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Water-energy nexus and its efficiency in China's construction industry: Evidence from province-level data

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Abstract

The rapidly growing construction industry has accelerated water and energy scarcity in China, threatening its sustainable development. This study integrates multi-regional input-output (MRIO) and data envelopment analysis (DEA) to investigate the water-energy nexus in the construction industry at the provincial level through the entire industrial supply chain. Results show that the construction industry accounts for 8.97% and 27.20% of virtual water and embodied energy in China, respectively. The western area experiences the most energy- and water-intensive construction processes given its backward economy and outdated technological development. The northern area faces great challenges with regard to energy intensity improvements, whereas the central regions suffer from large pressure relating to inefficient water use. The manufacture of non-metallic mineral products, smelting, and the pressing of metals are the largest suppliers of virtual water and embodied energy. The efficiency assessment results demonstrate that Jiangsu and Zhejiang are two DEA-effective regions. China has achieved a relatively high level of scale efficiency but suffers from backward technology.

1. Introduction

Water and energy, as essential resources for sustainable development, have attracted global concerns due to their intertwined connections and significant influence on human economy (Wu & Chen, 2017). Water is a basic resource for power generation, fossil fuel exploitation, and the production of other types of energy (Liu et al., 2015; Tan & Zhi, 2016; Wang, Cao, & Chen, 2017; Yang & Chen, 2016). Energy resources are also essential in the entire process of fresh water withdrawal, transportation, and wastewater treatment (Kim & Chen, 2018; Li, Li,

& Qiu, 2016; Plappally & Lienhard, 2012). The contradictions between water supply and energy demand impose a barrier on achieving sustainable construction in China (Nazemi & Madani, 2018). Importantly, water and energy resources are indispensable for sustaining urbanization and industrialization, especially with regard to the production of concrete and steel, which are primary materials for the construction processes (Kahrl & Roland-Holst, 2008). An in-depth investigation of the water-energy nexus could provide co-benefits for water conservation and energy security nationwide (Hussey & Pittock, 2012; Marsh, 2008).

The construction industry accounts for almost 40% of energy consumption and 25% of greenhouse gas emissions globally (Davies, Emmitt, & Firth, 2015; Parry, Canziani, Palutikof, Linden, & Hanson, 2007). The United Nations Environment Programme reported that the building sector was responsible for approximately 30% of global fresh water consumption (Meng et al., 2014). China experiences scarcity of water and energy resources due to its booming economy and growing population (Liang & Zhang, 2011). China's annual construction accounts for almost half of the newly-built floor area in the world; this leads to large amounts of resource consumption and roughly 41% of world's total CO_2 emission from construction (Huang, Krigsvoll, Johansen, Liu, & Zhang, 2018). Moreover, the entire supply chain of China's construction industry experiences significant water and energy wastage due to low production efficiency and outdated technological implementation (Xue, Wu, Zhang, Dai, & Su, 2015). Recent research has shown that the embodied energy consumption per unit of monetary output of China's construction sector had long been the highest in the world (Liu, Wang, Xu, Liu, & Luther, 2018). Therefore, assessing the water-energy nexus, especially the efficiency of water-energy consumption, is an urgent and imperative issue for achieving resource conservation in China's construction industry.

At present, the water-energy nexus has been extensively studied at multiple scales. At the national level, relevant investigations have covered a broad range of countries, including the United States (Ackerman & Fisher, 2013; Webber, 2011), India (Malik, 2002; Shah, Giordano, & Mukherji, 2012), Brazil (Vieira & Ghisi, 2016), Australia (Talebpour, Sahin, Siems, & Stewart, 2014), Saudi Arabia (Rambo, Warsinger, Shanbhogue, John, & Ghoniem, 2017), Turkey (Eren, 2018), Spain (Hardy, Garrido, & Juana, 2012), and Chile (Vergara, Bravo, Undurraga, & Ortega, 2017). In recent years, special attention has also been paid on the water-energy nexus in China (Gu, Fei, & Yu, 2014; Kahrl & Roland-Holst, 2008). In addition, topics including tradeoffs between different levels of decision makers (Zhang & Vesselinov, 2016), the spillover effects of policies (Zhou, Li, Wang, & Bi, 2016), and element and pathway nexus based on network analysis (Duan & Chen, 2017) have also enjoyed a certain level of coverage. At the regional level, Wang and Chen (2016) investigated the water-energy nexus in the Beijing-Tianjin-Hebei agglomeration by building a network model on the basis of multi-regional input-output (MRIO) and ecological network analyses, whilst Bartos and Chester (2014) assessed the potential co-benefits of water and energy savings under eight scenarios in Arizona by developing a spatially explicit model of the water-energy nexus. Results showed that water conservation strategies can influence energy consumption to a remarkable level and vice versa. At the city level, Chen and his colleagues conducted a series of studies to investigate the energy-water nexus in Beijing considering its important administrative and economic status (Chen & Chen, 2016; Fang & Chen, 2017). The water-energy nexus in other metropolises, such as Tianjin (Jiang et al., 2016), New York (Engström et al., 2017), and México City (Moredia-Valek, Sušnik, & Grafakos, 2017), were also investigated. Meanwhile, instead of analyzing the interwoven connections of water and energy consumption, a number of investigations have been conducted to assess energy-related water consumption (Jackson, 2009; Li et al., 2016;

Thirlwell, Madramootoo, & Heathcote, 2019; Vilanova, 2015) or water-demanded energy use (Li, Feng, Yimling, & Hubacek, 2012; Qin, Curmi, Kopec, Allwood, & Richards, 2015; Shang et al., 2016; Tang, Jin, Feng, & Mclellan, 2018).

A vast body of work quantified water and energy consumption embodied in construction activities in a separate manner. Increasing attempts have been made to investigate water utility in the buildings and construction industries in recent years. For example, Meng et al. (2014) developed a systematic virtual water accounting framework for buildings by applying both process-based and input-output methods. The results demonstrated the critical role of the off-site water. Moreover, and based on comprehensive first-hand project data, Han et al. (2015) measured the virtual water consumption of a building in Beijing with nine sub-projects, indicating that building materials account for more than ¾ of total water consumption. Indeed, the water footprint of critical construction materials such as steel, cement, and glass has been further studied by recent researches (Gerbens-Leenes, Hoekstra, & Bosman, 2018; Hosseinian & Nezamoleslami, 2018). Lately Rahman, Rahman, Haque, and Rahman (2019) have recommended possible options to improve water management system in the construction industry. They found that recycled water has been increasingly used in the construction industry and that both water and energy are important when considering green buildings. Compared to water related studies, the immediate preceding past decades have witnessed more extensive research on energy related issues in the construction industry. At the national level, energy use and the carbon emissions of the construction industry have been systematically investigated in many countries such as China (Zhang, You, Jia, Chen, & Yu, 2018), Australia (Yu, Wiedmann, Crawford, & Tait, 2017), United States (Lu, Zhu, & Cui, 2012), United Kingdom (Alwan, Jones, & Holgate, 2017), Turkey (Arıoğlu Akan, Dhavale, & Sarkis, 2017), and Ireland (Acquaye & Duffy, 2010), As the fastest developing market, China's construction industry has received the most attention. For example, Chang and his colleagues conducted a series of studies on embodied energy quantification to explore the embodied energy consumption of the construction sector in China with a single-region input-output (SRIO) model (Chang, Ries, & Wang, 2010; Chang, Ries, & Wang, 2011; Chang, Ries, Man, & Wang, 2014). In like manner, Hong and his colleagues investigated the embodied energy use of China's construction industry in a multi-regional perspective (Hong, Shen, Guo, Xue, & Zheng, 2016; Hong, Shen, & Xue, 2016). Meanwhile, at the global level, Liu et al. (2018) assessed the embodied energy use in the construction sector globally and the results showed that energy consumption induced by intermediate demand was responsible for 90% of total energy usage. Carbon emissions caused by construction activities globally have also been explored with critical options for emission mitigation being identified (Huang et al., 2018). However, a separate quantification of natural resources without consideration of their intertwined relationship may lead to unexpected risks as water management strategies and energy conservation policies inevitably influence each other (Schwab, 2011). Moreover, there have only been a limited number of studies focused on the nexus of virtual water and embodied energy at the industrial level – and specifically the construction industry. This oversight is particularly pertinent to China given that construction is the leading contributor responsible for intensive water and energy consumption therein.

