Energy–water nexus under energy mix scenarios using input–output and ecological network analyses

Saige Wang[1], Brian Fath[2,3], Bin Chen[1,*]

1 State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, P.R. China

2 Department of Biological Sciences, Towson University, Towson, MD 21252, USA

3 Advanced Systems Analysis, International Institute for Applied Systems Analysis, Laxenburg A –2361, Austria

*Corresponding author: Bin Chen

State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, No. 19 Xinjiekouwai Street, Beijing 100875, P.R. China

Tel/Fax: +86 10 58807368

E–mail: chenb@bnu.edu.cn (Bin Chen)

Abstract

Increasing demand for energy, an evolving electricity-generation mix, and water demand from competing sectors have important implications for water budgets and energy planning. To evaluate the water-related impacts of energy-related decisions, we built a national energy–water nexus scenario analysis assessment framework by extending input–output analysis (IOA) to future scenarios of China's energy generation mix. The scenarios for China out to 2050 include four low-carbon-development scenarios that are planned in climate change mitigation roadmaps and one baseline scenario. Sectoral direct energy, direct water, water-related energy, and energy-related water consumption were inventoried. Sectoral embodied consumption of water and energy and their inter-sector flows were mapped using IOA to create energy–water nexus networks. A sectoral nexus was defined to investigate the impact of the energy–water linkage on energy and water systems. Sectoral control and dependence relationships were revealed by ecological network analysis. Results showed that nexus impact on the water system was larger than that on the energy system. The main export and import pairs—Chemical industry–Agriculture (Ag), Manufacturing–Ag, Ag–Metal smelting and pressing (Me), and Me–Electricity (El)—should be critical pathways for nexus management via the adjustment of sectoral economic relationships. The sectors with a high nexus impact—Ag, El, and Me—should decrease their energy and water consumption to achieve outsized system-wide savings. Sectors with a low nexus impact—such as domestic services; transport, storage and post services; and water production and supply—can increase their energy and water consumption with a lesser impact on the wider system. The low-carbon-development scenario exhibited the lowest nexus impact, followed by the enhanced low-carbon scenario, whose energy mix also exerted the lowest pressure on the water system. By analyzing the tradeoffs between energy, water, and carbon emissions under five scenarios, this study provides insights for nexus management on how to balance water shortage issues and the development of energy generation in future energy and water resource planning.

Keywords: Nexus; Low-carbon development; Climate change; Scenario analysis; Ecological network analysis

1 Introduction

Water and energy use is interrelated. Water is used for cooling power plants, for extracting, transporting, and processing fossil fuels, and for irrigating biofuel feedstock crops, while energy is used to collect, clean, move, store, and dispose of water [1–3]. Alongside its rapid economic growth and population expansion, increasing demand for water and energy is posing significant challenges for sustainable development in China [4]. The International Energy Agency's energy strategy scenario for China reported that the amount of water withdrawn for energy production will be 77% higher in 2030 than that the amount withdrawn in 2015, aggravating water scarcity risks under current the energy strategy[5]. Water-resource constraints on energy supply have become important aspects for both energy and water security [6]. To meet energy demand within water endowments, China has planned to shift its energy sources away from coal and hydropower towards those that are less water-reliant, such as wind and solar [7–8]. Considering the water–energy nexus when planning the energy generation mix not only helps to ensure a sustainable energy supply to meet increasing energy demand but also can diminish energy-related water consumption.

Despite its common usage, there is no formal definition of the 'energy–water nexus'. A suggested broad definition is that it addresses the interconnection or cause–effect relationships between water and energy [9]. That is, a change in one leads to a change in the other, owing to energy consumption by the water system and water use by the energy system. Here, we apply the energy–water nexus concept to investigate the mutual dependency of energy and water through coupled mechanisms that illustrate the interlinkages and conversion processes [10]. The complex interdependency between energy and water has the potential to exacerbate or mitigate energy and water risks [11–12].

Most research on the energy–water nexus has explored the interactions between energy and water systems by calculating the energy consumption for a water system and the water use for an energy system, both at the macro and micro scale [13–22]. The water use for an energy system has been investigated directly and indirectly at global, regional, and national scales [13–17]. For example, at the global level, Davies et al. estimated current water withdrawal and consumption by the electricity sector in fourteen geopolitical regions [13]. The authors also projected water use for electricity production out to 2095 while considering uncertainties in water withdrawal and consumption intensities, changes to power plant cooling systems, and adoption rates of water-saving technologies. At the national level, Holland et al. examined the impacts of energy demand on freshwater resources by evaluating water consumption for electricity production [14]. At the micro scale, Feng et al. integrated process-based life cycle analysis and input-output analysis (IOA) to account for the total life cycle water consumption for eight energy-generation technologies [15]. Their results demonstrated that a shift to low-carbon renewable electricity generation technologies like wind power, could potentially more than halve water consumption per kWh of electricity generated compared with that using the current fuel mix and electricity generating technologies. In addition, the life cycle water use for renewable energy has been investigated and compared to that for conventional energy generation [18–22]. For instance, Wu et al. investigated the water used by solar power infrastructure by employing a water-use-intensity database in IOA, and compared this with both withdrawal and consumption amounts by conventional power plants [18]. Their results showed surprisingly high levels of industrial water use attributed to solar power plant infrastructure, reaching more than twice the lifecycle freshwater use of a coal-fired power plant.

The energy consumed during the construction, operation, and maintenance phases of infrastructure in the water sector has been analyzed for specific components of the water cycle including the supply, distribution, end use, heating, and cooling of water; and the treatment of wastewater [23-30]. For example, Kenway et al. analyzed water-related energy consumption during the provision of water and its use; during wastewater treatment; as a result of the urban heat island effect; and other water-related energy consumption [25]. The authors estimated the water-related energy use in a hypothetical city of 1 million people and concluded that water-related energy use accounted for 13% of total electricity use and 18% of total natural gas use. A systematic framework to and analysis of urban water and energy were also developed to investigate the energy use related to end water consumption by end users in households, industry and commerce [24]. The authors reported that the energy consumed on account of the end uses of water typically accounted for more than 60% of Australian cities' total water-cycle-derived energy consumption.

There has, however, been very little work published that conceptualizes the role of the nexus in reconfiguring the interactions between energy- and water-related sectors in a socioeconomic system [31–36]. The energy–water nexus is becoming the focus in recent years as it becomes more recognized that sectoral economic interactions play an important role and magnify their interdependency in terms of resource use. Some studies have explored the direct and indirect interdependencies between energy and water in socioeconomic systems [37–49]. By tracking sectoral economic flows through a supply chain, IOA can investigate these interdependencies, which are a common focus in nexus studies [36]. Based on these sectoral interactions and exchanges with other economies through the supply chain, IOA–based approaches can assess both the direct and indirect energy consumption required to produce goods and services in a region [38]. Compared with conventional nexus studies, which prioritize specific interdependencies (e.g., by defining that specific processes require certain resources), the system-wide approach of IOA presents a more comprehensive picture that includes direct and indirect use profiles and hotspots. Pioneering works have used IOA case studies to focus on the interplay involved in the water–energy nexus [38–40]. For example, Wang and Chen proposed a modified IOA that provided a unified framework to analyze the tradeoffs between urban energy and water systems [39]. Fang and Chen used IOA and linkage analysis to detect synergetic effects of water and energy consumption, and their interactions among economic sectors [43]. Marsh suggested various IOA techniques to address multiple dimensions of the nexus (linkage, dependency, multiplier, and scenario analyses) [42]. Kahrl and Roland-Holst built relevant metrics to quantify the nexus from physical, monetary, and distributive perspectives [6].

