The role of energy-water nexus in water conservation at regional levels in China

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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 production has led to widely debated issues such as water shortage and water pollution. Studies on their interrelation – i.e. the energy-water nexus – indicate that energy conservation impacts water resources. Energy conservation can bring synergy on water resources, but it is an unsettle issue to what degree energy conservation could indirectly protect water resources. In this work, we built an accounting framework to assess the synergy of energy conservation on both water quantity and quality at regional levels. Multiregional input-output (MRIO) analysis and economic parameters such as water price and treatment costs of water resources are applied to evaluate the value of synergy. The results show that Jiangsu saved the largest quantity of water with a volume of $63.7 \times 10^8$ m$^3$, while Hunan achieved the largest reduction of wastewater with a volume of $3.2 \times 10^8$ m$^3$ during 2007–2012. The total synergy was divided into two aspects: internal and external. The former was generally larger in most regions except Qinghai, Ningxia, Hainan, Shaanxi, Anhui and Inner Mongolia. The results of an economic assessment show that China achieved $1.1 \times 10^{12}$ yuan of economic benefit through the synergy benefits from a holistic perspective. Jiangsu, Shanghai, Fujian, Shandong and Heilongjiang were primary beneficiaries due to their significant synergistic water saving and high shadow price of water resources. The proposed assessment framework may help understand the situation of regional resources conservation from both synergistic and economic perspectives.

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1. Introduction

Approximately 80% of world population faces high-level water risks (Vorosmarty et al., 2010; Bakker, 2012); Severe disruptions of energy supply also occur frequently in many regions due to energy shortages (Kitamura and Managi, 2017; Chalvatzis and Ioannidis, 2017). Predicted increases in population coupled with rising per capita income and associated changes in consumption habits put unprecedented stress on energy and water resources in the foreseeable future (Tilman et al., 2011; Chu and Majumdar, 2012; Gençer et al., 2017). It is noteworthy that these two global sustainability challenges are closely intertwined (Scott et al., 2011; Hamiche et al., 2016; Zhang and Vesselinov, 2016; Jin et al., 2017), but are often studied and managed separately (Liu et al., 2015b).

Faced with energy and water shortage, China has attached high importance to energy/water conservation while maintaining stable economic development. Promoting energy and water conservation has been mandatory goals in recent China's development programs (Dai et al., 2017; Tang et al., 2018). Both the 12th Year Plan (2011–2015) (The State Council of PRC, 2011a) and the 13th Five-Year Plan (2016–2020) (The State Council of PRC, 2016) have underlined measures to control the intensity of energy and water resources usage on both national and regional scales. In China, water consumption for energy generation was projected to increase by 83% in 2035 in comparison to 2010 (IEA, 2012). If energy could be saved, a certain volume of water would also be potentially saved. Existing energy-water nexus studies have focused on consumptive relations between the two resources, such as water use intensity for thermoelectric power plants. The importance of this nexus in broader resource conservation has been widely neglected.

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Understanding how water resources can be affected by energy conservation is vital for China, where the synergistic conservation of energy and water is under vigorous promotion.

Water consumption for various energy types is differing. Previous studies have made contributions to quantification of water consumption coefficients in energy production with a focus on coal, oil, gas and electricity (Table 1). These address different geographical scale, including well-level, plant-level, regional level and national level. However, they do not take into account the regional disparity of water use for energy production.

Previously, Tang et al. (2018) and Jin et al. (2017) calculated water consumption for energy production and assessed synergies of energy conservation on water resources at national level. However, such analyses cannot reflect important regional differences in energy-related water consumption. The same energy generation output in different regions may consume widely different amounts of water. Zhang and Anadon (2013) found that the gap of lifecycle water consumption of coal, crude oil, natural gas in different regions of China can differ up to 1.4 times, 616 times, and 617 times. Furthermore, energy consumption in a region is partially derived from other regions. Previous studies have largely bypassed such interconnections and differences of energy products when assessing the energy-water nexus within a target region in China. There is a gap in existing knowledge for studies quantifying water consumption of energy activities from both multi-energy and multi-regional perspectives.

