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Research article

Identifying the critical transmission sectors with energy-water nexus pressures in China's supply chain networks

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ABSTRACT

Energy and water resources are drawing increasing attention in China as indispensable elements of economic development and social stability. Energy and water are interconnected in economic systems. Although the nexus between them has been widely studied, few insights can be acquired by the intermediate transmission pressures across supply chains. Combing betweenness-based method and multi-regional input-output (MRIO) analysis, we, in this study, identified critical transmission sectors and main driving factors resulting from the usage structure. In details, we found that *Metallurgy* (S14) in *Shandong, Henan, Jiangxi, Anhui, Sichuan, Zhejiang, Hunan,* and *Jiangsu*, *Electricity and hot water production and supply* (S22) in *Beijing* and *Guizhou*, and *Nonmetal production* (S13) in *Henan* are the most critical transmission sectors bearing energy-water nexus pressures, ranking at the top 100 in China's supply chain networks. Roughly, the usage structure was mainly dominated by fixed capital formation, urban household consumption and trade export, and therefore should be given priority to mitigate environmental pressures. Our study provides a novel perspective of sector-specific and province-typical policy recommendations for mitigating energy-water nexus pressures in China's supply chain networks.

1. Introduction

Socioeconomic development relies heavily on sustainable utilization of energy and water resources (Acquaye et al., 2017; Arthur et al., 2019; Mikulčić et al., 2019) which are intertwined with each other in economically productive activities (Duan and Chen, 2017; Stillwell, 2019; Zhou et al., 2019a). In an industrial process, the energy production cannot be separated from a certain amount of water supply, and water usage is also usually accompanied by a demand for energy (Feng et al., 2019b; Liao et al., 2019; Nawab et al., 2019; Shang et al., 2016). As the vital material basis for socioeconomic development, both of them have been over-consumed during the past decades. On a global scale, the population expansion and economic growth have increased the demand for energy and water resources for years , especially in some regions and countries that have long been plagued by energy- and/or water-scarcity (Hossain, 2019; Liu et al., 2016; O'Neill et al., 2017). Despising the interdependence between them within the economic system will result in resource waste and ineffective management. Accordingly, research into the energy-water nexus may serve as the prerequisite for policy integration and technology choice in synergic conservation (Abegaz et al., 2018).

This issue is crucial for China as it is facing severe energy and water shortages across provinces (Jiang, 2009). Interprovincial natural resource (energy and water) transfer causes several problems such as regional inequity resource overexploitation, which in turn challenges the uneven natural resource supply and demand (Feng et al., 2019a; Su et al., 2018; Zhou et al., 2019b). For example, the South of China is relatively more abundant in water resources than energy; while the North of China is relatively more abundant in energy reserves but water resource in these provinces is much scarcer than the southern provinces. (Cai et al., 2014). Specifically, 80% of China's fossil fuel reserves are located in the water-starved North and West (Byers et al., 2014).

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Treating these acute resource threats and mitigating energy/water pressures is a matter of urgency.

Previous studies have made significant efforts to develop tailored policies to mitigate environmental pressures. Most of them have attempted to identify the critical sectors that affect energy and water resource consumption from both the production and consumption sides (Feng et al., 2019b; Okadera et al., 2015; Wang et al., 2018b). For example, at the national level, Zhu et al. (2015) and Cai et al. (2014) evaluated water usage for energy production. At the province level, there have been many studies evaluating the complex interactions between water usage and energy generation among Liaoning (Okadera et al., 2015), Inner Mongolia (Xin et al., 2015) and Ningxia (Li, 2014) provinces. At the city level, Hu et al. (2013) investigated embodied sectors within the water-energy nexus in Beijing-Tianjin-Hebei. Despite the energy-water nexus has been widely studied by the above methods, it is worth noting that sectors in the broad economic system can indirectly influence the flows of resources in addition to direct production activities and final demand sectors.

To address these shortcomings, a betweenness-based method was proposed by Liang et al. (2016b) to mitigate environmental pressure., Afterward, Yang et al. (2018) further improved this method by combining a network framework to examine supply chain paths extracted from structural path analysis that pass through particular transmission sectors. Feng et al. (2019a) carried on a case study in Shanxi Province to measure the betweenness of sectors, noting that *Mining and Processing of Metal Ores* was a key transmission sector, which was usually ignored by other existing methods, as well as *Transportation, Storage and Posts*, *Hotel and Restaurants* in the upstream supply chains. In addition, Yang et al. (2019) employed the betweenness-based method and principal component analysis to target the energy-water carbon pressure transmission center sectors in Shanghai. The previous studies provide present a good basis for going deep to explore the energy-water nexus issue.

Obviously, water and energy scarcity coupled with uneven spatial distributions leads to the regional disparity in energy-water nexus pressures across the whole supply chain in China. Targeting the critical transmission sectors and jointly improving the utilization efficiency of energy and water resources have been recognized as significant strategies for ecological sustainability. Nevertheless, some research gaps still exist in the above-mentioned researches. Firstly, aiming to identify the critical transmission sectors of energy-water nexus with the new characteristics for different provinces and sectors in China. Secondly, the change in energy and water intensities are useful indicators that synthesize the relative evolutions of energy-water nexus pressure, while these changes have not been fully investigated. Furthermore, it is necessary and efficient to manage energy and water resources considering the dual factors of quantity and intensity. Identifying the linkages across key transmission sectors as well as jointly improving their efficiency have been considered to be a win-win strategy for environmental sustainability. Thirdly, understanding the usage structure between energy and water is necessary by the encouragement of productivity improvements in the transmission centers. However, few have presented in-depth analyses of the usage structure of energy-water nexus pressures.