Moreover, there are "structural tensions" between the water and energy sectors, where stresses and insecurities in one sector simultaneously become stresses for the other, and may lead to questionable tradeoffs between the security of water and energy resources [38-40, 47-50]. [46, 51]. Two major network analyses—complex network analysis and ecological network analysis (ENA)—have therefore been employed to investigate the relationships between various compartments of real complex systems [52, 53]. Complex network analysis focusses on the probability for nodes that their adjacent neighbors linked, and analyzes their dynamic process in the context of a hierarchical structure [54]. It has been developed to demonstrate the topological proximity of distant individuals, giving rise to the "small-world phenomenon" in analyses of network structure and network evolution [53,55]. In comparison, ENA initially applies mathematical methodologies to flow–storage models to identify holistic and emergent properties of ecosystem behavior and examine the structure and flow of energy and materials in ecosystems. By applying IOA techniques to ecosystems, ENA is a branch of ecology that uses tools to describe "ecological relationships" in socioeconomic systems, including competitive, exploitative, and mutualistic relationships. By linking the flow of energy through a food web with the flow of energy through a socioeconomic system, the interdependence of organisms in an ecosystem can be explicated by implementing environmental concepts and capturing an object's external relationships as input and output exchanges with its environs. ENA research to determine the interdependence of organisms in an ecosystem based on their direct and indirect use of energy bifurcated into two sub-areas: environ analysis and ascendancy analysis. Four ecological network parameters have been developed in ENA to examine the structure and interactions among components; namely, amplification, homogenization, indirect effects, and synergism. ENA is now a powerful tool for investigating the interactions between different system components, and can be augmented by a series of "network statistics"—such as the indirect effects ratio, control and dependence analyses, utility analysis, and through-flow analysis—which provide extra insights into the interwoven relationship between nodes that arise from direct and indirect flows. ENA has also been effective for investigating system-level properties by analyzing a resource's cycling index, robustness, and resilience to reveal characteristics of the system's structure and function [52, 56]. These characteristics can then be used to identify pathways that can regulate the system [57].

Recently, in the context of the increasing importance of interregional and international trade, nexus studies have combined ENA with IOA to explore structural properties and sectoral interactions of extended economic systems, and to analyze and investigate the pathways and properties of nexus systems [38-44]. For example, Chen and Chen built a systems-oriented urban energy–water nexus network and analyzed its structural properties and sectoral dynamics using IOA and ENA [38]. Yang and Chen combined these two methods to examine mutual interactions and control situations within the wind-power-generation system [43]. Wang and Chen established a multi-regional nexus network based on multi-regional IOA and ENA to explore the structural properties and sectoral interactions within urban agglomerations [40]. However, nexus issues in energy and water policy are rarely studied from a systems perspective, an area that urgently requires investigation. Particularly in energy-development planning, the role of water stress issues is insufficiently considered as a part of nexus management [15, 20, 50, 51].

This gap is partially addressed in this paper by analyzing the direct and indirect impacts of different energy mix scenarios on water consumption. Section 2 describes the methodology for analyzing nexus impacts, and the influences of the energy mix on energy and water systems under different scenarios. Section 3 presents the results and discusses the tradeoffs between energy, water, and carbon emissions under different scenarios. Finally, a range of conclusions are provided in Section 4 to evaluate the different scenarios from an energy–water nexus perspective.

2 Methodology

Five energy mix scenarios for China were set up based on the National Energy Planning and Global Low-Carbon Development Mitigation Planning scenarios (see Figure 1) [11, 12, 30].

The direct consumption of energy and energy consumption arising from the consumption of water were inventoried and used to calculate the indirect energy consumption through IOA at a sectoral level. The direct and indirect energy and water-related energy were then combined to yield embodied energy, which was used to build the nexus network model. A similar process was applied to the direct consumption of water and water consumption arising from energy processes to calculate the amount of embodied water, which was then also employed in the nexus network model. Then, the ENA tools control and dependence analyses were used to further investigate the sectoral relationships in the energy and water nexus networks. Flow analysis was used to identify critical pathways for nexus management.

[Figure 1 could be here]

We grouped the 42 sectors in the original input–output tables into 30 sectors for China to align with energy consumption data; the details of which are shown in Table 1. Combining indicators for water and energy-related water, we defined a nexus impact for the water system to analyze the effects of different energy scenarios on the water system. The sectoral nexus impact for the energy system was investigated by analyzing the energy and water-related energy network to identify critical sectors for energy-side nexus management. The sectoral nexus impacts under different scenarios were compared and analyzed using ENA. By comparing the nexus impacts for different scenarios, the influences of the energy mix on the energy and water systems were quantified to assess the pressure that energy development imposes on water resources. Finally, the features of the scenarios and the tradeoffs between energy, water, and carbon emissions were discussed using nexus accounting.

[Table 1 could be here]

2.1 Inventory analysis

The direct energy consumption of the i^{th} sector (E_i) was calculated as the sum of consumption of nine energy types (including coal, oil, natural gas, nuclear, hydropower, wind power, solar power, and biomass), i.e., $E_i = \sum_{m=1} e_i^m$. The direct water consumption of the i^{th} sector (W_i) was calculated from the sum of all water types (surface water, groundwater, desalinated water, and reclaimed water), i.e., $W_i = \sum_{m=1} w_i^m$.

The consumption of water-related energy and of energy-related water were calculated using water and energy intensities, respectively. Here, “related” was defined as representing interconnections or cause-and-effect relationships between water and energy. When a change occurred in water use or water infrastructure (such as increased consumption or the installation of a new supply source), changes in energy use would occur if there was energy use "related" to the water. Energy-related water use was divided into water used for coal, natural gas, electricity generation, and hydropower. Water-related energy use was calculated from the full lifecycle process by adapting the work of Kennway. Here, the change in energy use attributed to water consumption was accounted for by calculating the energy for: (i) the provision of water (*wp*); (ii) the use of water (*wu*); and (iii) the resources required for wastewater treatment (*wr*) [24, 26, 27]. The sectoral amount of water-related energy was calculated using the sector's direct water consumption for the *m*th sector and the corresponding energy intensity ($\bar{e}^{wp}$, $\bar{e}^{wu}$, and $\bar{e}^{wr}$), as shown in Eqs. 1–3:

$$f_i^{wp-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wp} \quad (1)$$

$$f_i^{wu-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wu} \quad (2)$$

$$f_i^{wr-ene} = \sum_{m=1} w_i^m \times \bar{e}^{wr} \quad (3)$$

Energy-related water (*e–water*) was divided into the following categories: (i) water for electricity consumption (*ee*); (ii) water for coal consumption (*ec*); and (iii) water for other consumption (*eo*) [26, 28]. Similarly, sectoral energy-related water use was computed based on the *m*th sector's direct energy consumption and corresponding water intensity ($\bar{w}^{ee}$, $\bar{w}^{ec}$, and $\bar{w}^{eo}$), as shown in Eqs. 4–6 [23, 30]:

$$f_i^{ee-wat} = \sum_{m=1} e_i^{ee} \times \bar{w}^{ee} \quad (4)$$

$$f_i^{ec-wat} = \sum_{m=1} e_i^{ec} \times \bar{w}^{ec} \quad (5)$$

$$f_i^{eo-wat} = \sum_{m=1} e_i^{eo} \times \bar{w}^{eo} \quad (6)$$

Water-related energy and energy-related water were calculated to investigate the energy–water nexus. Embodied energy (f_i^{h-ene})was calculated from the sum of the direct energy consumption (f_i^{ene}) and water-related energy (f_i^{wat}, f_i^{wu-ene}, f_i^{wu-ene}, and f_i^{wr-ene}), (see Eq. 7). Similarly, embodied water (f_i^{h-wat}) was calculated by summing the direct water consumption (f_i^{wat}) and energy-related water (f_i^{ee-wat}, f_i^{ec-wat}, and f_i^{eo-wat}) (see Eq. 8).

$$f_i^{h-ene} = f_i^{ene} + f_i^{wp-ene} + f_i^{wu-ene} + f_i^{wr-ene} \quad (7)$$

$$f_i^{h-wat} = f_i^{wat} + f_i^{ee-wat} + f_i^{ec-wat} + f_i^{eo-wat} \quad (8)$$

2.2 Flow analysis

Using monetary input–output tables, we employed consumption coefficients to build the environmental input–output model that described the energy, water-related energy, water, and energy-related water flows between sectors.

Using the Leontief model, embodied energy flows (f_{ij}^{ene}) and embodied water flows (f_{ij}^{wat}) between sectors were calculated by Eqs. 9–10 [37, 58 –63]:

$$F_{n\times n}^{ene} = (I - A)^{-1} \times E_{n\times n}^{diag} \quad (9)$$

$$F_{n\times n}^{wat} = (I - A)^{-1} \times W_{n\times n}^{diag} \quad (10)$$

where I is the n×n identity matrix; A is the direct requirement matrix, which was calculated by the monetary flows divided by the economic outputs of these sectors; $E_{n\times n}^{diag}$ is a diagonal matrix transformed from energy consumption, E_i; and $W_{n\times n}^{diag}$ is a diagonal matrix transformed from water consumption, W_i.