Energy production not only consumes water during operation, but may also emit wastewater with damaging effects on local water systems. Some has highlighted water pollution as an even more severe threat to future supply of clean water than concerns over available water quantities (Li, 2013; Mhlongo et al., 2018). Future water quality trends in China are not bright due to large percentages of surface and groundwater resources faced with poor quality (Zuo et al., 2014). Water pollutants emitted from mining and petrochemical industries were identified as main culprits in this situation (Li, 2013; Northey et al., 2016). Both central and regional governments have recently been taking forceful measures to save energy that obviously could assist with mitigation of local energy-related water pollution. Previously, few studies have assessed synergy effects of energy conservation on water quality at regional level in China. Some studies have assessed the local water pollution caused by energy production (Osborn et al., 2011; Darrah et al., 2014; Shang et al., 2018). Water pollution transfer — despite its comparative importance — has not attracted as much attention as energy-related carbon emissions transfer, which has been studied at national level (Guan et al., 2012; Liu et al., 2015a) and regional level (Sugar et al., 2012; Shao et al., 2016).

The energy-water nexus, as used many papers and reports, is an ambitious illustration of interwoven interactions involving water and energy. Earlier nexus literature was focused on accounting of energy-related water consumption. However, it is insufficient to prove the importance of this nexus merely because the two resources are to some extent linked (Wichelns, 2017). Synergistic conservation strategies of energy and water will be challenging to develop and implement without proper evaluation on the entire nexus. Water supply costs vary widely in different regions, leading to different of nexus conditions in various regions. Hence, this paper fills a gap in existing literature by performing economic evaluation on the synergy of energy conservation on water resources.

The remainder of this paper is organized as follows: Section 2 introduces the calculation model of the synergy of energy conservation on water resources and data processing; Section 3 offers the results and discussion of synergy analysis; Section 4 provides the conclusion and policy implications.

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2. Method and data

2.1. Energy-water consumption relations

The input-output (IO) analysis was first put forward by Leontief (1936). IO modelling can reflect the interdependence between production and distribution of various economic sectors. IO frameworks have been widely used to calculate resources consumption and pollution transfer, such as energy consumption (Tang et al., 2016; Sun et al., 2017), water consumption (Wang and Chen, 2016; Liu et al., 2017) and carbon emissions (Xu et al., 2017). Sectoral disparities can be investigated through sector-sector input-output analysis, whereas regional disparities can be studied by multiregional input-output (MRIO) analysis (Wang et al., 2017). MRIO has frequently been used to assess regional energy and water issues, such as virtual water and embodied energy (Feng et al., 2014; Ali et al., 2018; Sun et al., 2018). The data used in this paper were collected and processed to match the year of MRIO table during the research period. In addition, this study chose MRIO tables and merged sectors according to data availability and compatibility with existing studies focusing on energy-water assessment (Liang et al., 2012, 2014; Wang et al., 2013; Guan et al., 2016). The sectors used are shown in Table S2.

The synergy of energy conservation on water quantity and quality in 30 provinces during 2007–2012 period has been calculated. Firstly, the water consumption of economic sectors is calculated. The mathematical expression of direct consumption coefficients is as follows (Zhang et al., 2013, 2016):

$$
\theta_i = \frac{f_i}{x_i} \quad (i, j = 1, 2, \ldots, n)
$$

Where $\theta_i$ is the direct water consumption per economic output of sector $i$ ($x_i$); $f_i$ refers to the amount of direct water consumption.

Sectors not only consume water in a direct way, but also indirectly consume water from other sectors by consuming their products. The complete water consumption coefficients of sectors can be obtained with the direct water consumption coefficients multiplied by complete consumption matrix, as shown in Eq. (2):

$$
CWM_{i \times n} = \theta_{i \times n} (I - A)^{-1} \cdot n = 42
$$

where $CWM_{i \times n}$ is the vector of complete water consumption for unit output. For example, $CWM_{j1}$ denotes the complete water consumption of sector $j$ for unit monetary output within region $r$; unit: m$^3$/CNY; $\theta_{i \times n}$ is a diagonal matrix transformed from $\theta$; $I$ is a n $\times$ n identity matrix; $A$ is the direct requirement matrix calculated by the monetary flows among the sectors of each region in 2007.