Overall, this study aims at answering the following questions: which provinces and sectors are the critical transmission centers for mitigating water/energy pressures from the betweenness-based perspective in terms of quantities and intensities of energy and water resource usage? What are the important driving factors affecting energy and water usage? By using a betweenness-based analysis, policymakers may discover new ways to control and alleviate energy and water stress in the 30 Chinese provinces.

2. Methodology

The input-output analysis was originally proposed by Leontief (1936). Mixed-unit environment multi-regional input-output (EMRIO) is an extension of standard monetary input-output analysis in which monetary data on energy and water-related sectors are substituted for energy and water usage data in physical units. The basic expressions of the EMRIO model are as follows:

$$X = AX + Y = (I - A)^{-1}Y \tag{1}$$

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1s} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2s} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{is} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{s1} & a_{s2} & \cdots & a_{sj} & \cdots & a_{ss} \end{bmatrix} \tag{2}$$

where column vector X is the total output of an economic system; matrix$A$ represents the technical coefficients; column vector Y is the final consumption of specific amounts of products produced in each sector, including rural household consumption, urban household consumption, government consumption, fixed capital formation, inventory increase, and export; the matrix$(I - A)^{-1}$ is the Leontief inverse matrix, indicating the total amount of both direct and indirect inputs per unit of final demand.

Based on the EMRIO, a betweenness-based method is used to estimate the energy and water usage transmitted in the supply chain networks. The betweenness centrality metric is derived from networks that have been investigated in network theory (Freeman, 1979; Freeman et al., 1980; Newman, 2010). Causal-effect chains exist in networks, such as the transmission of information among people in social networks, or the propagation of intermediate flows in trade networks among provinces. As a result of local disturbances, paths linking different nodes (the communication paths connecting people, or supply chain paths linking different sectors) play fundamental roles. A key concept is betweenness centrality which captures the importance of components of a network (nodes or links) in relation to the paths passing through them (Freeman, 1977; Liang et al., 2015; White and Borgatti, 1994).

In this study, the provincial trade network within an input-output structure is represented by a network, with the nodes being province-sectors and the (directed) links being input flows among them. Specifically, the betweenness centrality of a node (or link) can capture the node's power to transmit energy/water flows from upstream sectors to downstream ones, providing a new perspective for identifying the critical transmission sectors that can potentially reduce energy/water demand through improvements in production efficiency (see Fig. 1).

Following this example, the betweenness centrality of sector i can be formulated as(Liang et al., 2016b):

$$b_i = \sum_{s=1}^{n}\sum_{t=1}^{n}\sum_{r=1}^{\infty} q_r \times w(s, k_1, k_2, \ldots k_r, t) \tag{3}$$

where $w(s, k_1, k_2, \ldots k_r, t)$ is the energy/water usage associated with all

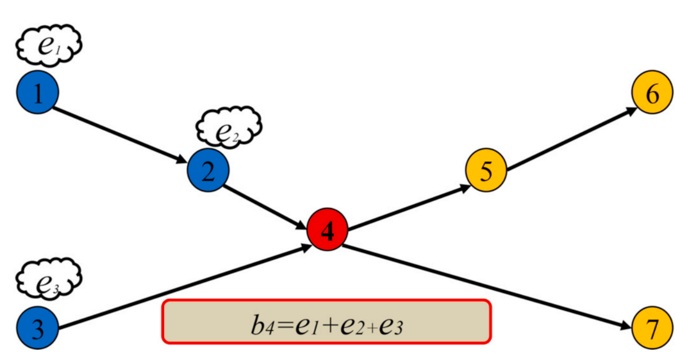


Fig. 1. Example of betweenness centrality for a sector 4.