In a similar manner the energy-related water flows (f_{ij}^{e-w}) and the water-related energy flows (f_{ij}^{w-e}) were calculated using Eqs. 11–12:

$$F_{n\times n}^{w-e} = (I - A)^{-1} \times E_{n\times n}^{diag} \times E_{W n\times n}^{diag} \quad (11)$$

$$F_{n\times n}^{e-w} = (I - A)^{-1} \times W_{n\times n}^{diag} \times W_{E n\times n}^{diag} \quad (12)$$

where $E_{W n\times n}^{diag}$ is a diagonal matrix transformed from the water-related energy consumption; and $W_{E n\times n}^{diag}$ is a diagonal matrix transformed from the energy-related water use.

2.3 Control and dependence analyses

ENA was applied to the nexus networks to evaluate the cycling and resilience of economic systems. In particular, the control allocation coefficient (*CA*) and the dependence allocation coefficient (*DA*) were used to quantify the control and dependence relationships between economic sectors [52, 53]. The integral flow, defined as *N* or *N′* depending on whether the flow was out of or into the node, respectively, was used to explain the influence that one region exerts on another within the overall system configuration, as shown in Eqs. 13–14:

$$N = (n_{ij}) = \sum_{n=0}^{\infty} G^n = (I - G)^{-1} \quad (13)$$

$$N' = (n'_{ij}) = \sum_{n=0}^{\infty} G'^{n} = (I - G')^{-1} \tag{14}$$

where $\mathbf{G} = [g_{ij}]$, $g_{ij} = f_{ij}/T_j$; f_{ij} refers to the energy or water flow from sector j to sector i; $\mathbf{G'} = [g'_{ij}]$; $g'_{ij} = f_{ij}/T_i$; and $T_j \equiv T_j^{(\text{out})} = \sum_{i(\neq j)=o}^{n} T_{ij}$.

Combining the two integral matrices (N and N'), we calculated CA and DA to quantify the control and dependence relationship between regions using Eqs. 15–16.

$$CA=(ca_{ij}) \equiv \begin{cases} n_{ij} - n'_{ji} > 0, ca_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{i=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \le 0, ca_{ij} = 0 \end{cases} \tag{15}$$

$$DA=(da_{ij}) \equiv \begin{cases} n_{ij} - n'_{ji} > 0, da_{ij} = \dfrac{n_{ij} - n'_{ji}}{\sum_{j=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \le 0, da_{ij} = 0 \end{cases} \tag{16}$$

where $0 \le da_{ij}, ca_{ij} \le 1$. CA and DA were formulated from the difference between two pair-wise integral flows (i.e., n_{ij} and n'_{ji}) that were normalized according to the two involved environs. The ca_{ij} term indicated the control degree of compartment j on compartment i based on compartment j's output environ. The da_{ij} term indicated the dependence degree of compartment j on compartment i from compartment j's input environ.

To study the nexus impact on the control relationship between regions in the network, we defined $ca_{ij}^{e,n}$ based on the CA of direct energy ($ca_{ij}^{e,n}$) and water-related energy (ca_{ij}^{w-ene}), and $da_{ij}^{e,n}$ based on direct energy (da_{ij}^{ene}) and water-related energy (da_{ij}^{w-ene}), the details of which are shown in Eqs. 17–18:

$$ca_{ij}^{e,n} = \frac{ca_{ij}^{w-ene} \times f_{ij}^{w-ene} + ca_{ij}^{ene} \times f_{ij}^{ene}}{f_{ij}^{w-ene} + f_{ij}^{ene}} \tag{17}$$

$$da_{ij}^{e,n} = \frac{da_{ij}^{w-ene} \times f_{ij}^{w-ene} + da_{ij}^{ene} \times f_{ij}^{ene}}{f_{ij}^{w-ene} + f_{ij}^{ene}} \tag{18}$$

where f_{ij}^{w-ene} indicates the water-related energy flow from region i to region j, and f_{ij}^{ene} refers to the direct energy flow from region i to region j.

We examined the nexus impact on the dependence relationship between regions for the water system in a similar manner. Here, we defined $ca_{ij}^{w,n}$ based on the CA of direct water (ca_{ij}^{wat})

and energy-related water (ca_{ij}^{e-wat}), and $da_{ij}^{w,n}$ based on *DA* of direct water (da_{ij}^{wat}) and energy-related water (da_{ij}^{e-wat}), as shown in Eqs. 19–20:

$$ca_{ij}^{w,n} = \frac{ca_{ij}^{e-wat} \times f_{ij}^{e-wat} + ca_{ij}^{wat} \times f_{ij}^{wat}}{f_{ij}^{e-wat} + f_{ij}^{wat}} \tag{19}$$

$$da_{ij}^{w,n} = \frac{da_{ij}^{e-wat} \times f_{ij}^{e-wat} + da_{ij}^{wat} \times f_{ij}^{wat}}{f_{ij}^{e-wat} + f_{ij}^{wat}} \tag{20}$$

where f_{ij}^{e-wat} indicates the energy-related water flow from region *i* to region *j*, and f_{ij}^{wat} refers to the direct water flow from region *i* to region *j*.

2.4 Nexus impact

To quantify the effect of energy-related water on water system, we defined the nexus impact on water (NI_{wat}) by combining sectoral energy-related water and sectoral total water consumption (see Eq. 21). Similarly, we defined the nexus impact on energy (NI_{ene}) to investigate the effect of water-related energy on the energy system using sectoral water-related energy and total energy consumption (see Eq. 22). The nexus impacts can describe the degree to which the energy and water systems are impacted.

$$NI_{\text{wat}} = \left(\frac{f_i^{e-w}}{f_i^{wat} - f_i^{e-w}} \right) \times 100\% \tag{22}$$

$$NI_{ene} = \left(\frac{f_i^{w-e}}{f_i^{ene} - f_i^{w-e}} \right) \times 100\% \tag{23}$$

2.5 Scenario Analysis

The energy-generation-mix scenarios for 2050 shown in Table 2 were adapted from work by the Chinese Academy of Engineering (CAE) and the Energy Research Institute of the National Development and Reform Commission (ERI-NDRC) [64-69]. The baseline scenario (S1) was established from CAE data for a primary energy structure based on scientific capacity and energy use. Other scenarios were adapted from work by ERI-NDRC with S4 and S5 drawn from the Integrated Policy Assessment Model for China (IPAC model). In the scenarios, carbon emissions were highest for S2, followed by S4, S1, S3 and S5. Water use data were compiled from China's Environmental Statistical Yearbook and coefficients were adapted from the work of Feng and Kenway [15, 24, 25, 27]. Economic input–output data for the 42 sectors in China for 2012 were obtained from the China Statistical Yearbook [67].

[Table 2 could be here]

3 Results and discussion

3.1 Inventory analysis

The inventory identified the metal smelting and pressing sector (Me) as having the largest embodied energy consumption (606.4E+09kWh). Other sectors with high levels of embodied energy include: domestic services (Do); chemicals (Ch); transport, storage and post services (TS); nonmetallic mineral products (No); and electricity, steam and hot water production and supply (El) (Figure 2). For water-related energy consumption, Me also exhibited the second highest water-related energy consumption and thus plays an important role in the embodied energy network. Results for water-related energy were similar to overall sectoral energy consumption patterns; Me, El, TS, Do, and No consumption levels were much larger than those of other sectors. The water-related energy of these five sectors was approximately 100E+09 kWh.

[Figure 2 could be here]

Sectoral profiles for water consumption are shown in Figure 3. Direct water consumption by agriculture, forestry, animal husbandry and fishery (Ag); El; Ch; Me; and Do were 178.9 E+08 L. Energy-related water consumption showed a similar pattern to total water consumption with values for Ag, El, Ch, Do, and Me being much larger than those for the other sectors. These results corresponded closely to those for energy consumption. Ag and El were the main water-consuming sectors with direct water consumption accounting for a large proportion of the total; Ag, in particular, required large amounts of water. Thus, Ag and El are key sectors to focus efforts for decreasing energy and water consumption.

The proportions of energy-related water consumption and water-related energy consumption of each sector's total energy and water consumption were calculated to investigate the energy–water nexus at a sectoral level. Direct consumption of energy and water were found to be responsible for a large proportion of sectors' total energy and water consumption. Comparing results from the different scenarios showed energy-related water consumption was highest for the enhanced low-carbon Scenario 2, followed by low-carbon Scenario 2, low-carbon Scenario 1, the primary energy structure scenario, and the enhanced low-carbon Scenario 1.

