (2):

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

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

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

We then calculated the energy–related water and water–related energy for all economic sectors. Adapted from previous studies [17,18], the energy for water consumption was categorized by utilization stages, including: energy for (i) water provision (wp); (ii) water use (wu); and (iii) wastewater resources disposal (wr). The energy–related water (e–water) was divided into the following categories: water for (i) electricity consumption (ee); (ii) coal consumption (ec); and (iii) other consumption (eo). The amount of sectoral water–related energy was calculated based on the sector's direct water consumption for the mth type and the corresponding energy intensity ($\overline{e}^{wp}$, $\overline{e}^{wu}$, $\overline{e}^{wr}$), using Eqs. (3)(5) [30,35].

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

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