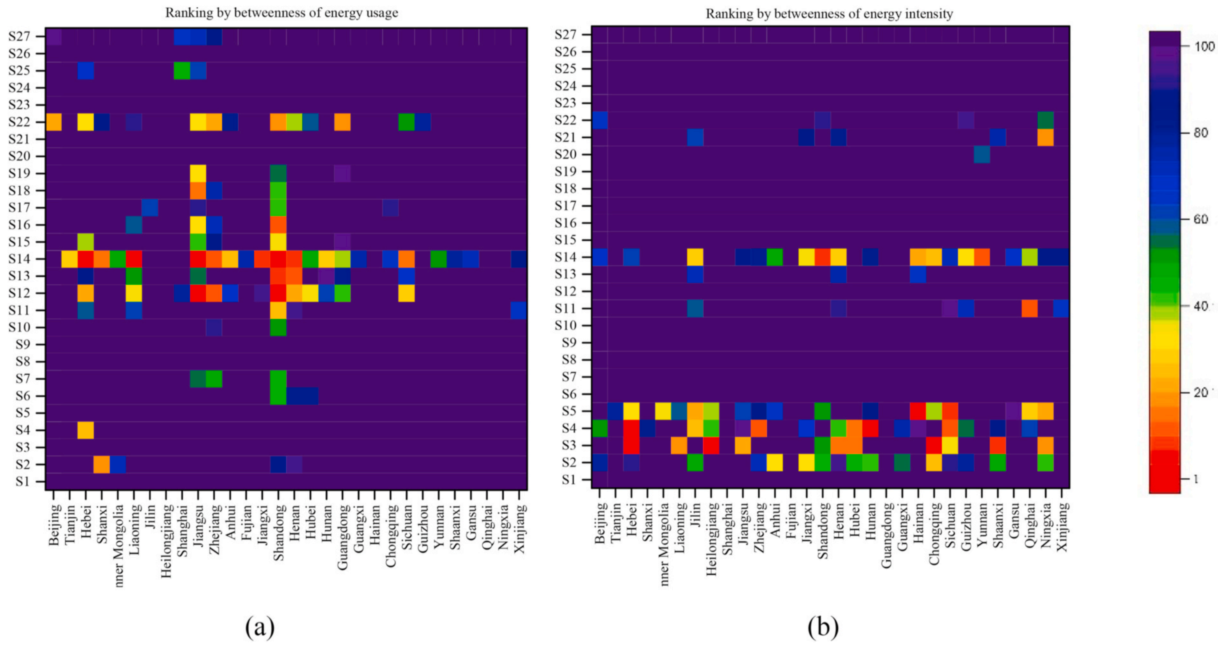


Fig. 2. Ranking by betweenness-based energy usage and energy intensity in 27 sectors/30 provinces of China (top 100).

supply chain paths from sector s to sector t passed through r sectors. these sectors via sector i. q_r represents the times of sector i appears in the supply chain paths. Based on the idea of structural path analysis, $w(s, k_1, k_2, \dots k_r, t)$ can be formulated as $f_s a_{sk1} a_{k1k2} \cdots a_{k_r t} y_t$,$f_s$ represents the intensity of energy/water at the beginning sector of the supply chain; Y_t is the final demand as seen in the EMRIO table from the sector t;$a_{pr1} p_{r1r2} \cdots a_{rkq}$ are technical coefficients showing the transmission process along the supply chain paths.

We further define the following supply chain path:

$$\begin{aligned} b_i(l_1,l_2) &= \sum_{1\le k_1,\dots k_{l_1}\le n} \sum_{1\le j_1,\dots k_{j_2}\le n} f_{k_1} a_{k_1k_2}\cdots a_{k_{l_1}v} a_{vj_1}\cdots a_{j_{l_2-1}j_{l_2}} y_{j_{l_2}} \\ &= \sum_{\le k_1,\dots k_{l_1}\le n} f_{k_1} a_{k_1k_2}\cdots a_{k_{l_1}v} \sum_{1\le j_1,\dots k_{j_2}\le n} a_{vj_1}\cdots a_{j_{l_2-1}j_{l_2}} y_{j_{l_2}} \\ &= f' A^{l_1} J_v A^{l_2} y \end{aligned} \tag{4}$$

where l_1 represents the upstream industrial supply chain, l_2 represents the downstream industrial supply chain. The basic betweenness centrality metric in IO is presented in Eq. (5), in which the individual supply chain paths can be extracted by unraveling the Leontief inverse matrix using a Taylor expansion (Lenzen, 2007; Liang et al., 2014, 2016a; Suh and Heijungs, 2007).

This is shown in Eq. (5).

$$L=(I-A)^{-1}=I+A+A^2+A^3+\dots \tag{5}$$

Defining$T = LA = AL = A + A^2 + A^3 + \dots$, add to Eqs. (3) and (4), the betweenness centrality of the sector i can be represented as:

$$\begin{aligned} b_i &= \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} b_i(l_1,l_2) = \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty}\left(fA^{l_1}\mathrm{J}_iA^{l_2}y\right) \\ &= \sum_{l_1=1}^{\infty}\left(fA^{l_1}\mathrm{J}_i\sum_{l_2=1}^{\infty}\left(A^{l_2}y\right)\right) = \left(\sum_{l_1=1}^{\infty}\left(fA^{l_1}\right)\right)\mathrm{J}_i\left(\sum_{l_2=1}^{\infty}\left(A^{l_2}y\right)\right) \\ &= f\left(\sum_{l_1=1}^{\infty}A^{l_1}\right)\mathrm{J}_i\left(\sum_{l_2=1}^{\infty}A^{l_2}\right)y = fT\mathrm{J}_iTy \end{aligned} \tag{6}$$

where t_{ij} in the matrix $T = LA$ represents the economic outputs of sector i caused directly and indirectly by the upstream input used to produce the unitary output of sector j; In view of $T = L - I$, matrix T reflects the indirect requirements for the unitary output of each sector; and $b_i$represents the betweenness centrality of sector$i$. Obviously, sectors that appear more frequently in supply chain paths have more chances to reduce upstream energy/water flows pressures than less frequent ones.[1]

3. Data and treatment

In this paper, the national MRIO table was applied to obtain economic data for the 30 provinces/27 sectors in China. The data for energy inventories in terms of different fuel types were derived from the China emission account and datasets (CEADs).[1] The total water usage data of 2012 was obtained from the China Statistical Yearbook (NBSC, 2013a). Overall, four types of data sources, comprising all of the most recent available data, were used in this study.

In the national MRIO table, there are 22 provinces, 5 autonomous areas, and 4 municipalities (Beijing, Shanghai, Tianjin, and Chongqing), with 42 economic sectors for each. In light of various sector classifications in energy/water inventories, we categorized the data pertaining to MRIO and energy/water inventories into 27 economic sectors, consisting of 1 primary industrial sector, 23 secondary industrial sectors, and 3 tertiary industrial sectors, according to data availability and data-matching principles(Peters et al., 2007). It should be noted that Taiwan, Hongkong, Tibet, and Macau are excluded from this study due to a lack of data availability.