[Figure 3 could be here]

International imports and exports of energy and water are shown in Figure 4. For energy imports, the Metal smelting and pressing sector was the top importer with a value of 47.1 E+09 kWh. This was followed by the Chemical industry (Ch); and the Others (OS) sector. Seven other sectors—coal mining; petroleum and gas(Pe); metal mining(Me); paper making, printing, stationery, and related products(Pa); metal products; electrical equipment(El-e); and leasing and commercial services(Le)—were also large importers of energy, with values greater than 8.0E+09 kWh. Le is the top energy-exporting sector with a value of 29.9E+09 kWh. This was followed by OS; Petroleum refining, coking and nuclear fuel processing(Pe-r); and textiles and clothing(Te) (29.1E+09, 25.3E+09, 24.7E+09, and 23.5E+09 kWh, respectively). Five further sectors supplied more than 10 E+09 kWh: wood processing and furnishing(Wo); metal products; El-e; Ch; and hotels and restaurants(Ho). Combining exports and imports revealed that the No; Pe-r; and Pa were net energy importers with values of 23.7E+09, 6.2E+09, and 6.5E+09 kWh, respectively. Conversely, the gas and water production and supply; Te; Ho; Ch; El-e; and Wo sectors were net energy exporters with values of 12.8E+09, 21.6E+09, 14.3E+09, 10.6E+09, 2.7E+09, and 5.7E+09 kWh, respectively.

For water, at 349.2E+08 L the Ag sector imported much more water than other sectors. Nine other sectors—Pe-r; No; Pa; Me; leasing and commercial services(Le); Pe; scientific research; El-e; and Wo—imported more than 2.0 E+08 L. For water exports, Ag was also the largest water-exporting sector with a value of 53.3 E+08 L. Nine sectors exported less than 18.0E+08 Le. The remaining nine sectors in the top 10 water exporters were Pe-r; Le; Wo; No; Te; electrical equipment; Ho; scientific research; and Pa. Comparing the export and import values, the following sectors were net water importers: Ag; Pe-r; No; Pe; scientific research; and Wa, with values of 295.8 E+08, 4.4 E+08, 5.1 E+08, 0.7 E+08, 0.3 E+08, and 0.1 E+08 L, respectively. The Pa; Me; Le; and El-e sectors were the main net water exporters with values of 3.3 E+08, 1.8 E+08, 1.4 E+08, and 0.2 E+08 L, respectively.

[Figure 4 could be here]

3.2 Energy and water flows between regions

The major energy exporter was the Ch sector and the main energy importer was the Me sector (Figure 5). The width of the flows illustrates their amount, and the figure also shows the degree of flows between import–export sector pairs, and how they contribute to sectoral totals. The flows are color coded to identity their direction and which sectors they are imported to. The percentage label for each flow represents the proportion that the inflow or outflow contributes to total regional consumption. For example, Ch exports a large amount of embodied energy to the Me (9.01E+10 kWh), No (6.67E+10 kWh), and textiles and clothing (4.67E+10 kWh) sectors, together representing approximately 95% of the Ch sector's total embodied energy consumption. The Me sector and the gas production and supply sector exported large amounts of embodied energy to manufacturing sectors like Me and Nm.

[Figure 5 could be here]

The main water exporters were the Ag, Ch, and manufacture of food products and tobacco processing (Ma) sectors. The Ch sector recorded the largest water outflow, exporting 9.69E+10 L to the Ag sector (Figure 6). The largest importer was the Ag sector, which accepted 53% of all exports, followed by the El sector (25%). Major water export–import pairs were Ch–Ag, Ma–Ag, Ag–Me, and Me–El.

[Figure 6 could be here]

3.3 Control and dependence analyses

The *CA* and *DA* results were revealed by combining data for direct energy, water networks, embodied energy, and embodied water networks. After considering the nexus impact, the control and dependence relationships between some sectors became stronger, while others became weaker. The control and dependence relationships for water systems between the sectors for the five energy mix scenarios after considering the nexus impact are shown in Figure 7. Comparing *CA* and *DA*, *DA* was more influenced by the nexus impact than *CA* under all five scenarios. *DA* was most affected in Scenario 3, followed by Scenarios 2 and 4. *CA* was most affected in Scenario 5, followed by Scenarios 3 and 1. We also identified major changes in the sectoral dependence relationships in different scenarios. For example, the sectoral control relationship for the water system in Scenario 1 was notably different (Figure 7a). The control of the petroleum and natural gas extraction sector over the other manufacturing products sector was strengthened by the energy–water nexus relationship. The dependence of the Ag sector on the Do sector was also strengthened owing to the energy–water linkage (Figure 7b). Because these connections were strengthened by the energy–water nexus, they may be critical pathways for coordinating nexus management.

[Figure 7 could be here]

3.4 Nexus impact

The ratio of water-related energy to direct energy illustrates the linkage between energy and water in the energy system, and this can describe the nexus impact on the energy system (NI_{ene}). The nexus impact on the energy system did not show a wide range, unlike that on the water system (NI_{wat}), as shown in Figure 8. The linkage had a larger influence on the water system than on the energy system. The nexus impact on the water system showed significant differences between the scenarios. NI_{wat} was lowest for the IPAC low-carbon-development scenario, followed by Scenarios 3, 5, 2, and 1.

[Figure 8 could be here]

4 Conclusions

In this paper, we extended future energy mix scenarios to perform an assessment of the energy–water nexus and analyzed the sectoral linkages for embodied energy and water consumption to identity pathways to decrease the interdependencies and inefficiencies that can arise from fragmented management approaches. The results showed that sectoral water-related energy use closely corresponds with energy consumption, particularly for the Me, TS, and Do sectors. The inventories for different energy mix scenarios provide insights into sectoral energy- and water-consumption patterns.

The sectoral embodied energy/water importer and exporter relationships were investigated using an inventory of sectoral economic activities. The main export and import pairs for water were Ch–Ag; Manufacturing–Ag; Ag–Me; and Me–El. These linkages represent critical pathways to manage the nexus via adjusting the economic structure.

Based on their direct and indirect usage, we analyzed the impact of the linkage relationship on sectors' energy and water systems for different scenarios. A higher nexus impact indicated a stronger influence of the energy–water linkage relationship, and can be used to identify energy mix scenarios that exert less pressure on the water system. Comparing the results for the different scenarios, the lowest water pressure exerted by energy development occurred in the IPAC low-carbon-development scenario. This was followed by the NDRC enhanced low-carbon scenario, the IPAC enhanced low-carbon scenario, the NDRC low-carbon scenario, and the baseline scenario.

Employing a new indicator that combines nexus impact with control and dependence analyses, sectors with high nexus impact, such as Ag, El, and Me were found to act as multipliers for resource consumption, i.e., one unit of resource consumption in these sectors will cause more than one unit of resource consumption across the whole system. Thus, sectors identified as having a high nexus impact should decrease energy and water consumption to achieve outsized system savings. Meanwhile, sectors with a lower nexus impact—such as Do, TS, and water production and supply—could increase their energy and water consumption with a lower corresponding impact on the overall system [70, 71]. Policy that shifts growth to these less-consuming sectors could lower overall energy and water consumption and yield commensurable decreases in environmental impacts [66].

The carbon emissions from the five energy mix scenarios can be ranked as: S5<S3<S1<S4<S2. The ranking for total energy generation with the same equivalent standard coal is similar: S5<S3<S1<S4<S2 but total coal generation shows a slightly different ranking: S3<S5<S1<S4<S2 while the ranking for total non–renewable energy is: S3<S2<S1<S5<S4. For total energy-related water consumption the ranking is: S5>S4>S2>S1>S3, and for water impacts it is S4<S3<S5< S2<S1. To illustrate the tradeoffs between aspects in these scenarios, we scored the six aspects (carbon emissions, energy generation, coal generation, non-renewable energy, energy-related water consumption, water impact) where a higher score indicates greater resource consumption and environmental impact (Figure 9). Scenarios with low carbon emissions can exhibit large water pressure, as shown by the results for Scenario 1. Adopting scenarios with lower energy-related water use can result in higher carbon emissions. For example, Scenario 2 emits the most carbon emissions, has the highest amount of total energy generation, uses the most coal, puts the second-largest pressure on water resources, and has the third-highest energy-related water consumption. Conversely, Scenario 3 consumes the least coal, has the highest non–renewable energy usage, has the smallest energy-related water consumption, emits the second-lowest amount of carbon emissions, and exerts the second-lowest water pressure. Thus, we recommend Scenario 3 over Scenario 2 on account of the former's lower scores for all six aspects. However, the tradeoffs between these aspects still need to be investigated.