In addition, efficiency assessment is another burgeoning issue in determining the sustainability of the construction sector. Several scholars have applied data envelopment analysis (DEA) to analyze the trajectory of the energy efficiency of the construction sector in China (Chen, Liu, Shen, & Wang, 2016; Xue, Shen, Wang, & Lu, 2008, 2015). However, current literature on efficiency assessment has predominantly focused on the direct energy input while ignoring the indirect effect induced by the upstream supply chain. As a result there has been a failure to detect the actual efficiency embedded in the trading process. In fact, indirect interaction is a dominant factor that influences the environmental impact and resource consumption of China's economy (Liu et al., 2012).

To address these gaps in current knowledge, this study investigates the water-energy nexus of China's construction industry with provincelevel data. It does so by detecting indirect interactions through the entire supply chain. Flow accounting and efficiency assessment of the water-energy nexus are conducted on the basis of MRIO and DEA methods. The findings are expected to provide a holistic understanding of the current status of the water-energy nexus in China's construction industry. This, it is hoped, can facilitate the synergy of reduction policies from water and energy perspectives. The remainder of this paper is organized as follows. Section 2 describes the methodology and data. Section 3 provides the main results of this study whilst Section 4 discusses the important findings. Finally, Section 5 proposes a series of conclusions and recommendations.

2. Methodology

2.1. Water-energy flow accounting

An ecological MRIO table was established to calculate the virtual water and embodied energy consumed by the construction sector throughout the entire supply chain. The input-output model, originally developed by Leontief, integrates ecological endowments into the economic network to reveal connections between resource and economy flows in and out of the targeted economy (Chen, Chen, & Chen, 2013). The MRIO table reveals the technical economic ties of industries in different regions from a wider scope than the SRIO (Hong, Shen, Guo et al., 2016). Table 1 shows the format of the MIRO table.

The monetary equilibrium in the MRIO table in Table 1 can be shown as:

Table 1

Multi-regional water-energy input-output table.

		Intermediate use							Final use			Output
		$R1$			…	Rm			$R1$	…	Rm	
		$S1$	…	Sn	…	$S1$	…	Sn				
$R1$	$S1$	u_{ij}^{rk}							y_i^{rk}			x_i^r
	…											
	Sn											
…	…											
$R1$	$S1$ …											
	Sn											
Added value												
Energy												
Water												
Total input												

$$\sum_{k=1}^{m}\sum_{j=1}^{r} x_{ij}^{rk} + \sum_{k=1}^{m} y_i^{rk} = x_i^r \quad (1)$$

x_i^r represents the output of the i-th sector in region r. y_i^{rk} is the final use of the i-th sector in region r for region k. The intermediate input from the i-th sector in region r to the j-th sector in region k is expressed as x_{ij}^{rk}.

Combined with the resource coefficient, the monetary equation (Eq. (1) can be expressed as:

$$\sum_{k=1}^{m}\sum_{j=1}^{n} e_j^k u_{ji}^{kr} + q_i^r = e_i^r x_i^r \qquad (2)$$

The resource consumption coefficients of the j-th sector in region *k* and the i-th sector in region *r* are denoted by e_j^k and e_i^r, respectively. q_i^r is the direct resource consumption of the i-th sector in region *r*. Therefore, the vectors and matrixes can be used to simplify the mathematical expression of the *m* × *n* equations which are established from the perspective of the entire national economy.

$$E^T = \left[\left(e_1^1 \ldots e_n^1 \right) \ldots \left(e_1^m \ldots e_n^m \right) \right], \quad Q^T = \left[\left(q_1^1 \ldots q_n^1 \right) \ldots \left(q_1^m \ldots q_n^m \right) \right], \quad X = \begin{bmatrix} x_1^1 & 0 & \ldots & 0 \\ 0 & x_2^1 & \ldots & 0 \\ \ldots & & & \ldots \\ 0 & 0 & \ldots & x_n^m \end{bmatrix}, \quad U = \left[\ldots u_{11}^{11} \ldots u_{nm}^{nm} \right]$$

|| $u1111$ ... $u111n$ || $u111m$ ... ... ||

|| $u...n111$ ....

$u...nn11$ | ... $unn1m$ ||

| $u...n11m$ ...

|

|

= | ... ... mm

| ... u_{1n} ||

|| $u11m1$ ... $u1mn1$ ... ... |

$u11...mm$ ...

$unnmm$ | ||

|| $u...nm11$ ......

$u...nnm1$ | ...

| $unmm1$

|

⌊

E and *Q* are the embodied resource intensity and direct resource consumption, respectively. The transposes of matrixes *E* and *Q* are denoted by E^T and Q^T, respectively. *X* represents the diagonal form of the total output matrix. *U* indicates the matrix of intermediate input. The relationship of *E*, *X*, *U*, and *Q* can be expressed as follows:

$$EX = EU + Q \quad (3)$$

$$E = Q\,X(-U)^{-1} \quad (4)$$

Consequently, a number of indicators can be derived at the industrial level.

(1) Total resource consumption

The construction industry's virtual water and embodied energy consumption over the entire supply chain (both direct and indirect), can be obtained by multiplying the virtual water and embodied energy intensity with the total output of the construction industry. The resource intensity vector of the regional construction industry $E_c = [e_c^1, e_c^2, \ldots, e_c^m]$ can be extracted from the coefficient vector E.

(2) Resources embodied in interregional trade

To determine the influence of interregional trade on resource flows, the interaction patterns of the virtual water and embodied energy of the construction industry among regions was further analyzed. The embodied resource imported to the construction industry in region r from other regions can be expressed as:

$$IM_c^r = \sum_{k \neq r}^{m} \sum_{i=1}^{n} e_i^k u_{ic}^{kr} \quad (5)$$

The embodied resource exported from region r to the construction industry of other regions is given as:

$$EX_c^r = \sum_{k \neq r}^{m} \sum_{i=1}^{n} e_i^r u_{ic}^{rk} + \sum_{k \neq r}^{m} e\, u_{dc}^{rk} \quad (6)$$

(3) Resource embodied in the inter-sectoral trade

To reflect the technical and economic linkages between sectors and to determine the effect of inter-sectoral trade on the resource consumption of the construction industry, the virtual water and embodied energy transferred from other sectors to the construction industry was quantified. The sectoral resource input (*SRI*) to the construction industry from sector *i* can be obtained as:

$$SRI_i = \sum_{r=1}^{m}\sum_{k=1}^{m} e\ uik \qquad ickr \qquad (7)$$

2.2. Efficiency assessment

DEA, as the leading method for quantitative multifactor efficiency benchmarking, has been widely adopted for efficiency assessment in the construction industry (Crawford & Vogl, 2006; Wang, Shen, Alp, & Barry, 2015; Xue et al., 2008, 2015; Zhang & Gu, 2014). Two types of DEA models have been most commonly used; DEA-Charnes, Cooper, and Rhodes (DEA-CCR) and DEA-Banker, Charnes, and Cooper (DEABCC). In comparison with the CCR model, which operates under the assumption of constant returns to scale, the BCC model is preferred for eliminating the effect of scale factors and for dividing the technical efficiency (TE) into pure technical efficiency (PTE) and scale efficiency (SE). TE can be expressed as TE =PTE*SE. Fig. 1 illustrates the decomposition and measurement of TE.