Previous studies did not consider water intensity differences in various energy products. In this paper, various water intensities for all energy products are distinguished. The complete water consumption per unit of energy within a region can be obtained from equation (2), as shown in Eq. (3):

$$
CWM_n = CWM_n \times \frac{OM_n}{OP_n}
$$

where $CWM_n$ (Table S3–S6) denotes the complete water consumption for unit production of energy $n$ within a region in 2007; $CWM_{m,r}$ denotes the complete water consumption of energy sector $n$ for unit monetary output within region $r$; $OM_n$ denotes the monetary output of energy sector $n$ within a region, unit: CNY; $OP_n$ denotes the physical output of energy sector $n$ within a region, unit: ton for coal and oil output, m$^3$ for natural gas, kWh for electricity output.

It is incorrect to take the energy consumption gap in different period as energy conservation because sectoral output changes in different years. Energy intensity reflects the variation of the energy used for unit product. Referring to existing researches (Jin et al., 2017; Gu et al., 2016), we use energy intensity change during 2007–2012 period to assess energy conservation. Therefore, energy intensity in 2007 is regarded as a baseline, and the intensity gap between 2007 and 2012 is used to calculate energy conservation. Then, energy conservation within a region can be obtained as shown in Eq. (4):

$$
EC_m = \left( \frac{e_{m,t}^{0}}{P_r^{0}} - \frac{e_{m,t}^{1}}{P_r^{0}} \right) \times P_r^{t}
$$

Where $EC_m$ denotes the conservation of energy $m$ ($m$ denotes various energy types) within a region; $e_{m,t}^{0}$ is the consumption of energy $m$ in year $t_0$; $P$ is the output during period $t$; $P_r^{0}$ is the output during period $t_0$, the unit of $P$ and $P_r^{0}$ is CNY. In this study, $t_0$ denotes the year 2007 (base year), $t_1$ denotes the year 2012; $\left( \frac{e_{m,t}^{0}}{P_r^{0}} - \frac{e_{m,t}^{1}}{P_r^{0}} \right)$ is the energy intensity gap between 2007 and 2012.

2.2. Synergy on reducing water consumption

Energy consumed within a region is generally supplied by both internal and external producers. Regions import various energy products to satisfy their internal energy demands. Energy products in different regions can vary greatly in water intensity. Thus, it is necessary to separately estimate water embodied in energy from other regions when quantifying energy-related water conservation within a region. However, it is challenging to identify sources of energy savings in a target region and it must be assumed that inter-regional trade coefficients are identical for analysis years (Liang et al., 2007). Energy conservations to other regions were allocated based on their share of the energy imports in the target region. The synergy of energy conservation on water savings within a region can then be calculated as follows (5–6):

$$
SW = \sum_m \left( \sum_r ECR_{m,r} \times CWM_{m,r} \times ECL_m \times CW_m \right)
$$

$$
ECR_{m,r} = \frac{EC_m \times ES_{m,r} \times ECL_m}{ELm}
$$

Where $SW$ denotes the synergy of energy conservation on water savings; $ECR_{m,r}$ denotes conservation of energy $m$ ($m \in [1, 10]$) imported from region $r$ (excluding the local); $CWM_{m,r}$ denotes complete water consumption coefficient of energy $m$ in region $r$; $ECL_m$ denotes local conservation of energy $m$ resulting from the conservation effort in target region; $CW_m$ denotes local complete water consumption coefficient of energy $m$; $EC_m$ denotes total conservation of energy type $m$ resulting from conservation effort in target region; $ES_{m,r}$ denotes energy $m$ supplied from region $r$ to target region; $ELm$ denotes total import of energy $m$ in target region.