[Figure 9 could be here]

A major aim of this paper is to inform policy and promote management solutions that integrate water and energy. This was carried out by investigating sectoral interactions using IOA and attempting to identify trade-offs between these sectors and to highlight their synergies and shared goals. As demonstrated, the IOA-based assessment framework can help examine the outcomes of implementing particular energy-generation-planning scenarios from a supply-side perspective. Meanwhile, the interdependency and structural intensions between energy and water can be quantified by ENA tools like control and dependence analyses. Through investigating different energy mix scenarios, tensions and negative tradeoffs can be identified and avoided—and synergies can be identified and promoted—by understanding the nexus impacts on energy and water in national energy-development planning and a nexus management framework.

Acknowledgements

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Highlights

- Input–output and ecological network analyses were combined with future energy mix scenarios
- Nexus impact on the water system was larger than that on the energy system
- Tradeoffs between energy, water and carbon for different energy mix scenarios were analyzed

Figure captions

Figure 1 Energy-water nexus under different energy generation scenarios assessment framework

Figure 2 Sectoral embodied energy consumption in China

Figure 3 Sectoral embodied water consumption in China

Figure 4 Imports and exports of top 10 sectors for energy and water

Figure 5 Embodied energy flows among sectors of China

Figure 6 Embodied water flows among sectors of China

Figure 7 Network control/dependence relationship among sectors of water nexus networks for five scenarios

Figure 8 Sectoral nexus impacts on energy and water systems

Figure 9 Comparison of five energy generation mix scenarios in context of carbon emissions, energy generation, coal generation, non-renewable energy, energy-related water consumption and water impact

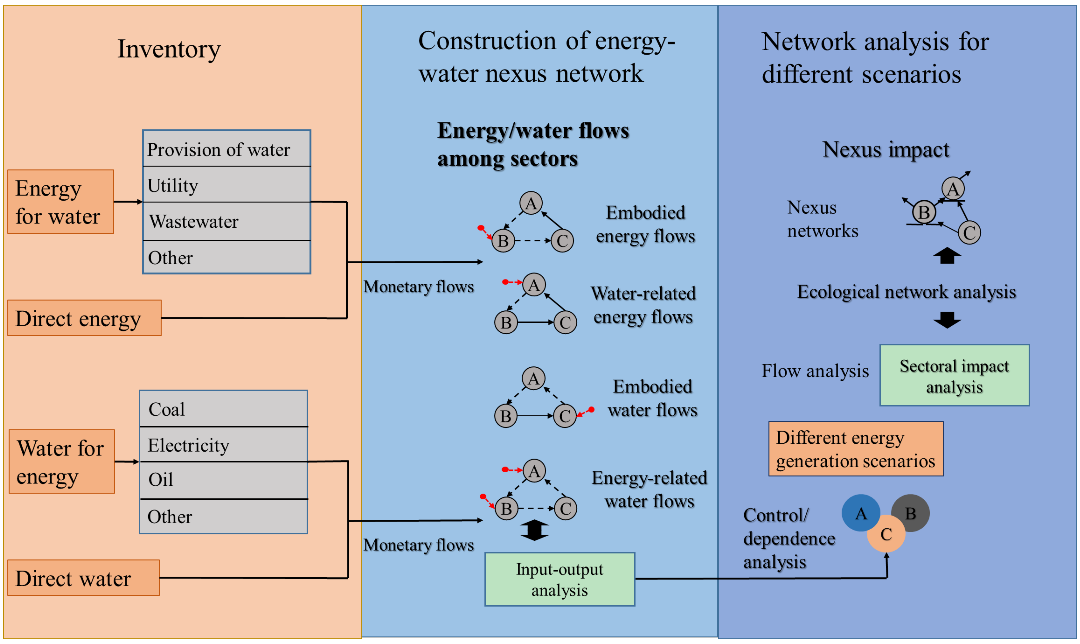


Figure 1 Energy-water nexus under different energy generation scenarios assessment framework

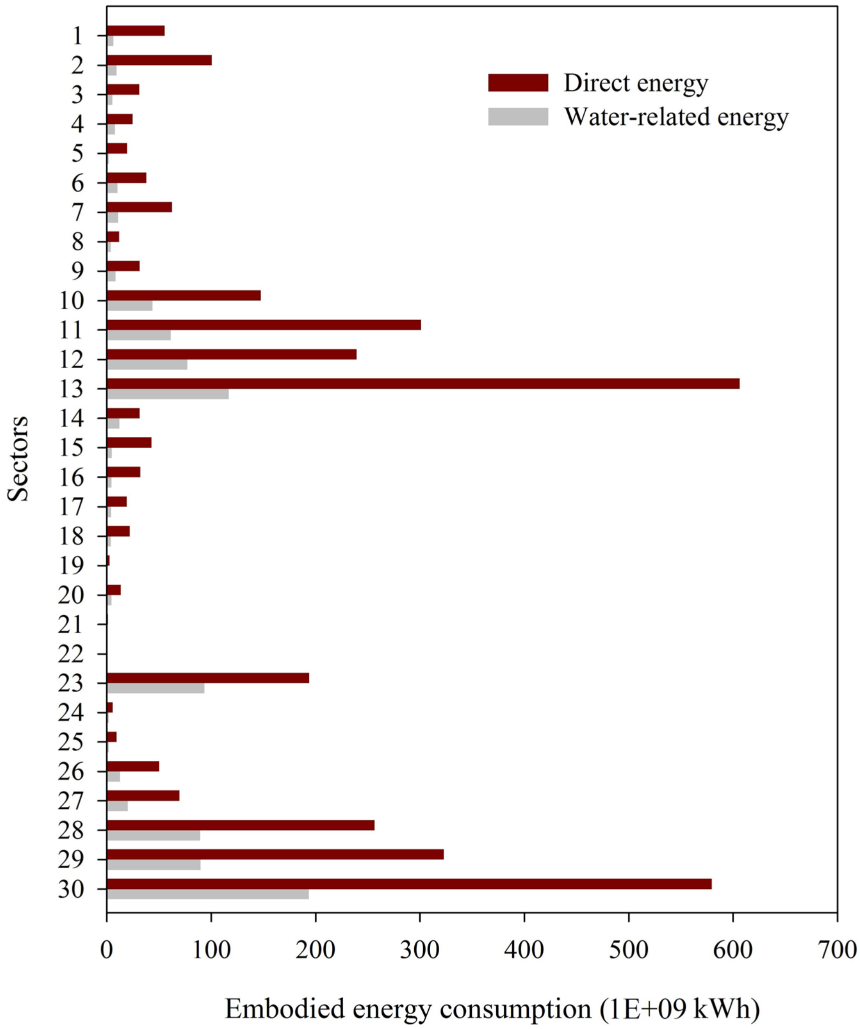


Figure 2 Sectoral embodied energy consumption in China

Note: 1, Agriculture, forestry, animal husbandry and fishery; 2, Coal mining; 3, Petroleum and natural gas extraction; 4, Metal ore mining; 5, Non–metal mining; 6, Manufacture of food products and tobacco processing; 7, Textiles, Wearing apparel, leather, fur, down and related products; 8, Sawmills and furniture; 9, Paper and products minerals, printing and record medium reproduction; 10, Petroleum processing, coking and nuclear fuel processing; 11, Chemical industry; 12, Nonmetallic mineral products; 13, Metal smelting and pressing; 14, Metal products; 15, General machinery and Special purpose machinery; 16, Transport equipment; 17, Electric equipment and machinery; 18, Electronic and telecommunication equipment; 19, Instruments and meters; 20, Other manufacturing products; 21, Scrap and waste; 22, Metal products, machinery and equipment repair services; 23, Electricity, steam and hot water production and supply; 24, Gas production and supply; 25, Water production and supply; 26, Construction; 27, Wholesale, retail trade services, accommodation and food serving services; 28, Transport, storage and post services; 29, Domestic services; 30, Others.