DEA-CCR can be expressed as follows:

$\min \theta$

n

$$s.t.\begin{cases}\sum_{j=1}^{n} x_j\lambda_j + S^- = \theta X_k;\\ \sum_{j=1}^{n} y_j\lambda_j - S^+ = Y_k;\\ S^+\geq 0,\ S^-\geq 0,\ \lambda_j\geq 0,\ j=1,2,\ldots,n\end{cases} \qquad (8)$$

θ is the efficiency of the construction industry in region k. x_j and y_j represent the input and output vectors in region j, respectively. λ_j indicates the weight of region j. S^- and S^+ denote the input and output slack variables, respectively. DEA-BCC is established by adding the constraint $\sum_{j=1}^{n}\lambda_j = 1$ to DEA-CCR. This can be expressed as:

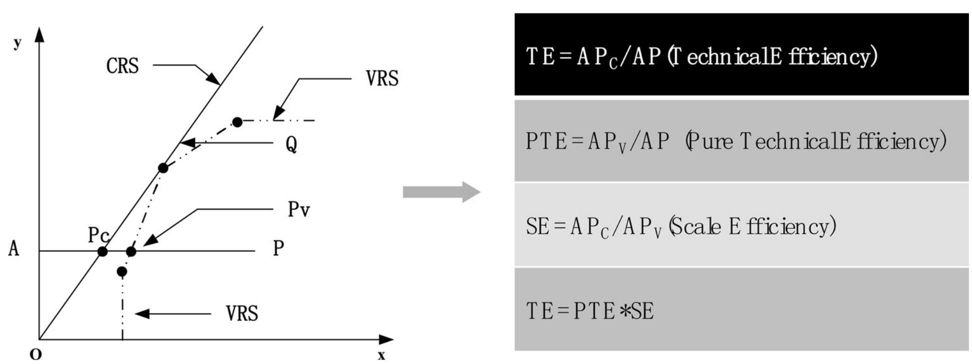


Fig. 1. Decomposition and measurement of efficiency.

$$\min \theta$$

$$\begin{cases}\sum_{j=1}^{n} x_j\lambda_j + S^- = \theta X_k;\\ \sum_{j=1}^{n} y_j\lambda_j - S^+ = Y_k;\end{cases}$$

$$
s.t.\ \begin{cases} \sum_{j=1}^{n} \lambda_j = 1 \\ S^{+} \geq 0,\ S^{-} \geq 0,\ \lambda_j \geq 0,\ j = 1, 2, \ldots, n \end{cases} \quad (9)
$$

To establish the DEA model in this study, the construction industry in each individual province was treated as a decision-making unit. Given that this study analyses the total efficiency of the water-energy nexus in the construction industry from the perspective of the entire supply chain, the virtual water and embodied energy consumption were selected as the input indicators. The annual floor area completed, and the added value of the construction industry (which are, together, widely used to represent physical and economic outputs at an industrial level), were selected as output indicators on the basis of the characteristics of the construction industry (Chen et al., 2016; Xue et al., 2008, 2015).

2.3. Data sources and processing

We used the 2010 MRIO table, which was compiled by the Chinese Academy of Sciences, to measure water and energy flows. Table 2 includes the monetary transaction data of 30 sectors in 30 regions (including 22 provinces, four municipalities, and four autonomous regions). The sectoral direct water consumption data was obtained and estimated through the following steps. Firstly, the water resource bulletins reported in each province in 2010 were collected to obtain the direct water consumption data for primary, secondary, and tertiary industries. Secondly, the sectoral water consumption data at the provincial level was calculated using the assumption adopted by Huang, Lei, and Wu (2017). Direct energy consumption data was obtained from the provincial statistical yearbooks and the regional energy balance tables in the Chinese Energy Statistical Yearbook. For the unpublished data of several provinces, this study used a similar method in water data consolidation to calculate the direct energy consumption of individual sectors. The data of the annual added value and the floor areas completed by local construction industry were derived from the Chinese Construction Statistical Yearbook in 2011. Table 2 lists the detailed information.

Table 2 Data types and sources.

Method	Data	Source
MRIO	MRIO table	•••• Chinese Academy of SciencesChina
	Sectoral direct water consumption	Water Resources BulletinWater resource bulletins of provincesAnnual Statistic Report onEnvironment in China
	Sectoral direct energy consumption	••• Provincial statistical yearbooks Chinese Energy Statistical Yearbook
	Annual added value	Chinese Construction Statistical Yearbook
DEA	Annual floor area completed	

3. Analysis of results

3.1. Inventory of embodied water-energy use in the construction industry

Fig. 2 shows that the total virtual water use of China's construction industry was 54.0 Gt; this is equivalent to approximately 8.97% of the nation's total water consumption. Jiangsu

(R10) and Guangdong (R19) consumed the largest amount of virtual water in the construction industry at 5.0 and 4.8 Gt, respectively, followed by Hubei (R17), Hunan (R18), and Zhejiang (R11) at 3.4, 3.0, and 2.8 Gt, respectively. The provinces which consumed the most virtual water predominantly located along the Yangtze and Pearl River Deltas, which are major urban agglomerations. In comparison, the construction industries in Qinghai (R28), Ningxia (R29), Hainan (R21), Tianjin (R2), and Shanxi (R4) consumed the least amount of virtual water with values ranging from 0.4 Gt to 0.8 Gt. A declining trend of virtual water consumption was observed from eastern to western China. Virtual water intensity varied amongst different regions; Guizhou (R24), Guangxi (R20), and Hubei (R17) showed comparatively lower virtual water intensity usage than their surrounding counterparts.

According to Fig. 3, the embodied energy consumption of the construction industry totals 904.9 million tones of coal equivalent (Mtce), approximately 27.20% of China's total energy consumption. The construction industries in Shandong (R15), Liaoning (R6), Guangdong (R19), Jiangsu (R10), and Zhejiang (R11) consumed the largest amount of embodied energy at 71.3, 70.3, 60.8, 52.0, and 44.7 Mtce, respectively. These provinces were all developed coastal regions with largescale construction activities. In contrast, the embodied energy consumption of the construction industries in Hainan (R21), Qinghai (R28), and Ningxia (R29) were 4.3, 7.1, and 10.9 Mtce, respectively. It can also be noted that, the embodied energy consumption in eastern regions was greater than that of the central and western regions; this is consistent with the distribution of virtual water consumption. Similarly, the embodied energy intensity represented a fluctuated trend, where western regions (such as Guizhou [R24], Yunnan [R25], Ningxia [R29], and Xinjiang [R30]) and parts of the northern regions (such as Inner Mongolia [R5] and Liaoning [R6]) experienced comparatively high intensities.