2.3. Synergy with reduced wastewater discharge

Significant volumes of wastewater can be generated during energy production. If directly discharged, various hazardous substances contained in wastewater could spread into and damage water ecosystems. Reducing wastewater discharge can reduce such environmental concerns and Shang et al. (2018) used wastewater discharge as an indicator to quantify impacts on water quality.
Similarly, this study used energy-related wastewater reduction to quantify positive effects on water quality. Only parts of all wastewater produced in energy production was discharged into environment as energy suppliers will treat some of the wastewater on site or transport it to treatment plants for processing or reuse. Therefore, wastewater treatment rate need to be considered when assessing wastewater discharge holistically. The wastewater data of energy production in each region are unavailable from government statistics. However, the ratio of freshwater to wastewater in the same energy sector remains relatively stable. Liang et al. (2014) calculated each industrial sector’s freshwater usage according to wastewater emission data and the ratio of freshwater to wastewater. This study obtained water consumption of each sector in every region and calculated wastewater discharge during energy m production based on the same method. The mathematical expressions are given below (7–9):

\[ DWW_m = WWP_m \times (1 - WTR_m) \]  

\[ WWP_m = DW_m \times RW_m \]  

where \( DWW_m \) denotes direct wastewater discharge during energy \( m \) production; \( WWP_m \) denotes produced volume of wastewater during energy \( m \) production; \( WTR_m \) denotes the rate of wastewater treated during energy \( m \) production; \( DW_m \) denotes the water consumption during energy \( m \) production; \( RW_m \) denotes the ratio of produced wastewater to water consumption during energy \( m \) production. Unit production of energy \( n \) within a region in 2012.

Using the same method as described in Eqs. (1)–(3), this study calculated \( CWW_m \) (Table S3-S6), which denotes the complete wastewater discharge for unit production of energy \( m \) within a region in 2012. On this basis, the synergy of regional energy conservation on wastewater reduction within a region can now be calculated, as shown in Eq. (9):

\[ SWQ = \sum_m \left( \sum_r ECR_{m,r} \times CWW_{m,r} + ECL_m \times CWW_{m,l} \right) \]  

where \( SWQ \) denotes the synergy of energy conservation on wastewater reduction; \( ECR_{m,r} \) denotes conservation of energy \( m \) imported from region \( r; CWW_{m,r} \) denotes complete wastewater discharge per ton of energy \( m \) produced in region \( r; ECL_m \) denotes local conservation of energy \( m; CWW_{m,l} \) denotes wastewater discharge per ton of energy \( m \) produced locally.

2.4. Economic benefits of the synergy

Excessive water consumption within energy production can lead to reduction of available water for other purposes, such as agricultural/domestic demands and other industries (Qin et al., 2015; Cai et al., 2018). Since water is a valuable natural resource in life and production, especially for areas facing water shortage, we consider freshwater as assets from an economic perspective. Water consumption in energy production has been commonly construed as an asset reduction (Can et al., 2011; Wang, 2016).

Discharged wastewater pollutes water environments and may significantly reduce available water amounts for exploitation. To eliminate such negative effects, all effective physical, chemical and biological measures should be implemented (Finkel and Hays, 2013; Dargheib et al., 2016; Guerra and Reklaitis, 2018). In other words, wastewater reduction implies cost savings from reduced volumes sent for treatment. To calculate this benefit, the replacement cost approach was adopted to address cost savings of all treatments related to pollution control. However, pollutants contained in the wastewater from different types of energy production can differ significantly, resulting in a large cost gap. Consequently, this analysis multiplied wastewater reduction of various energy activities by corresponding expenditure of treatment to assess economic benefits under the assumption that wastewater from the production of the same energy in different regions was treated in a near cost situation.