The energy usage data by energy types of different sectors were obtained from China Energy Statistical Yearbooks (NBSC,2013b). These inventories are combined with 45 production sectors, two residential (urban and rural) sectors, and 18 kinds of energy usage for the 30 Chinese provinces.

For water usage data, the sector of *Agriculture* in the four years were obtained from China Statistical Yearbooks and China Urban-Rural Construction Statistical Yearbooks (NBSC,2013a; MOHURD,2013). The sectors of industrial in 2012 were collected from Annual Statistic Reports on Environment in China (MEP,2013). Due to the absence of detailed sector-level sources of construction and the tertiary industry, we applied the method put forward by Zhang and Anadon (2014) to allocate the total water usage data proportionately among corresponding sectors in the MRIO. To be specific, the data for the construction

[1] http://www.ceads.net/.

sector is calculated based on the gap between the water usage for industry sectors as a whole and that for the secondary industry (NBSC, 2013a; MOHURD,2013). The water usage of the tertiary industry can be calculated as 55% of the sum of domestic living water and ecological water compensation, minus the water use of transport, storage, and post. The data for these sectors are taken from the Chinese Environmentally Extended Input-Output (CEEIO) database (Liang et al., 2016a,b,c), which assumes the water intensity of this sector the same as the intensity in the Chinese input-output table (Liang et al., 2016a,b,c; Liang and Zhang., 2013). The water usage for transport, storage and post can be calculated by direct water intensity multiplied by the corresponding monetary outputs.

4. Results and discussion

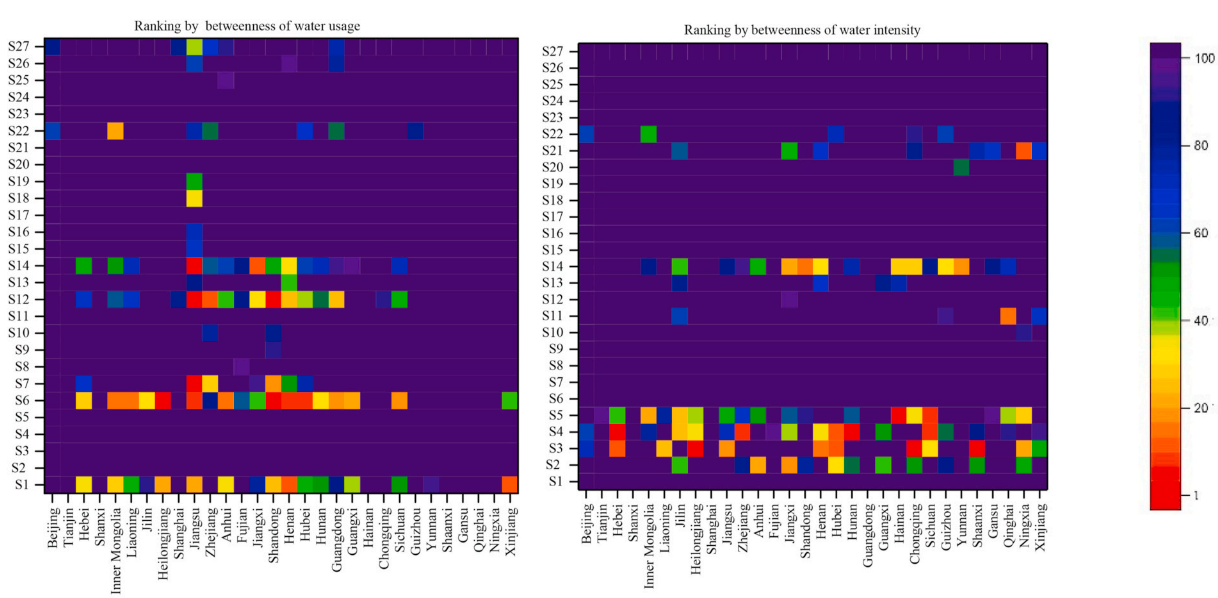
4.1. Betweenness-based energy and water usage

As shown in Fig. 2 there were distinct differences between energy usage and energy intensity. In terms of energy usage, *Chemical industry* (S12), *Metallurgy industry* (S14) and *Electricity and hot water production and supply* (S22) performed critical functions for energy transmission in the national supply chain network. Additionally, there were other industrial sectors, such as *Metal mining industry* (S4), *Nonmetal products industry* (S13), *General and specialist machinery industry* (S16), *Textile industry* (S7), *Petroleum refining, coking industry* (S11) and *Food processing and tobacco industry* (S6) in *Hebei, Liaoning, Jiangsu, Zhejiang, Shandong,* and *Henan* that can be recognized as critical transmission sectors. In terms of energy intensity, *Coal mining industry* (S2), *Petroleum and gas industry* (S3), S4, *Nonmetal mining industry* (S5) and (S14) had relatively poor performances. Furthermore, *Jilin, Shandong, Chongqing,* and *Ningxia* should be given priority for improving energy efficiency across the supply chain.