Figs. 4 and 5 present the amount and intensity distributions of the water-energy nexus of provincial construction industries. The distribution amount was more concentrated where

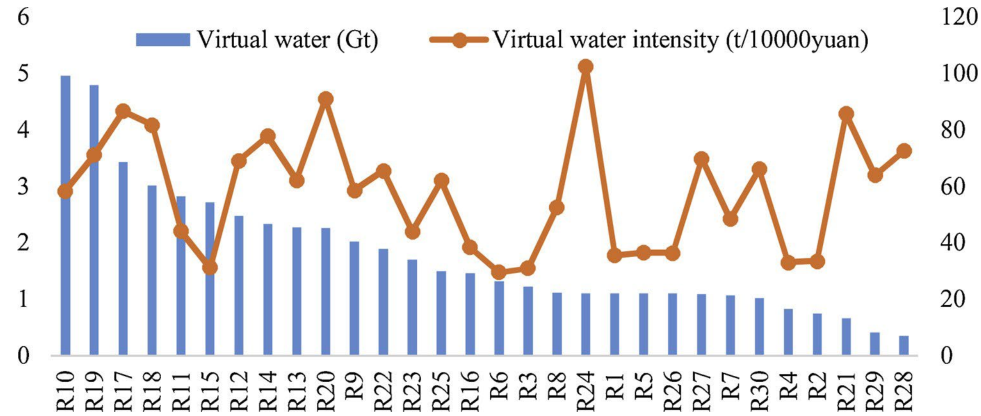


Fig. 2. Virtual water performance of provincial construction industries.

provinces shared a similar consumption status in virtual water and embodied energy use. The fit slope in Fig. 4 indicates that Chinese provinces faced a more severe situation in water consumption than energy use in their local construction sectors. Of all the regions, Guangdong (R19) and Jiangsu (R10) were the leaders in virtual water and embodied energy consumption; a consequence of their large-scale construction activities. The embodied energy and virtual water intensities represented a discrete distribution with a broad range of values. A close examination of this distribution revealed that the western area (Guizhou [R24], Gansu [R27], Qinghai [R28], and Xinjiang [R30]) used the most energy- and water-intensive construction process given their backward economy and outdated production technology. In contrast, the northern area (Liaoning [R6], Shanxi [R4], Inner Mongolia [R5]) faced the greatest challenges in energy intensity improvement because most of the northern regions were mineral-resource-abundant province, which were rich in raw materials for building construction, such as crude oil, raw coal, and metallic minerals (NBSC, 2012). In contrast, the central regions (Jiangxi [R14], Hubei [R17], and Hunan [R18]) suffered from inefficient virtual water usage.

3.2. Interregional and inter-sectoral water-energy flows

3.2.1. Interregional analysis

Fig. 6 illustrates the import status of provincial construction industries with regard to virtual water and embodied energy consumption. Fig. 6(a) shows that the construction industries of Jiangsu (R10), Zhejiang (R11), Guangdong (R19), Shanghai (R9), and Beijing (R1) received the largest virtual water import from other provinces. These five regions possessed two distinct features with regard to their water consumption structure. The virtual water consumption in the local construction industries of Jiangsu (R10), Zhejiang (R11), and Guangdong (R19) were characterized by self-sufficiency with only a small amount of water (15.0%–28.7%) being imported from other regions. In

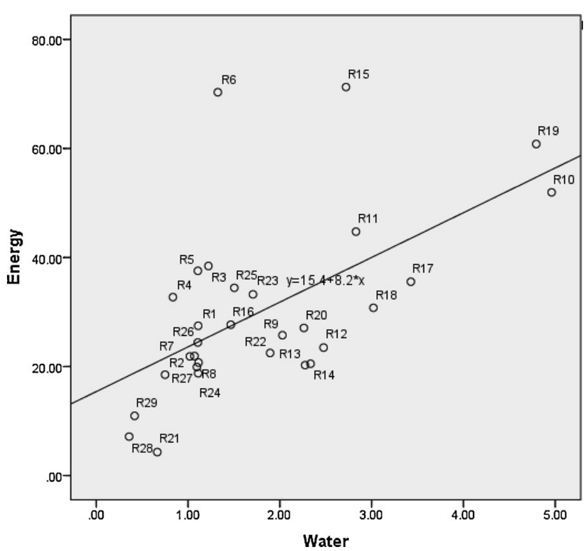


Fig. 4. Distribution of provinces with regard to virtual water and embodied energy consumption.

contrast, Beijing (R1) and Shanghai (R9) were typical import-oriented water consumption regions; imported water was dominant and accounts for 54.8% and 38.0% of supply, respectively. The most significant import water flows included the flows starting from Anhui (R12) to the construction industry of Jiangsu (R10) and from Hebei (R3) to the construction industry of Beijing (R1); these possessed volumes of 0.22 and 0.17 Gt, respectively. This finding is highly related to the exploitation relationship in the agglomeration economies, where

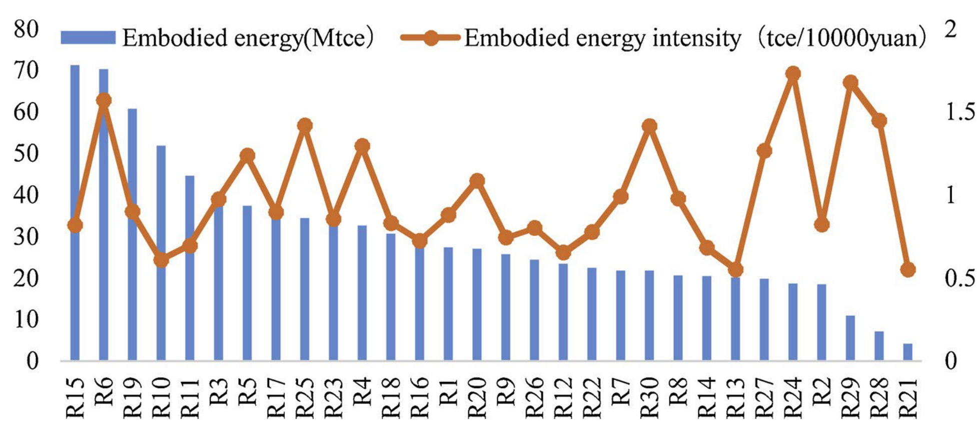


Fig. 3. Embodied energy consumption of the construction industry.