An economic assessment model (EAM) was proposed evaluate the total synergy of energy-related water conservation, including water saving and wastewater reduction. The mathematical expressions are given below (10–12):

\[ EB_W = \sum_k SW(k) \times WP_{sh}(k) \]  

\[ EB_{WQ} = \sum_k SWQ_{en}(k) \times WC_{DP, en}(k) \]  

\[ EB_T = EB_W + EB_{WQ} \]  

Where \( WP_{sh}(k) \) denotes the shadow price of water resources in kth region; \( en \) denotes the energy types. Here, we classified 10 energy types into four energy sectors (Coal Mining and Dressing, Petroleum and Natural Gas Extraction, Petroleum Processing and Coking, Production and Supply of Electric Power and Heat Power); \( SWQ_{en}(k) \) denotes the wastewater reduction from the conservation of energy \( en \) in kth region; \( WC_{DP, en}(k) \) denotes the treatment cost of wastewater produced in the production of energy \( en \) in kth region; \( EB_W \) denotes the benefits brought by energy-related wastewater saving; \( EB_{WQ} \) denotes the benefits brought by energy-related wastewater reduction; \( EB_T \) denotes the total benefits brought by energy conservation.

2.5. Data sources

The economic MRIO tables for 30 Chinese regions originated from Feng et al. (2011) and Mi et al. (2017), where MRIO was used to study Chinese CO2 emission flows and water footprints. The energy categories consumed by economic sectors used in this study were coal, crude oil, natural gas, coke, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas (LPG), and electricity. These categories are widely used in Chinese energy statistics. Consumption data of coal, crude oil, natural gas, coke, gasoline, kerosene, diesel oil, fuel oil and electricity were collected from “China Statistical Yearbook” (National Bureau of Statistics of China, 2015a) and “China Energy Statistical Yearbook” (National Bureau of Statistics of China, 2015b). LPG consumption data were calculated by adding up all gas consumption of urban and rural households and firms based on “China Urban Construction Statistic Yearbook” (National Bureau of Statistics of China, 2008a, 2013a) and China Urban-Rural Construction Statistic Yearbook” (National Bureau of Statistics of China, 2008b, 2013b).

Water consumption data for economic sectors in each region were collected from “China Economic Census Yearbook” (National Bureau of Statistics of China, 2008c), “China Water Bulletins” (Ministry of Water Resources, 2007, 2012) and “China Statistical Yearbook on Environment” (National Bureau of Statistics of China, 2008d, 2013c). However, national statistics did not contain detailed sectorial classification for every year, as sectoral and regional breakdown of water consumption was only provided for 2008. This was handled by the same approach as in a previous study by Jin et al. (2017), referring to Liang et al. (2012, 2014), Guan et al. (2014) and Researching Group of Chinese Input-Output Association (2007).
The shadow price of water resources was taken from Shang et al. (2018), in which shadow price of five administrative districts (Eastern China, North China, South China, Western China, and Northeast China) were presented after assessing a number of project reports (Table S7). The rate of wastewater treated and the expenditure of wastewater treatment of energy sectors were obtained from “China Statistical Yearbook on Environment” (National Bureau of Statistics of China, 2013c). Wastewater treatment expenditures included energy consumption, equipment maintenance, staff wages, management fees, pharmacy fees, and other expenses associated with operation of a facility (Table S8).

3. Results and discussion

3.1. Synergy on water saving

Energy-related water savings in each region was calculated after specifying energy categories and inter-regional trades as shown in Fig. 1. This synergy varies widely among different regions in China. The top five regions with positive water savings are Jiangsu, Guangdong, Shanghai, Hunan, and Heilongjiang (63.7 × 10⁶ m³, 35.4 × 10⁶ m³, 34.2 × 10⁶ m³, 31.7 × 10⁶ m³, 28.4 × 10⁶ m³ respectively). Regions that have not achieved synergistic water conservation are Ningxia, Qinghai and Xinjiang as their energy intensities did not decline. It is evident that regions with negative water savings did not perform well with improving energy intensity as a whole during 2007–2012. Jin et al. (2017) showed that the total synergistic water saving of energy conservation for energy sectors was 12.4 × 10⁶ m³ in 2007–2012. Gu et al. (2016) focused on Chinese industrial sectors, the results showed that during the 12th Five-Year Plan period, major industrial sectors have obtained 19.2 × 10⁶ m³ of synergistic water saving. Compared with these studies, we find that the synergy of energy conservation on water saving is more remarkable after incorporating all efforts of energy conservation at regional levels.

