Environmental Science and Pollution Research (2022) 29:7703–7720
https://doi.org/10.1007/s11356-021-15719-z

RESEARCH ARTICLE

Exploring the driving forces on sustainable energy and water use in China

Lingling Wang[1] · Enjun Xia[1] · Zixiang Wei[2] · Wei Wang[1]

Received: 4 February 2021 / Accepted: 26 July 2021 / Published online: 3 September 2021

Abstract

With the rapid growth of global demand for water and energy, the two increasingly restrict economic and social development. The total energy consumption and water use are positively correlated. Identifying the key drivers influencing the energy-water development can realize national resource management and sustainable supplement. In this context, this study aims to capture the key driving forces that affect the sustainable energy-water development characteristics in Chinese change processes throughout 2000–2017. Five driving forces, the EW intensity effect, industrial structure effect, GDP value-added effect, income improvement effect, and population-scale effect, were further decomposed by the logarithmic mean Divisia index (LMDI) model to explore the energy consumption and water use. Our findings indicated that the largest and lowest energy consumers were the manufacturing and construction sectors, while agriculture accounted for the largest share in water use. During the three time intervals, the cumulative effects increased the EW use, but the contributions were declining. Further, these effects had a more prominent influence on water use than energy consumption; GDP value-added effect, income improvement effect, and population-scale effect increased the EW use, while intensity effect played a vital role in decreasing EW use during the study period. Notably, the industrial structure effect had a seesaw role during 2000–2006, which led to a tradeoff between various driving factors. In future sustainable issues, policymakers should pay more attention to energy-saving than water-saving to achieve the national energy and water conservation targets.

Keywords Energy consumption · Water use · Sustainable energy-water use · Driving forces · China

Introduction

As precious natural resources and critical strategic resources, water and energy are essential to promote sustainable economic and social development. In the context of global climate change and continuous population growth, the demand for water and energy resources will continue to grow. It is expected that by 2035, global energy demand and water consumption will increase by 35% and 85%, respectively. The situation of water resources and energy security is considerably complicated. As the world's largest energy and water resource consumer, China is currently undergoing rapid industrialization, urbanization, and modernization deployment. Energy and water have become significant factors that limit environmental and ecological development in China. During the 13th Five-Year Plan period, China predicts that by 2020, energy use per unit of GDP will fall by exceeding 15%; that of water use per 10,000 yuan of GDP and per 10,000 yuan of industrial added value will decline 23% and 20%, respectively, compared to 2015 (China 2020). Additionally, most of the energy industry is a high-water industry, and water shortage will directly affect their layout and scale. Therefore, water use and energy consumption are inherently interdependent, which the sustainable development of energy and water has become increasingly important (Gu et al. 2014). Under such circumstances, exploring the effects of key drivers on energy-water

Responsible Editor: Eyup Dogan

✉ Enjun Xia
enjunxia@bit.edu.cn

Lingling Wang
3120160717@bit.edu.cn

Zixiang Wei
viovci@gmail.com

Wei Wang
wangwei_666892@163.com

[1] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

[2] Intellectual Property and Achievements Center, China Institute of Marine Technology & Economy, Beijing 100081, China

use is of great significance for sustainable development targets.

Energy and water have become critical indicators of society's sustainability. Sustainable development of water resources and energy has gradually drawn scientists' attention. The research carried out unanimously believes that both are facing the pressure of shortage, which is still intensifying. Energy extraction, processing, transportation, and utilization require a certain amount of water consumption. Conversely, the purification, delivery, and distribution of water are inseparable from energy (Siddiqi & Anadon 2011). Beyond the resource use nexus between energy and water, the two have the characteristics of complementary products in economics. Improving energy efficiency can reduce water resource pressure, while increasing water efficiency can reduce energy consumption accordingly (Ding et al. 2020, Li et al. 2019c, Zhang & Anadon 2013). For example, Kahrl and Roland-Holst (2008) examined the two most scarce resources of energy and water in China and engaged in the influence of water use on energy consumption. Gu et al. (2014) adopted an input-output analysis to estimate the impacts of energy conservation policies in multiple industries. They pointed out that energy-saving resolutions in these industries would serve as water savings. Only by synergistically promoting and rationally allocating energy and water can we regularly help achieve these two resources' green development.

Continued energy consumption in China is a critical issue that has become increasingly important to scholars and policymakers' communities in recent years. Those studies can usually discuss the crucial driving factors to influence energy consumption (Wang et al. 2020, Yang et al. 2020), the relationship between economic growth and specific energy use (Song et al. 2019, Zhang & Cheng 2009), and changing trends (Crompton & Wu 2005). Meanwhile, water use change is another critical issue that draws increasing attention all around the world. Numerous studies on Chinese water analysis have been conducted to explore water footprints in different regions (Yao et al. 2019, Zhao and Chen, 2014), influence factors (Fan et al. 2017, Kong et al. 2021), and water consumption in different sectors (Chen et al. 2020). The representative studies above on energy consumption and water use in China are listed in Table 1.