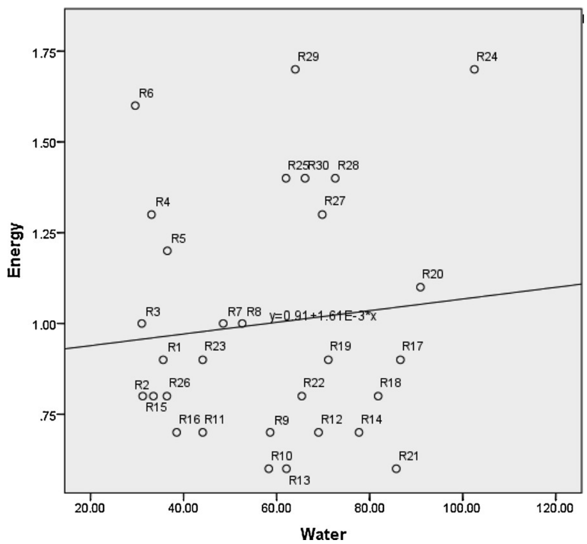


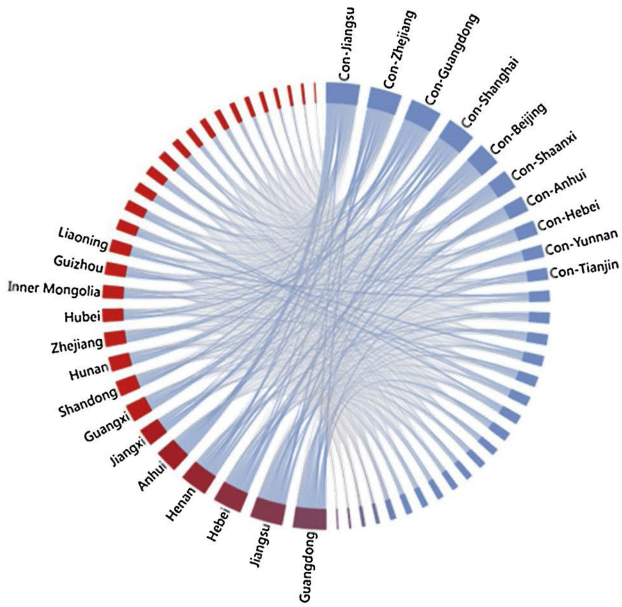
Fig. 5. Distribution of provinces with regard to virtual water and embodied energy intensity.

Jiangsu (R10) is at the top of the hierarchy in the Yangtze River Delta and Beijing (R1) takes priority in the Beijing-Tianjin-Hebei agglomeration. Zhejiang (R11) led in the embodied energy import required by local construction industry with a volume of 21.9 Mtce, followed by Beijing (R1), Jiangsu (R10) and Shanghai (R9) with volumes of 21.1, 18.9, and 15.3 Mtce, respectively. Similar to the virtual water consumption structure, Beijing (R1) and Shanghai (R9) were import-dependent regions, with imported energy accounting for more than 75.0% of the two regions' total embodied energy consumption. A close examination of Beijing's imported energy flows shows that the most greatest energy inflow was from Hebei (R3) with a volume of 12.8 Mtce; this equated to approximately half of the embodied energy consumption used by the construction industry of Beijing (R1). Such exploitation partnership was vital for the sustained development of Beijing (R1). Hebei (R3) and Henan (R16), as the leading energy suppliers for construction activities nationwide, accounted for approximately 40% of the energy-importing flows and have significant connections to the construction industries of

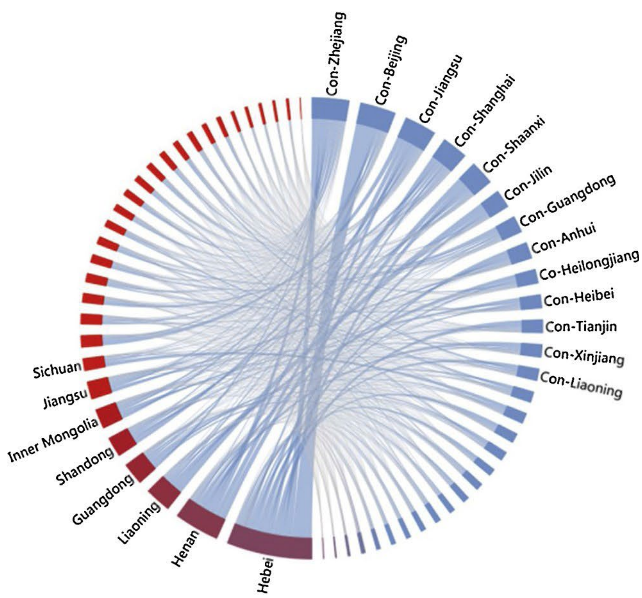
Zhejiang (R11), Beijing (R1), Jiangsu (R10), and Shanghai (R9) through the interregional trading process.

Fig. 7 presents the export status of provincial construction industries with regard to virtual water and embodied energy consumption. Fig. 7(a) shows that Hunan (R18), Jiangsu (R10), Shanxi (R4), Chongqing (R22), and Sichuan (R23) were the leading regions in virtual water export with a total amount of 2.2 Gt, which was equal to 77.1% of China's total interregional water export for construction industries. Most provincial construction industries were net importers of virtual water with the exceptions of Hunan (R18), Chongqing (R22), Sichuan (R23), Henan (R16), and Qinghai (R28). Fig. 7(b) illustrates that the construction industries of Shaanxi (R26), Hunan (R18), Jiangsu (R10), Sichuan (R23), and Chongqing (R22) exported a large amount of embodied energy to other regions; some 40.8 Mtce (73.0% of the total export of provincial construction industries in China). The major receivers of water and energy included Inner Mongolia (R5), Hebei (R3), Guangdong (R19), Shaanxi (R26), and Hunan (R18), which were predominantly tied through service trading processes such as the labor and consulting services provided by construction companies. In summary, dramatic similarities were observed in the interregional trade between virtual water and embodied energy consumption in the construction industry in China.

Fig. 8 demonstrates net transactions of water and energy induced by construction activities. For both virtual water and embodied energy, 16 provinces were identified as net importers while 14 provinces were net



(a) Virtual water import



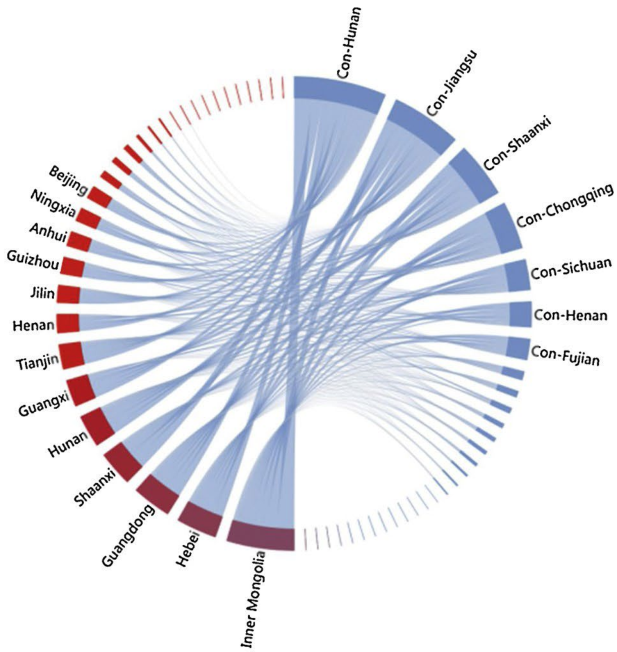
(b) Embodied energy import

Fig. 6. Interregional trade of virtual water and embodied energy of the construction industry.