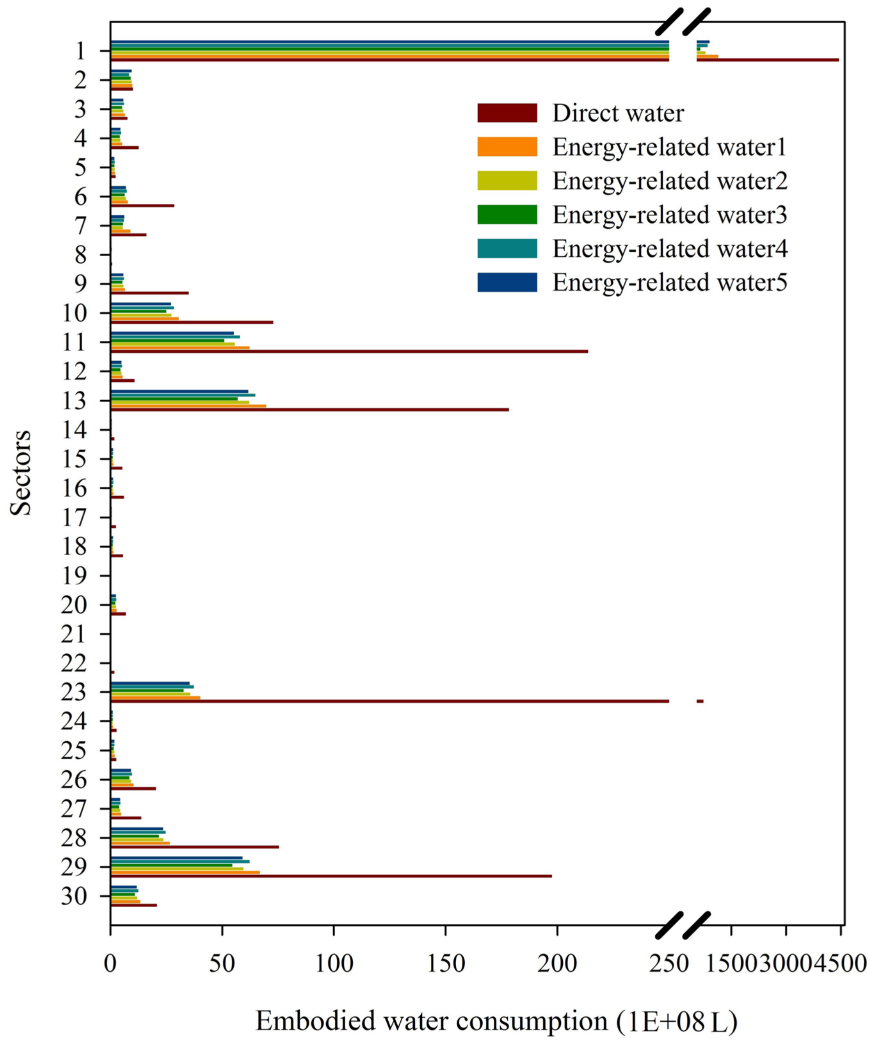


Figure 3 Sectoral embodied water consumption in China

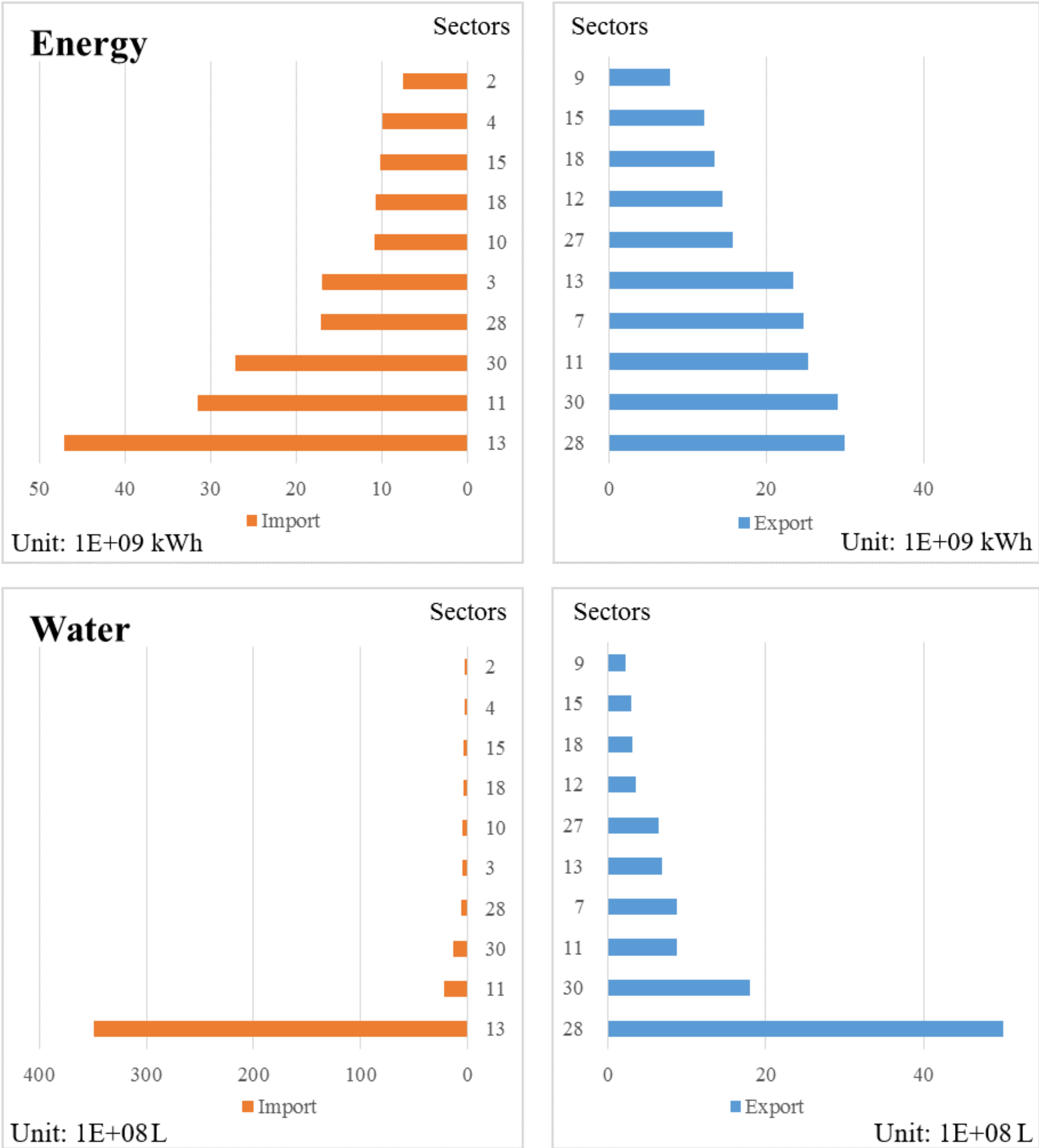


Figure 4 Imports and exports of top 10 sectors for energy and water

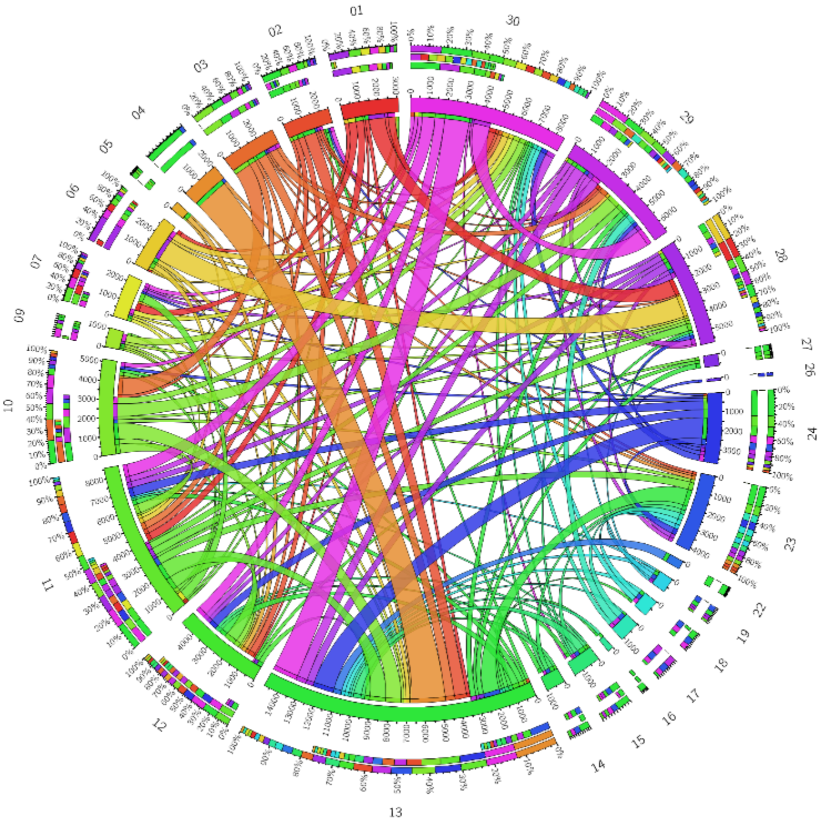


Figure 5 Embodied energy flows among sectors of China