The energy saved in a region can be classified into two sources: internal- and external-energy conservation. “Internal energy conservation” denotes local energy products saved within the region itself, while “external energy conservation” denotes reduced export of local energy products due to energy demand decline in other regions. Synergistic energy conservation on water resources within a region could then be divided into two aspects: internal- and external-synergy. Internal synergy denotes the synergy of internal energy conservation on local water resources, and the external synergy denotes the synergy of external energy conservation on local water resources.

As shown in Fig. 2, internal synergy is generally larger than external in each region except Qinghai, Ningxia, Xinjiang. These three regions have not achieved any internal synergy by reducing their energy intensity, although they obtained water savings (0.08 × 10⁶ m³, 0.11 × 10⁶ m³, 2.52 × 10⁶ m³) by external synergy from other regions. It is evident that water savings in these regions (Beijing, Shanghai, Jiangsu, Fujian, Jiangxi, Hubei, Hunan, Guangxi, Chongqing, Sichuan) are mainly dependent on their own reductions of energy intensity as their proportions of internal synergy in the total synergy are all over 90%.

As described, a beneficiary region can get external synergy from the other 29 regions (origin region). If these relations are represented by flow paths, then there are 900 (30 × 30) flow paths in total. Table 2 presents top ten paths that contain 27% of the total water savings resulting from external synergy. Remarkable external synergy occurred in North-east China during 2007–2012, where Heilongjiang and Jilin have passively saved water due to energy conservation in Liaoning. By observing both origin and beneficiary sides, we can see that regions such as Jilin, Shandong, Jiangsu, Hebei — all brought remarkable synergy to others — were also primary beneficiaries heaping benefits of energy conservation efforts of other regions.

Water consumption can widely differ for different types of energy or the same type of energy in different areas as calculated in this analysis. Moreover, each region promoted energy conservation in different ways. Consequently, different types of energy played different roles in the synergy. Hence, there is vital to quantify various contributions from different energy types to better illuminate their importance for synergetic effects. As shown in Fig. 3, both electricity and coal are important for achieving synergistic water savings, with proportions of 30.01% respectively 27.94%. Specifically, the largest beneficiary from electricity savings was Jiangsu. Meanwhile, synergies related to coal savings were mainly seen in Shanxi, Shandong, Henan, Hebei and Anhui with share ranging from 13.56% to 17.40%.

Governmental plans for eliminating backward capacity and developing clean energy have significantly reduced capacity of water intensive facilities during the studied time frame (National Development and Reform Commission, 2008). Meanwhile, water-cooling technologies in electric power generation have also advanced significantly due to development planning in each region. Shifting away from outdated open-loop to closed-loop cooling has reduced water withdrawals significantly (Wen et al., 2015). For coal, the central government (The State Council of PRC, 2010) and local governments continuously eliminated excessive capacity. Cutting overcapacity contributed significantly to synergistic water savings.

3.2. Synergy on wastewater reduction

Energy conservation also brought synergy in wastewater reduction in energy production areas. Fig. 4 shows the map of wastewater reduction derived from energy conservation during 2007–2012. China achieved 23.47 × 10⁶ m³ of wastewater reduction in total. The top five benefited regions were Hunan, Henan, Guangdong, Jiangsu and Hubei (3.2 × 10⁶ m³, 1.9 × 10⁶ m³, 1.7 × 10⁶ m³, 1.1 × 10⁶ m³ respectively). Ningxia, Qinghai and Xinjiang did not achieve wastewater reduction during this period.

As shown in Fig. 5, internal synergies are generally larger than external counterparts in each region except Ningxia, Xinjiang, Hainan, Shaanxi, Anhui, and Inner Mongolia during 2007–2012. Although Ningxia and Xinjiang did not achieve internal synergies, they both reduced energy-related wastewater by reducing energy.
exports to other regions. External synergies are larger than the internal ones in Anhui, Hainan, Shaanxi and Inner Mongolia, which indicates that they relied more on the energy conservation efforts of other regions despite their own internal efforts. The origins and beneficiaries of external synergy can also be expressed with flow paths shown in Fig. 6. Main beneficiaries were Heilongjiang, Anhui, Henan, Jiangsu and Hebei, while main origins were Liaoning, Jilin, Jiangsu, Zhejiang, and Shandong.