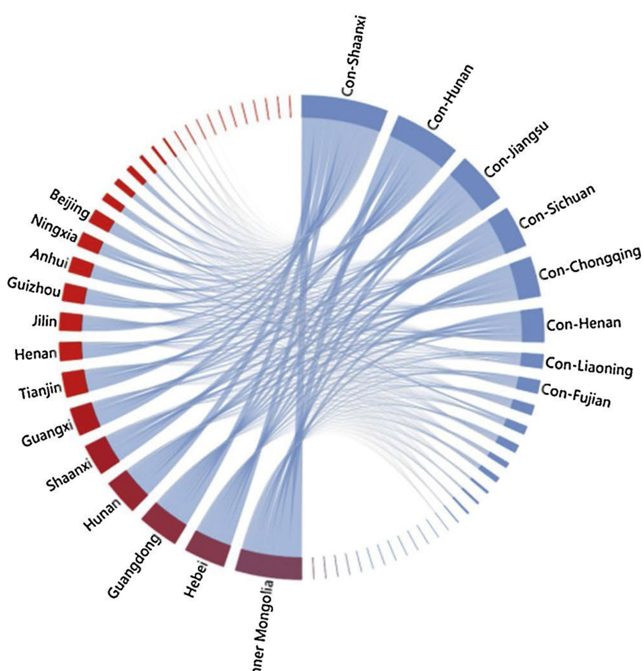
exporters. Most water and energy net importers were located in the developed coastal areas with Beijing (R1), Shanghai (R9), and Zhejiang (R11) being the top three receivers. Among exporters, Henan (16) was the largest water supplier, followed by Hebei (R3) and Jiangxi (R14). There is, as the section has demonstrated, an evident trend of water and energy resources moving from inland regions to coastal areas in keeping with the process of economic development.

3.2.2. Inter-sectoral analysis

The sectoral virtual water consumption was more evenly distributed than the sectoral embodied energy input (See Fig. 9). Specifically, S13 (manufacture of non-metallic mineral products) and S14 (smelting and



(a) Virtual water export



(b) Embodied energy export

Fig. 7. Interregional trade of virtual water and embodied energy of the construction industry.

pressing of metals) were the largest suppliers of virtual water and embodied energy consumption of China's construction industry. In particular, S13 was responsible for 23% of virtual water consumption and 38% of embodied energy consumption. As a consequence, it acted as the main driver for virtual water and embodied energy use within the construction industry. Amongst tertiary industries, S25 (transportation, storage, posts, and telecommunications) exported the largest amount of resources to the construction industry and accounted for 9% of virtual

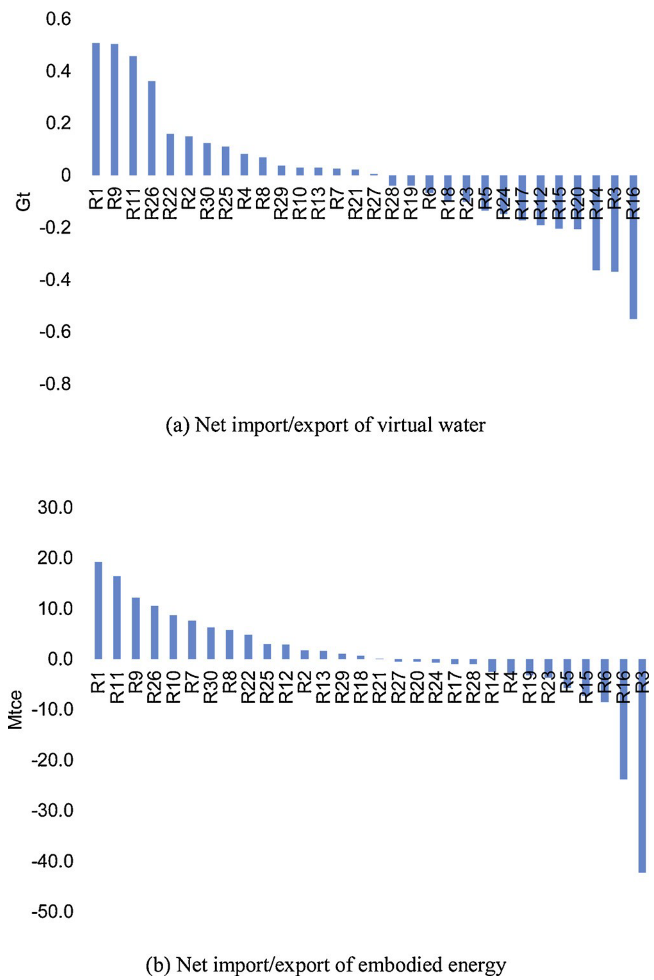


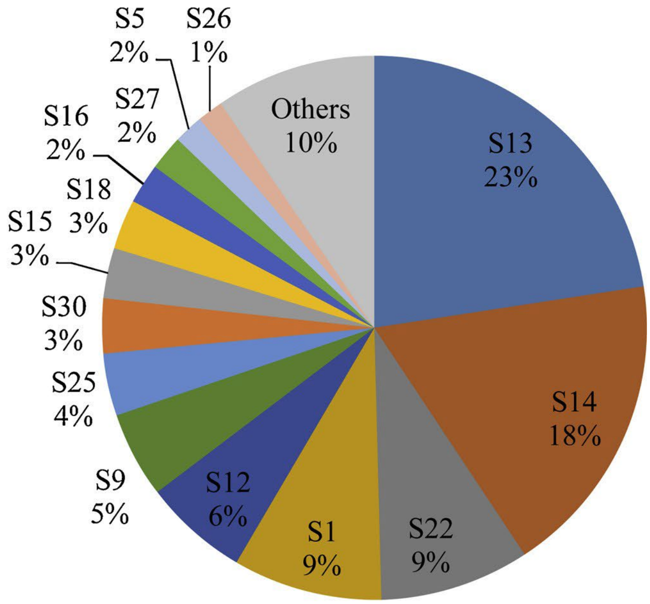
Fig. 8. Interregional net transactions of water and energy induced by the construction industry.

water and 5% of embodied energy consumption. The main reason was that S25, as an economic sector located in the upstream supply chain of the construction industry, played a dominant role in providing transportation, warehousing, and other services for building materials and equipment.

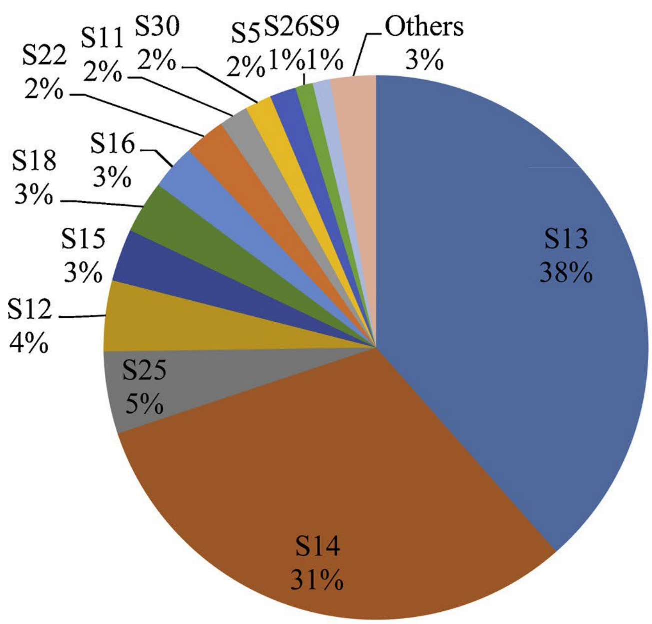
3.3. The total efficiency of the water-energy nexus in the construction industry

Fig. 10 shows that the water-energy nexus exhibited comparatively low total efficiencies across provinces; half of the regions had record scores of less than 0.5; this indicated that the majority of provincial construction sectors in China were both water and energy inefficient. Zhejiang (R11) and Jiangsu (R10) were the two leading DEA-effective regions, followed by Liaoning (R6), Henan (R16), and Fujian (R13); each possessed total efficiency higher than 0.8. The distribution of water-energy efficiency was similar to the consumption pattern; the ranking of total efficiency was highly related to the level of regional economic development.