The substantial discrepancies between quantity and intensity of energy usage can be attributed to geographical location, resource endowment, and economic structure. Energy intensity reflects energy efficiency to some extent. As shown in Fig. 2, high energy usage but low energy intensity can be seen in some sectors, such as S22 in *Beijing, Hebei, Jiangsu, Zhejiang* and so on, but failed to energy intensity in these provinces except to *Ningxia*. S22 was widely used in all provinces of China. The sectors with high energy usage but low energy intensity represented the development of the economy in terms of infrastructure. Additionally, this sector had high use efficiency in all fields based on technological innovation and implementation of energy conservation and emission reduction measures. Therefore, it was difficult to reduce energy pressures by improving this sector's efficiency or changes in policy. Similarly, there were sectors where energy intensity was low even though they were important transmission sectors. For example, S12, *Metal products industry* (S15), *General and specialist machinery industry* (S16), *Transport equipment industry* (S17), S18, S19 and *Transport and storage* (S25). These sectors were not considered when improving energy efficiency. It was worth noting that S22 in *Ningxia* was a key transmission sector for reducing energy pressures in China since in *Ningxia* this sector had low energy use but high energy intensity. It was useful to evaluate the energy pressure caused by this sector's economic activities. It means that the critical transmission sector had more opportunities for energy conservation and emissions reduction. We can improve this sector's efficiency to reduce energy usage and carbon emissions both upstream and downstream in the supply chain. Thus, sectors with relatively high energy intensity that only transmit small amounts of energy usage contribute more to environmental stress. These included S2, S3, S4 and S5. These sectors had significant potential for mitigating energy pressures.

Similarly, betweenness-based quantities and intensities of water usage were presented in Fig. 3. The six key transmission sectors with high water usage were *Agriculture* (S1), S6, S7, S12, S14 and S22. The provinces with major water usage were *Hebei, Inner Mongolia, Jiangsu, Zhejiang, Shandong, Hubei*, and *Guangdong*. The five critical transmission sectors with high water usage and intensity were S2, S3, S4, S5 and S14. Based on this perspective, the typical provinces with a high demand for water usage were *Jilin, Jiangsu, Henan, Chongqing, Sichuan*, and *Ningxia.*

As shown in Fig. 3, there was a large gap between water usage and intensity between transmission sectors according to betweenness-based accounting. The water usage of S2 and S12 were ranked as high order in most provinces, whereas these sectors' intensities were ranked below the top 100. This phenomenon reflected these sectors' high potential for improvement of water efficiency. Contrarily, for S2, S3, S4 and S5, the rankings according to water usage intensity were among the highest of all provinces, whereas the water usage of these sectors was low. This result indicates that these sectors, as crucial transfer sectors with high water usage but low intensity, deserve special attention when



(a) (b)

Fig. 3. Ranking by betweenness of water usage and water intensity in 27 sectors/30 provinces of China (top 100).

developing strategies and policies for resource conservation and environmental pressure mitigation. In a traditional study, it was easy for policymakers to overlook the role that sectors with high water usage but low intensity played in the transmission of environmental stress because they pay more attention to the sectors' quantity with high water usage and failed to consider the intensity. Therefore, it was recommended that policymakers consider the water usage of all sectors. Likewise, the importance of sectors with high water intensity also needed close attention.

It is widely acknowledged that energy and water usage varies greatly across different industries and regions in China as a result of the uneven distribution of natural endowment, industrial superiority and applicable technologies. Hence, it is pressing for China to formulate differentiated policies to manage the nexus between energy and water resources properly with regard to production activities and consumption patterns.

4.2. Identification the critical sectors with energy-water nexus pressures

Fig. 4 illustrated betweenness-based energy-water nexus pressure from the perspectives of both quantity and intensity. The horizontal and vertical axes represented the ranking of energy quantity (intensity) and the ranking of water quantity (intensity), respectively. The top 100 sectors for each were represented by the red dashed line and green dashed line, respectively. The red solid line showed the same rankings for energy quantity (intensity) and water quantity (intensity). Thus, sectors near the red solid line were transmission sectors for energy-water nexus pressures. From a macro perspective, the ranking of sectoral energy-water nexus by quantity and intensity includes 52 and 91 sectors, respectively. According to Fig. 4, the energy-water intensity had more nexus than quantity. The closer to the red solid line, ranked by the top 100, the more nexus between the two corresponding energy/water pressures.

Table 1 depicted the quantity and intensity of energy-water nexus and the corresponding rankings of each sector and each province from a microcosmic perspective. Seven sectors: S12 in *Shandong, Jiangsu, Zhejiang, Henan, Sichuan, Hubei*, and *Guangdong*, S14 in *Hebei, Jiangsu, Shandong*, and *Henan*, S13 in *Henan*, S18 in *Jiangsu* and *Jiangxi*, S22 in *Guangdong*, S7 in *Shandong* and *Zhejiang*, S6 in *Shandong* were ranked in the top 100 by quantity, using the betweenness-based method for energy-water nexus. Similarly, there were five sectors: S4 in *Hunan, Hebei, Sichuan, Zhejiang*, and *Hebei*, S3 in *Chongqing, Hebei, Heilongjiang, Shaanxi, Qinghai, Hubei, Henan, Liaoning* and *Ningxia*, S5 in *Hainan* and *Sichuan*, S14 in *Shandong* and *Yunnan*, *Other manufacturing* (S21) in *Ningxia* ranked in the top 100 intensity, using this method for energy-water nexus. Based on the sectoral perspective, there were some

Table 1
Sectors ranked by quantity and intensity of energy and water by the betweenness-based method.