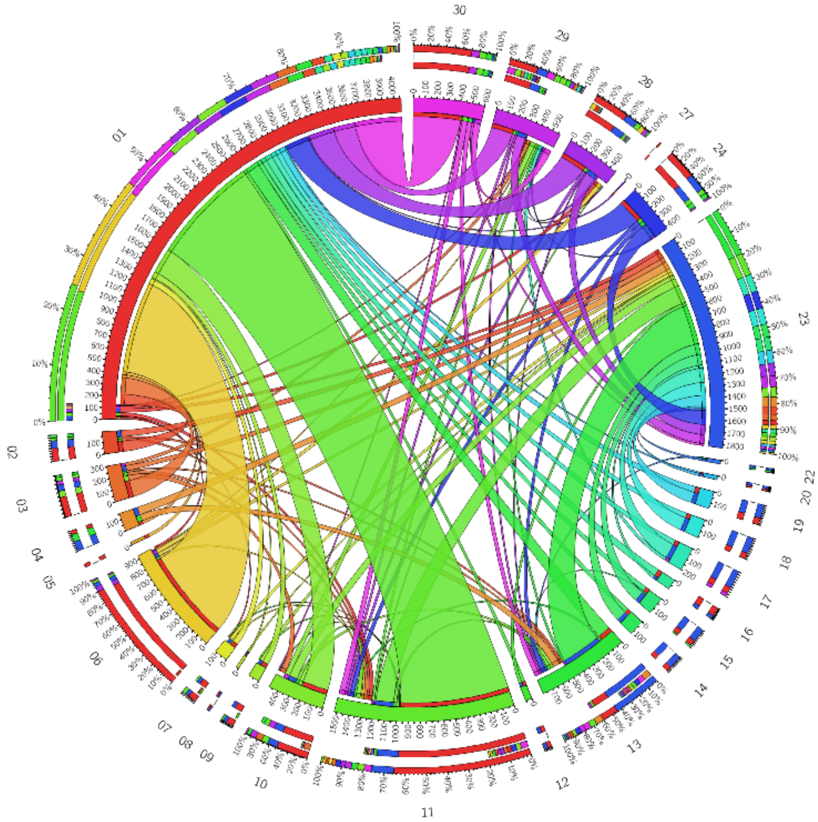
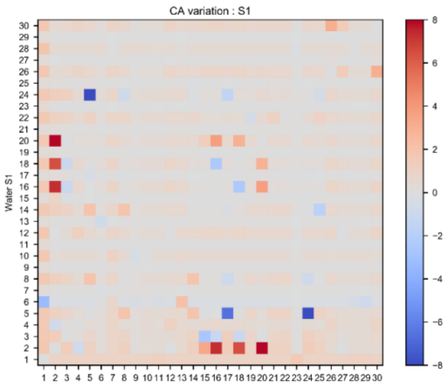
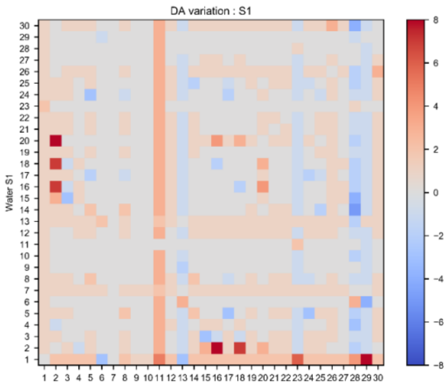
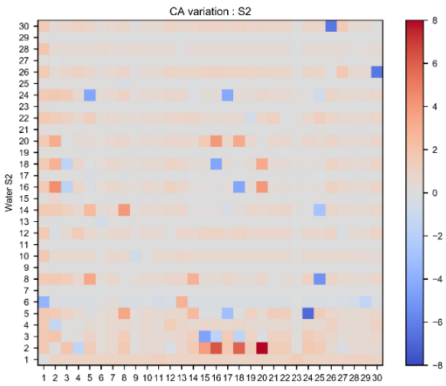


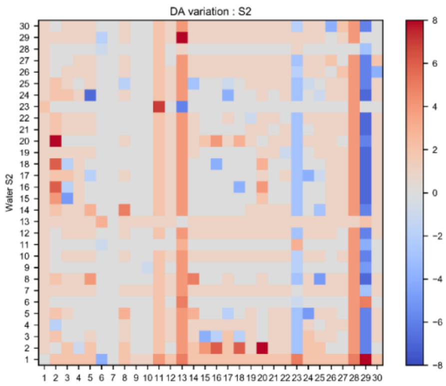
Figure 6 Embodied water flows among sectors of China