Fig. 7 displays the contributions from different types of energy and coal dominates the contribution to synergic water saving with its share of 51.39%. The calculations showed that this synergy was mainly from considerable coal conservation. The contribution from electricity conservation was also crucial in water savings with a share of 15.05%. However, it was much smaller than coal due to relatively low ratio of wastewater discharge from the electricity sector.

3.3. Economic benefits of the synergy

Synergies of energy savings on water resources can be divided into two aspects: synergy on water quantity and quality. The total economic benefit of the synergy in each region were obtained after adding up the economic value of energy-related water savings and energy-related wastewater reductions as shown in Fig. 8. China achieved economic benefits worth $1.1 \times 10^{12}$ yuan during 2007–2012. Jiangsu, Shanghai, Fujian, Shandong, and Heilongjiang were primary beneficiaries due large amounts of synergistic water savings and high shadow price of water resources.

The economic benefits of wastewater reduction were very small compared with water savings. However, wastewater could cause serious damage to surrounding ecological systems and local residents that potentially may cause huge losses in the long term. From this research, it was found that each region could only see minor

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<th>Origin → Beneficiary</th>
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<td>4.71</td>
<td>Zhejiang → Jiangsu</td>
<td>1.30</td>
</tr>
<tr>
<td>Liaoning → Jilin</td>
<td>3.39</td>
<td>Jiangsu → Shandong</td>
<td>1.28</td>
</tr>
<tr>
<td>Zhejiang → Anhui</td>
<td>1.70</td>
<td>Hebei → Jiangsu</td>
<td>1.23</td>
</tr>
<tr>
<td>Shandong → Heilongjiang</td>
<td>1.39</td>
<td>Jilin → Heilongjiang</td>
<td>1.04</td>
</tr>
<tr>
<td>Tianjin → Jiangsu</td>
<td>1.33</td>
<td>Shandong → Hebei</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Notes: “Origin” denotes the region that has produced spillover effect on water saving by saving energy; “Beneficiary” denotes the region which has reduced energy-related water use due to the potential decline of energy demand in “Origin”; “Spillage” denotes the synergistic water saving of “Beneficiary” due to energy conservation in “Origin”.

Fig. 2. Internal and external synergy of energy conservation on water savings in each region.

Table 2
Main water flow paths derived from external synergy between regions during 2007–2012.
economic benefits even if they do not deal with energy related wastewater at all. Conversely, vigorously advancing construction of water treatment facilities and improved treatment efficiency might yield major potential returns at a low cost. This is the real road to fortune for all regions in the long run - not to mention a legal and moral responsibility of sustainable development.

3.4. Sensitivity analysis

Synergies were essentially determined by two factors: regional energy intensity and water consumption coefficients of energy. All regions and energy types were subjected to sensitivity analysis for examining dominant factors. Like Chang et al. (2014) and Scherer and Pfister (2016), factors which have major influence on synergies were presented (Figs. 9 and 10). For every 1% change of these factors, the water saving and wastewater reduction will have corresponding changes, but no more than 0.15% and 0.1% respectively. Fig. 9 shows that all important factors revolve around electricity, thus highlighting its significance compared with other types of energy. However, the total synergy had low sensitivity to most factors, including water consumption coefficient of electricity in Jiangsu. Fig. 10 presents the primary sensitive factors of the synergy on wastewater reduction. In comparison, coal intensity and wastewater discharge coefficient of coal were relatively important factors. However, the total synergy had low sensitivity to the change of each single factor.

4. Conclusion and policy implications

4.1. Conclusion

The synergy of energy conservation on water quantity and quality were collectively assessed using the proposed accounting framework. Energy-related water savings and wastewater reduction were systemically calculated by categorizing water consumption and wastewater discharge into water for ten categories of energy production, to analyze characteristics of regional energy-water conservation synergies. Comprehensive insights into the synergies in economic terms were obtained by combining MRIO with economic assessments. Sensitivity analysis examined and identified influential factors that strongly affect the synergy of energy conservation on water resources. This synergy assessment framework may provide an integrated tool for understanding and controlling regional resource conservation prospects from a holistic perspective.