Critical sector of energy-water nexus	Ranking by Quantity		Critical sector of energy-water nexus	Ranking by Intensity	
	Energy	Water		Energy	Water
Chemical industry (S12) in Shandong	1	4	*Metal mining* (S4) in Hunan	1	1
Metallurgy (S14) in Hebei	2	48	*Petroleum and gas* (S3) in Chongqing	2	2
Metallurgy (S14) in Jiangsu	3	5	*Metal mining* in (S4) Hebei	3	3
Metallurgy (S14) in Shandong	4	49	*Petroleum and gas* (S3) in Hebei	4	11
Chemical industry (S12) in Jiangsu	5	1	*Nonmetal mining* (S5) in Hainan	5	6
Metallurgy (S14) in Henan	7	32	*Petroleum and gas* (S3) in Heilongjiang	6	4
Metallurgy (S14) in Jiangxi	9	11	*Metallurgy* (S14) in Shandong	7	16
Chemical industry (S12) in Zhejiang	11	12	*Petroleum and gas* (S3) in Shaanxi	8	5
Nonmetal products (S13) in Henan	13	43	*Nonmetal mining* (S3) in Sichuan	9	8
Electrical equipment (S18) in Jiangsu	15	35	*Metal mining* (S4) in Sichuan	10	9
Electricity and hot water production and supply (S22) in Guangdong	17	54	*Metal mining* (S4) in Zhejiang	11	7
Chemical industry (S12) in Henan	20	26	*Petroleum refining, coking, etc.* (S11) in Qinghai	12	14
Chemical industry (S12) in Sichuan	28	44	*Metallurgy* (S14) in Yunnan	13	17
Electronic equipment (S19) in Jiangxi	31	47	*Petroleum and gas* (S3) in Hubei	14	10
Chemical industry (S12) in Hubei	35	37	*Petroleum and gas* (S3) in Henan	15	15
Chemical industry (S12) in Guangdong	40	24	*Metal mining* (S4) in Hubei	16	12
Textile in (S7) Shandong	44	17	*Petroleum and gas* (S3) in Liaoning	17	25
Food processing and tobaccos in Shandong	46	2	*Petroleum and gas* (S3) in Ningxia	18	21
Textile (S6) in Zhejiang	49	29	*Other manufacturing* (S21) in Ningxia	19	13

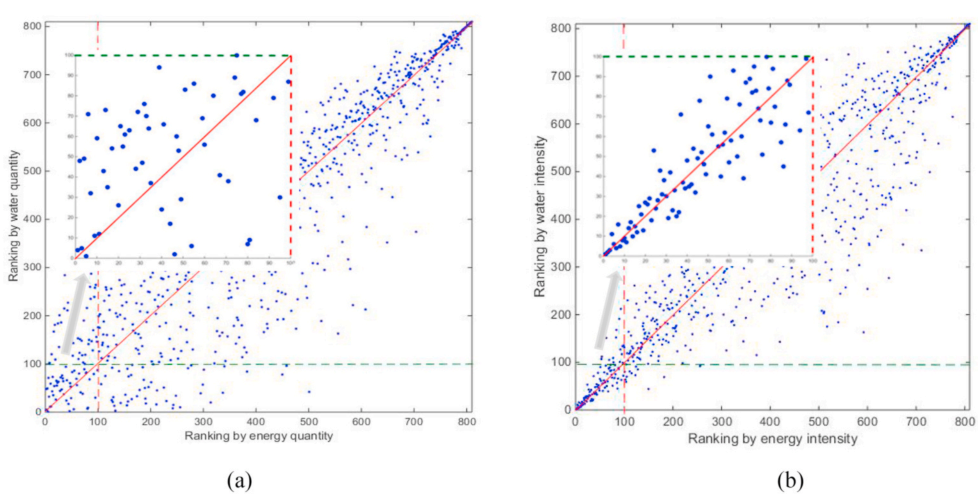


Fig. 4. The ranking of sectoral energy-water nexus by quantity and intensity.

differences between quantity and intensity. For quantity, the main sectors focused on the S12*,* S14*,* S13*,* and S18. For the intensity of energy-water nexus, the main sectors were associated with S4*,* S3*, and* S5. The reason for it was the differences in efficiency among sectors. Although the pressure of quantity on the environment in some sectors was relatively large, that of intensity was very small. Usually, these sectors were more mature and received higher attention from the government and researchers, such as the sectors that appear on the left, but not on the right in Table 1. There were some sectors where the pressure on the environment of quantity was very small, while that of intensity was large. These sectors were often neglected as transmission sectors, but, improving their efficiency can significantly relieve environmental stress. Such sectors appear not on the left, but on the right in Table 1. From the provincial perspective, the main provinces listed in the top 100 for quantity were developed provinces and the main provinces listed in the top 100 for intensity were undeveloped provinces, where the economy was struggling even with the presence of abundant coal and mineral natural resources. The reason for this significant difference was China's geographical location, population distribution and economic situation. From the perspective of quantity, economically developed regions and densely populated provinces generate higher environmental pressure, but from the perspective of intensity, these provinces produce very low environmental pressure. As a result, it was difficult to mitigate energy/water pressure in these provinces by improving transfer efficiency.

Above all, sectors that also appeared in a province in Table 2 have the highest potential for the mitigation of energy/water stress. Critical transmission sectors can transmit the highest energy-water pressures. These sectors not only ranked in the top 100 for quantity but also intensity. If energy (water) can be saved, a certain volume of water (energy) could also potentially be saved, It was worth noting S14, as one of the important pillar industries in China, acted as the critical resource transmission center due to its diversity of operations and close links in many areas with other industries. Actually, China's *Metallurgy* industry became the largest one in the world in 2011 and contributed half of the growth of the world metallurgy market over the past two decades. By increasing the utilization efficiency of energy and water from upstream sectors, it can effectively reduce energy-water nexus pressure while guaranteeing adequate supply to downstream sectors.