This study further investigated the non-DEA-effective provinces from technology and scale aspects (Fig. 11). Liaoning (R6), Qinghai (R28), and Hainan (R221) were technologically effective, whereas the SEs of the construction industries of Shandong (R15) and Liaoning (R6) were highest. In general, SE was higher than TE with more than 50% of the provincial construction sectors being more than 0.7. Thus, most parts of China have achieved a relatively high SE but suffered from backward technology. China’s construction industry remains



(a) Inter-sectoral water import



(b) Inter-sectoral energy import

Fig. 9. Inter-sectoral trade of virtual water and embodied energy to the construction industry.

technologically inferior. In fact, as a result of rapid urbanization, building construction processes in China are dependent on mass energy inputs to achieve scales of production, whereas technical aspects lad behind.

4. Discussions

4.1. The ability to save water-energy consumption from a multiregional perspective

Fig. 12 shows that Jiangsu (R10) and Zhejiang (R11) have achieved the frontier of DEA efficiency with no room for further optimization in either virtual water or embodied energy consumption. For virtual water saving, the construction industry of Guangdong (R19) had the largest saving potential with 3.3 billion tons of water ineffectively used, followed by Hubei (R17), Hunan (R18), Jiangxi (R14), and Guangxi (R20). These five regions played a crucial role in achieving water reduction at an industrial level because they were responsible for 42.1% of the total water conservation in China's construction industry. For embodied energy conservation, Liaoning (R6) was the leading province with a potential of saving 51.1 Mtce, followed by Shandong (R15), Guangdong (R19), Inner Mongolia (R5), and Yunnan (R25). Notably, Guangdong (R19) should be ambitious in its virtual water and embodied energy reduction targets as a consequence of its serious resource depletion issues arisen by local construction industry. Moreover, according to Fig. 6(a) and (b), apart from its leading role in resource consumption, the construction industry of Guangdong (R19) was also a major importer of water and energy through the supply chain. This inefficient behavior was the result of both local and foreign resource utilization. Consequently, Guangdong should also implement rigorous policy instruments during the resource bargaining process.

4.2. Comparison of total and direct efficiencies of the water-energy nexus

In previous studies, direct water and energy consumption data was commonly selected as the input indicators to evaluate efficiency in specific fields. To show the importance of indirect effects, this study conducted a comparative analysis of the total and direct efficiencies of the water-energy nexus in the provincial construction industry of China (Fig. 13). The average value of total efficiency was lower than that of direct efficiency, indicating that the construction efficiency was overestimated in previous research. In the direct efficiency assessment, the construction industries of six provinces (Beijing [R1], Heilongjiang [R8], Zhejiang [R11], Jiangsu [R10], Shandong [R15], and Henan [R16]) were DEA effective with a value of 1. A review of by-product effects through multilateral trading in the entire supply chain showed that the resource utilization efficiency of construction industries in Beijing (R1), Shandong (R15), and Heilongjiang (R8) were affected by a large amount of water and energy inflows from other provinces through interregional trade. This would generate negative effects on each area's local efficiency. Moreover, the neglect of upstream resource transactions may lessen the efficiency by underestimating the value. For instance, the total efficiencies of Fujian (R13) and Sichuan (R23) were improved through upstream interactions in the intra-regional and interregional trading processes. The gap between direct and indirect efficiencies confirmed that the indirect effects induced by the iterations of trading processes were significant in China's modern economy (Hong, Shen, Guo et al., 2016; Hong, Shen, Xue, 2016; Zhu et al., 2012).

From a spatial perspective, the importance of indirect trading efficiency emphasizes the necessity of regional integration if one wishes to achieve a low-resource construction process. Resource-saving benefits can be achieved by the structural optimization of interregional trading. The policy instruments launched by central government are fundamental to this being achieved (Grossman & Helpman, 2015), and are especially critical when local governments have incentives to fragment (Fang & Chen, 2017). Increasing economic integrations are boosting free mobility and the distribution of building related production essentials are improving resource efficiency significantly (Fang & Chen, 2017). Moreover, economic unification can stimulate the formation of industrial specialization, which is beneficial in mitigating unnecessary resource loss during the production process (Hong, Tang, Wu, Miao, &

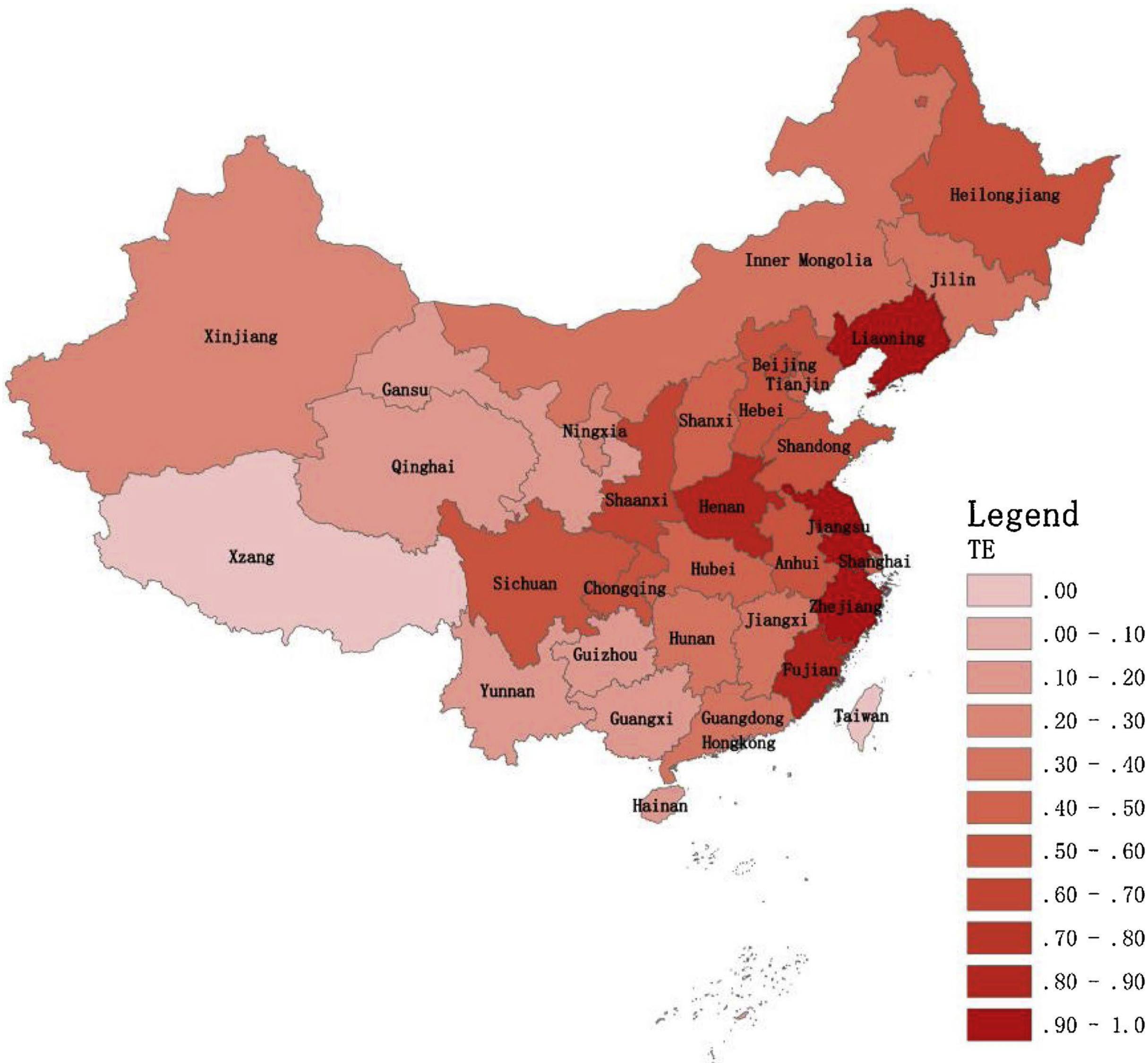
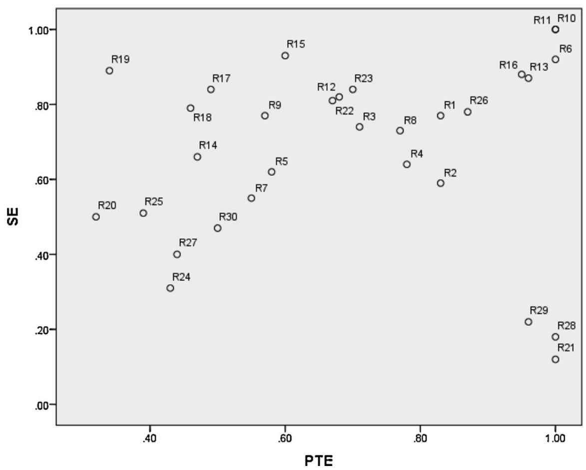