Since energy and water consumption are closely related to the achievement of environmental sustainability, recent studies included water and energy in the same framework and selected the ratios of resource consumption as analysis structure in specific sectors (Yang et al. 2018, Zhang et al. 2019). To date, existing energy-water studies have widely extended their scopes and scales and have gradually transferred to explore the role of socio-economic factors and EW-corresponding policies on resources' sustainable management (Arthur et al. 2019, Li et al. 2020, Liu et al. 2020). Meanwhile, the energy-water sustainable development is affected by various aspects. Li et al. (2019a) indicated that socio-economic and sector-wide forces should be included in the influence patterns. Globally, economic growth and population drive demand for resources (Fang & Yu 2021, Scott et al. 2011, Shi et al. 2019a, Yu et al. 2020). Undoubtedly, the market and consumption of water and energy resources are rapidly rising due to population growth, industrialization, urbanization, and climate change (Chen & Chen 2016, Liang et al. 2020, Schmidt & Matthews 2018, Shi et al. 2019b).

In existing studies, most scientists have devoted themselves to exploring sustainable energy-water development from different scales, such as sectors, countries, regions (Fang et al. 2020, Yu & Fang 2021). Liao et al. (2019) undertook the link between energy demand and water consumption in the rural and urban household sectors. They explored the effects of four driving factors from the province scale. Yang et al. (2019) targeted the key transmission sectors of the energy-water-carbon nexus to mitigate the substantial pressures in cities. Bazilian et al. (2011) studied the relation of water-energy-food from the perspective of developing countries and then proposed a modeling framework that specifically addressed the nexus design. Additionally, many scholars have researched the relationship between energy and water in typical Chinese cities and areas. Wang et al. (2018) investigated the water, energy, and emission nodes in three regions: Beijing, Tianjin, and Hebei. They indicated that the objective plan could reduce emissions of two harmful gases and dust while employing less energy and more water as tradeoffs. Fang and Chen (2017) detected the synergic impacts of energy and water use and interactions between economic divisions, and they revealed the vital virtual water and embodied energy supplement sectors in Beijing. Alternatively, Liang et al. (2020) explored the socio-economic forces of water withdrawals consumed by local energy needs in China from 2007 to 2012 and pointed out that population growth was the driving force for increased water withdrawals. We found that nearly 70% of studies focused on the individual urban and urban agglomeration levels (Ding et al. 2020).

Even though previous studies have examined the effect of environmental factors within urban sectors, cities, or provinces, it cannot be ignored that the driving forces have contributed to sustainable energy-water development at the national scale. The research of sustainable energy-water development on the national level has received growing attention recently. Xiang and Jia (2019) summarized that energy demand has not yet been the main inhibiting force for national water supply in 2015, while burdensome energy demands were predisposed to reduce specific water policies' effectiveness. Chao et al. (2018) investigated the influencing factors behind transforming water use mechanisms in the thermoelectric power industry. The results showed that the construction of large coal-fired power generation hubs had raised water shortage pressure in many arid and water-scarce regions in northwestern regions of China, whereas the freshwater extraction was irrelevant with

Table 1 Representative studies on energy consumption and water use in China in recent years

Source	Study object	Study period	Methodology	Main findings
Wang et al. (2020)	Key drivers of energy consumption growth in China, the USA, and India	1965–2015	Geographical detector models	Coal intensity is the most significant driver to change energy use in China and India, while individual incomes and oil intensity are the leading factors for the USA. Three drivers interact and promote each other when affecting overall energy consumption
Song et al. (2019)	Decoupling relationship between metal consumption and economic growth	1997–2015	Structural decomposition analysis	Economic development and metal consumption show extended negative decoupling; capital formation is the primary driver of metal consumption, while the metal intensity and Leontief effect are potential forces to reduce metal use
Crompton and Wu (2005)	Forecasting China's energy consumption	1953–2003	Bayesian vector, autoregressive model	The total energy consumption increases slower than the average rate in the past decade. Slower economic growth and structural adjustment in the Chinese economy cause a decline in energy consumption
Zhang and Cheng (2009)	Energy use, carbon emissions, and economic growth in China	1960–2007	Granger causality	From economic growth to energy use and from energy consumption to carbon emissions, there is a Granger causality in the long run. However, neither carbon emissions nor energy use will lead to a GDP increase
Yang et al. (2020)	The change in carbon emissions from China's fossil energy consumption	2006–2018	LMDI	GDP and energy efficiency were the main factors affecting carbon emissions. Per capita GDP contributed the most to increase carbon emissions, while energy efficiency inhibited it
Chen et al. (2020)	The crucial driving forces of irrigation water use and its spatial change	2000–2015	Regression-PCA	Water use structure, irrigation technology, and planting structure are the crucial drivers in most regions in China. Irrigation technology, economic development, and annual rainfall decrease water consumption
Fan et al. (2017)	Urban water consumption and key drivers	2000–2015	Correlation analysis and random forest analysis	China's per capita daily water use is significantly influenced by meteorological forces, socio-economic status, water supply, and protection. Factors are different in high-, medium-, and low-use cities
Kong et al. (2021)	Decoupling economic growth from water consumption	2004–2017	Water footprint, Tapio decoupling model	The water footprint is positively affected by the economic level, urbanization rate, and industrial structure. Progressing water-saving technologies is the critical way to realize strong decoupling
Zhao and Chen (2014)	The agricultural water footprint	1990–2009	LMDI	The economic activity effect, the population-scale effect, and the diet structure effect positively increase water footprint growth, while water efficiency improvement has significantly decreased water footprint
Yao et al. (2019)	Decomposing temporal-spatial water intensity in Yangtze River Economic Zone	2000–2015	IDA-LMDI	Industrial water intensity and industrial structure have positive effects on the reduction of water resources. Reduction of water consumption occurs in the primary industry and secondary industry