Overall, according to the estimated results, we found that the energy-water nexus pressures in Shandong, Hebei and Jiangsu were relatively great in China. It is widely acknowledged that these three provinces are comparatively well-developed economies with relatively complete supply chains within its territory. Moreover, exports played an important role in intensifying the energy-water nexus pressures in these two provinces that contributed more than one-third of China's total exports for a long time.

Table 2
Top 100 sectors ranked by quantity and intensity of energy and water by the betweenness-based method.

Critical sector of energy-water nexus	Ranking by Quantity		Ranking by Intensity	
	Energy	Water	Energy	Water
Metallurgy (S14) in Shandong	4	49	7	16
Metallurgy(S14) in Henan	7	32	28	31
Metallurgy(S14) in Jiangxi	9	11	35	20
Metallurgy (S14) in Anhui	25	63	48	46
Electricity and hot water production and supply (S22) in Beijing	23	61	66	60
Metallurgy (S14) in Sichuan	14	73	70	89
Nonmetal products(S13) in Henan	13	43	75	68
Metallurgy (S14) in Zhejiang	10	59	81	94
Metallurgy (S14) in Hunan	29	72	82	75
Metallurgy (S14) in Jiangsu	3	5	89	86
Electricity and hot water production and supply (S22) in Guizhou	77	81	94	63

4.3. Analysis of the driving factors for energy-water nexus pressures

In this section, we analyzed the energy-water usage construct from the provincial perspective. Additionally, we considered the control of energy/water pressure flows of this main item of final demand (fixed capital formation, urban household consumption and exports) by the encouragement of productivity improvements in the transmission centers. This was caused by the recent growth of fossil fuel-based economic and infrastructure construction in China. Furthermore, since China's accession into the WTO, increased in the trade have led to increased Chinese exports. Accompanying the fast development of the Chinese economy, the demands of urbanization were rising. Therefore, these energy-water nexus results for betweenness provided a reference for comprehensive environmental policymaking in China.

The volume of energy usage and water usage for the 30 Chinese provinces were obtained by summing the energy and water usage of each industrial sector. The energy and water usage associated with each final demand item were shown in Fig. 5, indicating that induced usage from fixed capital formation was relatively large. The exports of *Beijing, Tianjin, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong*, and *Guangdong* assumed an important role in energy and water usage. The proportion of urban residents in the remaining provinces was relatively high. It should be pointed out that *Sichuan, Hubei, Henan, Shandong, Jiangsu Hebei, Inner Mongolia*, and *Heilongjiang* provinces accounted for a relatively large proportion of rural residents. For example, *Shandong*, as the province with the highest energy usage, transmits 6.21×10^8 tce. Fixed capital formation transfers accounted for 50.54% of the total amount of final demand, while exports accounted for 20.8%. Energy usage created by other items of final demand accounted for only a small proportion. These included rural house usage (5.28%), urban household usage (14.5%), government usage (5.8%) and inventory increase (3.11%). Similarly, Jiangsu, as the province with the highest water usage based on the betweenness-based method, transmits 86.35 billion metric tons (Bt). Activities associated with final demand, such as fixed capital formation, export, and urban household usage were also very large. In terms of water usage, transmission accounted for 41.97% (36.24Bt), 29.54% (25.51Bt) and 15.7% (13.56Bt), respectively, much higher than that of all other activities contributing to final demand (12.8%).

5. Conclusions and policy implications

5.1. Conclusions

Water and energy, as essential material inputs for sustainable development, have aroused widespread concerns around the world due to their inter-connectedness. To date, identifying the key transmission sectors for supply chain energy and water resources pressure mitigation beyond the production and consumption perspectives bad been under-examined. Thus, trivializing of the transmission effect throughout the whole supply chain can inevitably hurts for efficiency improvement in resource-intensive sectors. Here, the methodology of combining betweenness-based method with MRIO analysis to recognize the critical transmission sectors for mitigating energy and water resources pressures in China's 30 provinces. We integrate energy and water resource stresses at the multiple province scale while simultaneously considering the different roles of quantity and intensity. We perform a usage structure analysis to identify the main inducing sectors and provinces, resulting in huge potential mitigation of energy/water pressures. Exploring the critical transmission sectors of energy-water nexus and the usage structure of final demand can provide more extensive information for evaluating the proposed policies for their potential future reductions in energy/water pressures.

Our findings show that *Metallurgy industry* (S14) in *Shandong* is the critical energy-water nexus transmission center. Meanwhile, *Metal mining* (S4) in *Hunan, Hebei, Sichuan, Zhejiang*, and *Hebei*, *Petroleum and gas* (S3) in *Chongqing, Hebei, Heilongjiang, Shaanxi, Qinghai, Hubei,*