Fig. 10. Total efficiency of the water-energy nexus in the construction industry.



sourcing regime should be well designed for those developed regions as they require a large amount of resources to be imported from other regions (Hossain, Sohail, & Ng, 2019). Furthermore, the transfer of advanced technologies and subsidies is of great concern to regions which have relatively low water-energy efficiency (Li & Han, 2018).

From a sectoral perspective, other economic sectors especially the major suppliers of construction products and services should be well managed. On the one hand, given the multiple connections from the construction industry to the whole economy, the efficiency improvements in the construction industry need joint efforts from economywide actions. On the other hand, as is shown in this research, the construction industry is highly dependent on sectors related to mineral and metals production. Therefore, implementing clean production technology and accelerating the technological progress of the sectors located at the upstream supply chain with intensive resource consumption is effective for total water-energy efficiency improvement.

Fig. 11. PTE and SE of the water-energy nexus in the construction industry.

4.3. Necessity of cross-scale tracking of energy and water flows from China

’s construction industry Shen, 2019). In addition, to optimize the external trading structure, less resource-intensive imports should be encouraged by tax relief or other

Economic globalization and booming international trade are reeconomic instruments (Chen et al., 2017). Moreover, the materials shaping global production activities and associated resources ﬂow

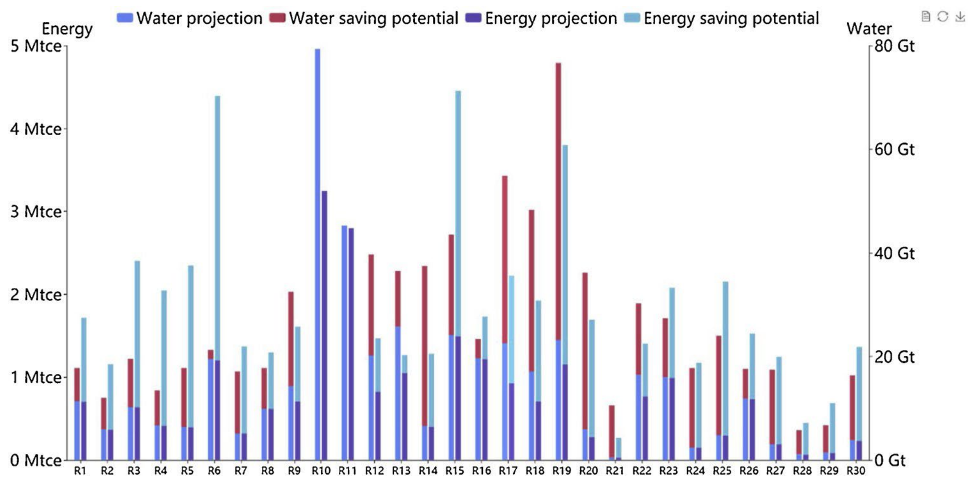


Fig. 12. Virtual water and embodied energy saving potential in the construction industry.

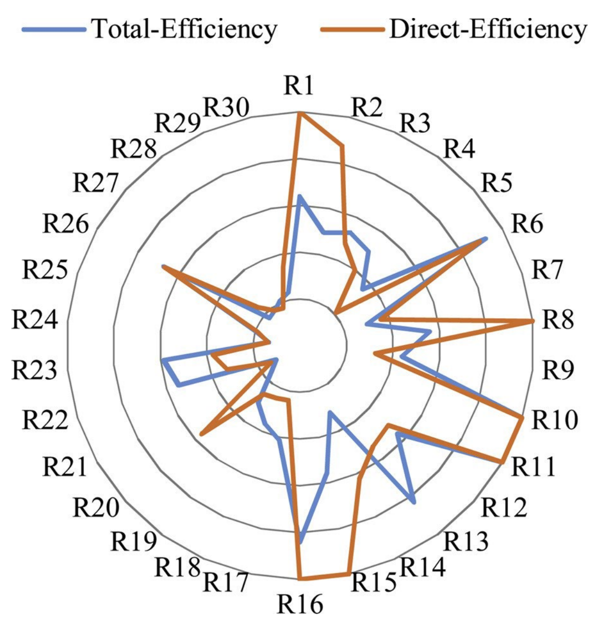


Fig. 13. Comparison of the total and direct efficiencies of water-energy consumption.

network on multiple scales (Meng et al., 2018; Wu & Chen, 2017). As a resource and labor-intensive industry, the construction sector is heavily involved in the complex global economic system (Li, Han, Liu, & Chen, 2019). The cross-scale flows of water and energy resources have become more intricate for construction activities especially since China joined the World Trade Organization which allows foreign building materials to be imported lower prices (Li & Han, 2018; Wu & Chen, 2017). Therefore, tracking water and energy mitigation opportunities along the complicated supply chains on multiple scales deserves greater attention.

5. Conclusion

This paper explored the water-energy nexus of provincial construction industries through flow accounting and efficiency assessment using MRIO and DEA models. The construction industry is responsible for 8.97% of virtual water use and 27.20% of embodied energy consumption in China. The western area possesses the most energy- and water-intensive construction processes, whereas the northern and central regions face great challenges in inefficient embodied energy and virtual water consumption, respectively. The import and export status of virtual water and embodied energy is highly related to the exploitation relationships of specific areas. The sectoral virtual water consumption is more evenly distributed than sectoral embodied energy flows. The ranking of total efficiency is highly related to the level of regional economic development, and follows the economic sequencing of the economy from the eastern area through the central area to the western area. China has achieved a relatively high SE but suffers from backward technology. The ignorance of indirect effects induced by the upstream supply chain may torture efficiency assessment results and lead to the misinterpretation of actual efficiency.

The findings of this study provide additional insights into the waterenergy nexus of China's construction industry with regard to how to relieve water and energy pressures at the provincial level. The results present robust evidence for understanding the current status of the energy-water nexus at the industrial level which, it is hoped, can facilitate decision makers to make top-down energy conservation strategies.

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