It was found that 27 regions achieved energy-related water saving during 2007–2012. By decomposition of these synergies into internal and external effects, it was found that internal synergies were generally larger than external ones in each region except Qinghai, Ningxia, and Xinjiang. These provinces did not achieve water savings by reducing their energy intensity, but rather obtained water savings by sharing energy conservation efforts from other regions. Remarkable external synergies occurred in the North-eastern part, where Heilongjiang and Jilin passively saved water by sharing energy conservation efforts of Liaoning. It was found that the largest quantity of wastewater reduction was seen in Hunan in terms of synergetic regional energy conservation on water quality. Internal synergies were larger than external ones in most regions except Ningxia, Xinjiang, Hainan, Shaanxi, Anhui, and Inner Mongolia.

An economic assessment model was proposed to evaluate the economic benefits of the synergy of energy conservation for both water quantity and quality and it was found that China achieved huge benefits during 2007–2012. Jiangsu, Shanghai, Fujian, Shandong and Heilongjiang were primary beneficiaries due to their
significant water savings and high shadow prices of water resources. Synergies on wastewater reduction did not make significant contribution to economic benefits in China.

Dominant factors behind synergies on water saving and wastewater reduction were investigated via sensitivity analysis. Compared with other types of energy, the water consumption coefficient of electricity in Jiangsu played the most important role in energy-related water saving, and coal intensity of Hunan was most important for energy-related wastewater reduction. However, total synergies had generally low sensitivity to a single factor.

4.2. Policy implications

The intention of studying energy-water nexus is to understand interrelations between these resources and to promote holistic and optimal management. Many energy-water nexus can be found in literature, but they mainly focus on calculation of energy and water flows, and overlooked the nexus role in resource conservation. Existing policies of central and local governments still set mandatory targets on energy and water consumption separately and this may lead to omit valuable synergies and more optimal options that could have been seen from an energy-water nexus perspective.

Firstly, it is necessary to clearly highlight the role of synergies within conservation instead of relying on simplistic and unconnected networks of energy and water flows. The results of this study offer insight into how energy savings could potentially affect
Sensitivity analysis of the variance in energy-related water saving. Notes: “CWW” denotes the wastewater discharged coefficient of coal; “EWW” denotes the wastewater discharged coefficient of electricity; “CI” denotes coal intensity; “EI” denotes electricity intensity. The percentage on the horizontal axis denotes the variance of the total wastewater reduction in response to 1% change in energy intensity and the wastewater discharged coefficients of energy in each region.

Secondly, a series of quantitative evaluation method of synergy should be put forward. Reducing energy-related water consumption and wastewater discharge has been widely recognized and proved quite economical. However, large-scale and formal regulations are hard to shape and correctly implement until costs and benefits are clearly defined and standardized. Energy-related water issues are still vague as the evaluation system is lacking in comparison with other environmental issues, such as greenhouse gas emissions, particle pollution, and land desertification. It is essential to adequately cover complete costs of water consumption and pollution caused by each type of energy when calling for actions to accomplish optimal energy-water conservation measures.

Finally, maximizing benefits of energy-related water conservation could be achieved by focusing on end use. Some argue that production-based perspectives are common approaches to reduction of air and water pollution, such as “supply-side reforms”. However, we argue that successful reduction rather is a task determined by economic transitions in a particular time. The results of this analysis highlight that the remarkable potential of energy-related water savings and wastewater reduction did not depend on energy producers such as Shanxi, Shaanxi, or Inner Mongolia. It rather mostly relies on economically developed regions, where the energy consumption and economic output were both comparatively large. Blindly restricting conservation measures to large suppliers of coal and coal power neglects the importance of intermediate and end users. As the Chinese economy shifts into a stage of high-quality development, it is imperative that coal and other resource usages are holistically optimized for the benefit of the entire nation.

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Appendix A. Supplementary data

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