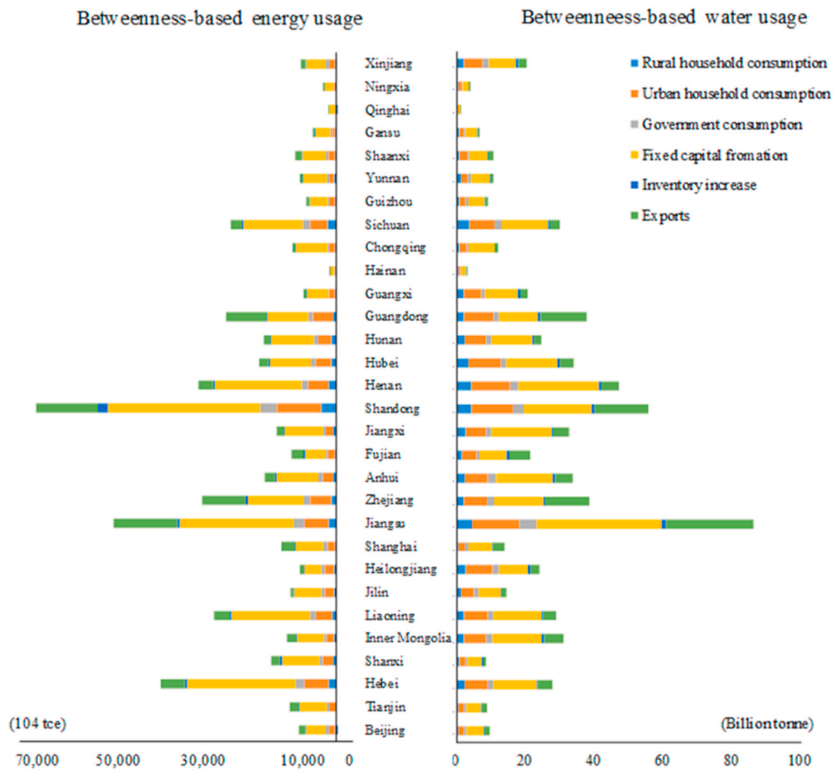


Fig. 5. Rank correlation of betweenness centrality indices between water and energy usage associated with the final demand in each province.

Henan, Liaoning, and *Ningxia* are responsible for the highest proportion of energy-water stress from the perspective of energy-water nexus intensity. Those findings show that it is necessary to take energy and water into consideration for resource conservation environmental pressure mitigation in these sectors. Although from the perspective of energy-water nexus, the quantity is high, the intensities of these sectors are low. For example, the *Chemical industry* (S12) in *Shandong, Jiangsu, Zhejiang, Henan, Sichuan, Hubei*, and *Guangdong*, S14 in *Hebei, Jiangsu, Shandong*, and *Henan*, *Nonmetal products industry* (S13) in *Henan*, *Electrical equipment industry* (S18) in *Jiangsu* and *Jiangxi*, *Electricity and hot water production and supply* (S22) in *Guangdong*, *Textile* (S7) in *Shandong* and *Zhejiang*, and *Food processing and tobacco industry* (S6) in *Shandong*. Thus, these sectors have limited potential for energy/water pressure mitigation. When we consider the usage structure of energy and water, the results show that the fixed capital formation, urban household consumption, and exports play an important role in driving energy/water pressures on the side of final demand.

5.2. Policy implications

According to the estimated results, some policy suggestions can be proposed. First, future energy and water resource management frameworks should focus on the sustainable development from a betweenness-based perspective. Second, as the critical indicators of energy-water nexus, policymakers should consider the quantity and intensity at the same time. From a macro perspective, the intensity of energy-water has more nexus than quantity. They should consider the actual role of these sectors in transmitting energy/water pressures and pay more attention to the intensity of the energy-water nexus. Third, policymakers should focus on the main inducing item-usage structure. They should take the different socioeconomic characteristics of different province and sector into account, especially the sectors drive large usage of fixed capital formation, urban household consumption, and export which have a huge potential for mitigating environmental pressures. It is urgent to make clear the usage structure of energy and water pressure in view of regional differences and inequalities in resource endowments.

Above all, this study can provide an effective reference for reliving the energy-water nexus in China's different provinces. Regarding those sectors with great betweenness-based energy-water nexus pressures, efforts should target at greening supply chain and controlling the irrational final demand. Besides, tax abatement and subsidy for the critical transmission sectors can be considered to encourage the import of intermediate products instead of local production.

Some limitations are worth mentioning from this study. our study includes uncertainties caused by the intermediate relationship between sectors, time-lag, and the fact that increased efficiency may result in more production and consumption with greater environmental pressures. These limitations give directions to future research. We suggest the future work in this vein consider identifying the supply chain paths of causing the high betweenness sectors. Thus, we can extract the key supply chain paths for targeted analysis by clearly knowing the industrial of upstream and downstream with key transmission sectors.

Credit author statement

Yiming Li, Conceptualization, Methodology, Validation, Writing-reviewing and editing. Lin Yang, Supervision, Validation, Writing-reviewing and editing. Dong Wang, Data curation, Software, Visualization, Writing- original draft preparation. Yu Zhou, Data curation, Software, Visualization, Writing- original draft preparation. Weijun He, Data curation, Software, Visualization, Writing – original draft. Bo Li, Data curation, Software, Visualization, Writing- original draft preparation. Yuantao Yang, Data curation, Software, Visualization, Writing-original draft preparation. Haodong Lv: Data curation, Software, Visualization, Writing- original draft preparation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Sector classification

No.	Sectors
S1	Agriculture industry
S2	Coal mining industry
S3	Petroleum and gas industry
S4	Metal mining industry
S5	Nonmetal mining industry
S6	Food processing and tobaccos industry
S7	Textile industry
S8	Clothing, leather, fur, etc.
S9	Wood processing and furnishing industry
S10	Paper making, printing, stationery, etc.
S11	Petroleum refining, coking, etc.
S12	Chemical industry
S13	Nonmetal products industry
S14	Metallurgy industry
S15	Metal products industry
S16	General and specialist machinery industry
S17	Transport equipment industry
S18	Electrical equipment industry
S19	Electronic equipment industry
S20	Instrument and meter industry
S21	Other manufacturing industry
S22	Electricity and hot water production and supply industry
S23	Gas and water production and supply industry
S24	Construction
S25	Transport and storage
S26	Wholesale, Retail Trade and Catering Services
S27	Other servers

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