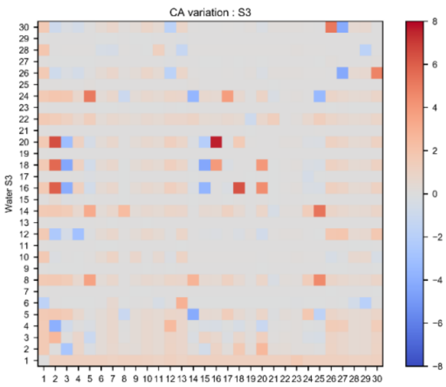


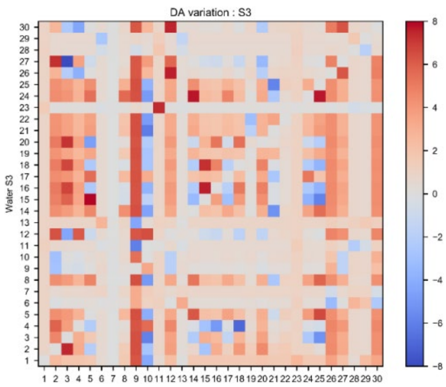
(a) *CA for S1* (b) *DA for S1*



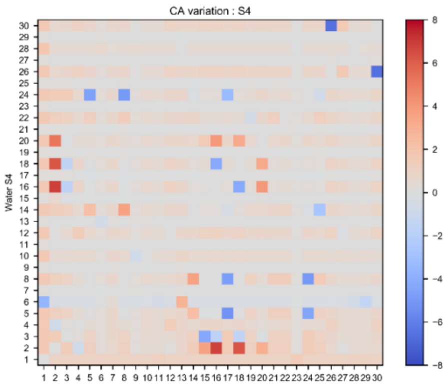


(c) *CA for S2* (d) *DA for S2*

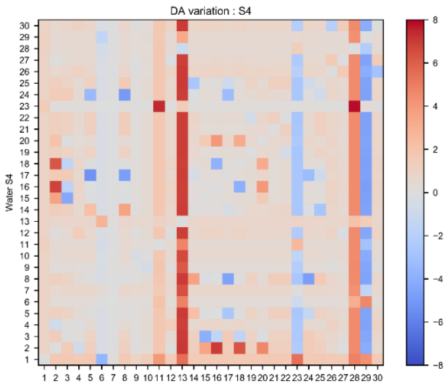




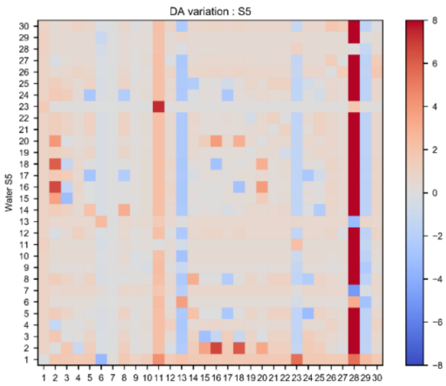
(e) *CA for S3* (f) *DA for S3*



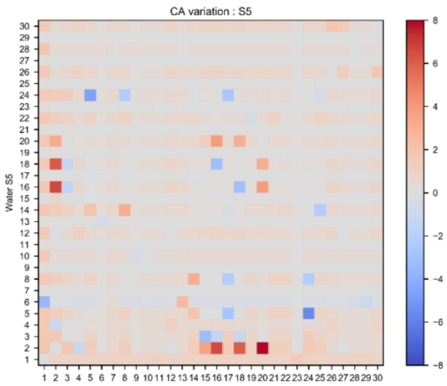
(g) *CA for S4*



(h) *DA for S4*



(i) *CA for S5*



(j) *DA for S5*

Figure 7 Network control/dependence relationship among sector

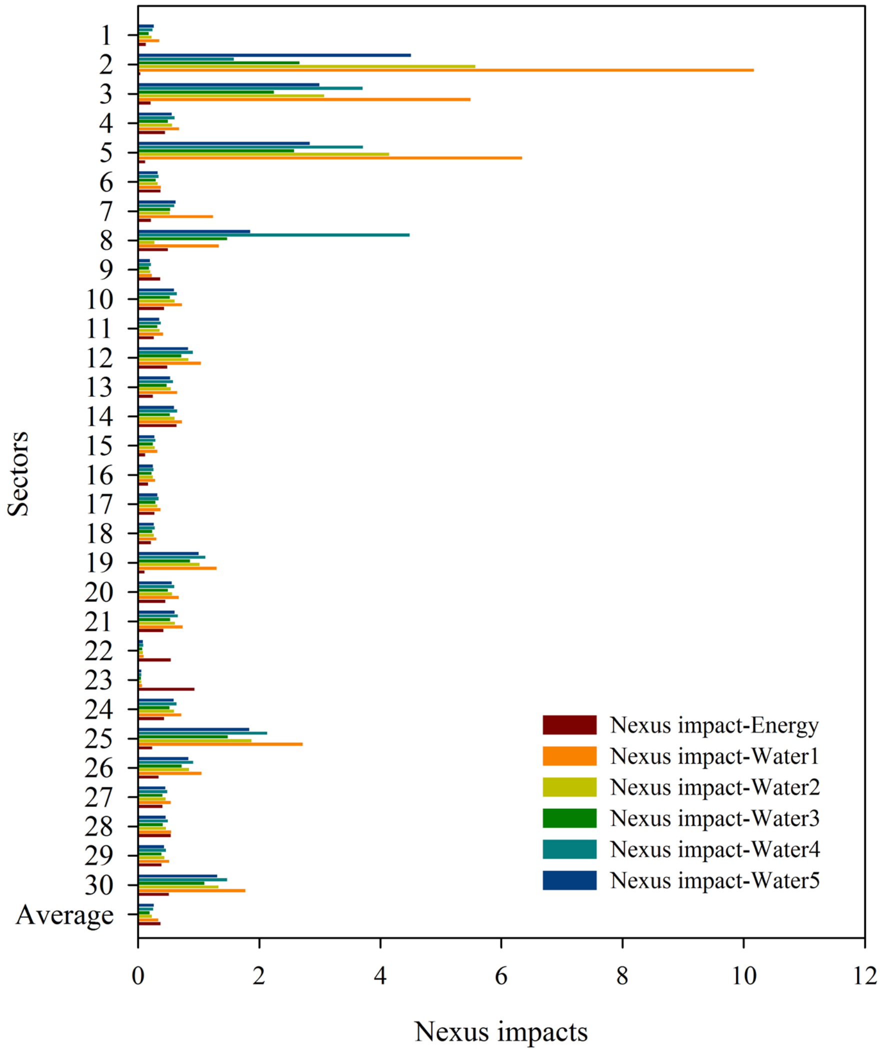


Figure 8 Sectoral nexus impacts on energy and water systems

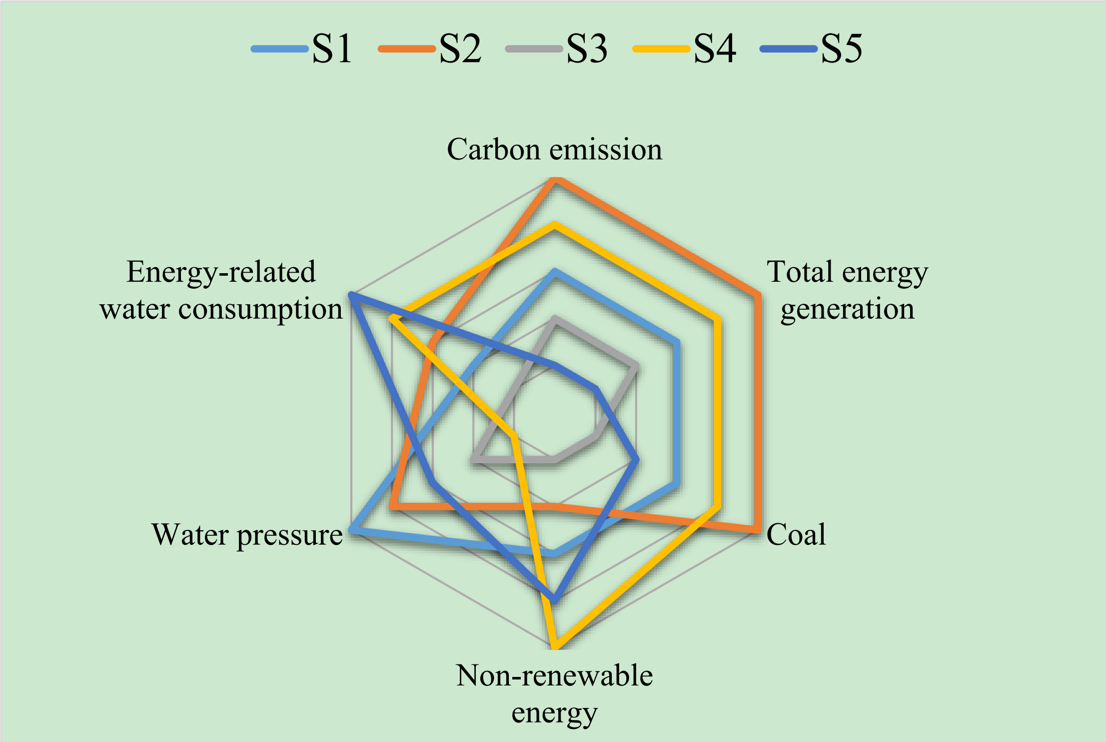


Figure 9 Comparison of five energy generation scenarios in context of carbon emissions, energy generation, coal generation, non-renewable energy, energy-related water consumption and water impact

Table list

Table 1 Economic sectors of the socio-economic system

Sector code	Sectors	Abbreviation	Sector code	Sectors	Abbreviation
1	Agriculture, forestry, animal husbandry and fishery	Ag	**16**	Transport equipment	Tr
2	Coal mining	Co	**17**	Electric equipment and machinery	El
3	Petroleum and natural gas extraction	Pe	**18**	Electronic and telecommunication equipment	El-t
4	Metal ore mining	Me	**19**	Instruments and meters	In
5	Non–metal mining	Nm	**20**	Other manufacturing products	OM
6	Manufacture of food products and tobacco processing	Ma	**21**	Scrap and waste	Sc
7	Textiles, Wearing apparel, leather, fur, down and related products	Te	**22**	Metal products, machinery and equipment repair services	Me-p
8	Sawmills and furniture	Sa	**23**	Electricity, steam and hot water production and supply	El-s
9	Paper and products minerals, printing and record medium reproduction	Pa	**24**	Gas production and supply	Ga
10	Petroleum processing, coking and nuclear fuel processing	Pe	**25**	Water production and supply	Wa
11	Chemical industry	Ch	**26**	Construction	Co
12	Nonmetallic mineral products	No	**27**	Wholesale, retail trade services, accommodation and food serving services	Wh
13	Metal smelting and pressing	Me-s	**28**	Transport, storage and post services	Tr
14	Metal products	Me-p	**29**	Domestic services	Do
15	General machinery and Special purpose machinery	Ge	**30**	Others	Ot

Table 2 Parameters in five scenarios(Unit: billion kWh)

Scenarios	Sum	Coal	Oil	Natural gas	Nuclear	Hydropower	Wind power	Solar power	Biomass	Others
S1	4713.1	1416.4	779.0	502.2	734.2	342.7	197.0	197.0	105.0	41.4
S2	4527.5	1631.3	891.3	538.1	525.0	318.3	187.2	220.6	12.5	215.7
S3	4087.9	1167.3	811.6	516.1	603.2	318.3	212.5	240.9	34.5	218.2
S4	4274.3	1615.0	834.4	606.4	618.6	343.5	137.6	16.3	55.4	47.2
S5	4081.4	1396.0	840.0	577.9	619.5	341.9	194.5	30.1	51.3	30.1

Note: S1, baseline scenario; S2, low-carbon scenario from NDRC; S3, enhanced low-carbon scenario from NDRC; S4, low-carbon scenario from IPAC; S5, enhanced low-carbon scenario from IPAC.