thermal power generation production at the national zone. Although sustainable development for the single resource has widely attracted scholars' attention, research conducted on the heterogeneity and tradeoffs of driving forces on EW use from a national perspective is still relatively limited.

Due to the diversifications of the driving forces, scales, and data sectors (Ding et al. 2020), there is no single methodology suitable for whole research situations. Thus, the LMDI method, input-output analysis (IO), life-cycle assessment (LCA), and structural decomposition analysis (SDA) are the four main ways for explaining and evaluating China's energy-water use. IO research and LCA can help quantify the consumption flow processes of energy and water from an economic structure perspective. However, IO analysis and SDA highly rely on limited data sources such as IO tables, which is challenging to apply in statistical yearbook data research. LCA has been utilized in a single sector, for instance, the primary industry, while it has not been adopted in multi-sector research (Ding et al. 2020). To some extent, the LMDI method can easily capture the impacts of driving forces, such as economic growth, population, urbanization, and technology efficiency, on energy-water development research (Li et al. 2019a). Notably, more and more studies adopt the LMDI modeling to identify the various factors for energy-related water withdraws, CO_2 emissions, and food (Chen & Zhu 2019, Dong et al. 2019, Shi et al. 2019a, Wang & Li 2018). For example, Li et al. (2019a) revealed the economy-wide and sector-wide drivers of EW nexus changes through the LMDI method and found that various drivers showed a synergistic effect to increase or decrease Beijing's EW use. Hence, in this work, we utilize the LMDI model to uncover the influences of crucial driving forces on the sustainable energy-water development in China.

Since China is an enormous resource-consuming country, understanding the key drivers of energy-water consumption can help with resource management and sustainable supplement. Thus, it is essential to grasp how various drivers affect energy consumption and water use in Chinese change processes. In our work, we explore the overall effects of various driving forces on energy consumption and water use, thereby further capturing the changes of contributions in three periods. Specifically, we aim to process the heterogeneity of influencing factors and then utilize the LMDI method to calculate the coordinated contributions of five drivers on energy-water use, capturing the natural characteristics of the energy-water use from a national perspective. Based on existing studies, here, we explore sustainable energy-water development by calculating the proportion of various effects on energy consumption and water use in three time intervals, which is in line with Yang et al. (2018), Yang et al. (2019), and Li et al. (2019b). The tradeoffs and selections of crucial driving factors refer to Li et al. (2019b) and Alun et al. (2016). This study considers five driving forces to analyze the sustainable energy-water development from 2000 to 2017. This paper also answers how China's development processes feedback on energy-water development, including population and economic growth, industrial structure adjustment, and technological progress.

This study addresses sustainable energy-water use and their driving forces, and the significant contributions in the paper are four aspects. First, the study below extends the application of Kaya identity LMDI modeling by introducing five driving factors (i.e., energy/water intensity, industrial structure, GDP value-added, income improvement, and population scale). To our knowledge, this method has been increasingly used in the fields of environmental research but has not yet been adopted to capture the critical driving forces for EW use at the national level. Second, since the two resources' overall characteristics are not well captured in few studies, this paper analyzes the overall changing trend from a sectoral perspective and then explores the relationship. Third, when discussing the driving factors, most energy-water consumption studies have not considered their differences; thus, this study reveals the heterogeneity of driving forces by characterizing their contributions' changes in energy-water consumption in different time intervals that fill this gap. Finally, to move beyond the framework and main findings, this paper draws a clear framework to capture the energy-water features and related driving forces and processes a comparison of these factors' contributions, which could reference decision-making and policy setting in China's energy and water issues' sustainable management.

The rest of this paper is structured as follows. The "Methods and data sources" section depicts the framework of EW nexus analysis, methods, and data sources. The "Characteristics of energy consumption and water use in China" section conducts the characteristics and relationships of energy consumption and water use in China from sectoral perspectives. The developed LMDI model is then utilized to capture the characteristics and evaluate the contributions of five driving forces; the results and discussion are presented in the "Results and discussion" section. The "Conclusions and policy implications" section draws the main conclusions and provides policy implications.

Methods and data sources

Framework for capturing energy-water flows characteristics

Figure 1 presents the conceptual framework of capturing the energy-water flows and driving factors. Energy consumption and water use are interdependent. Energy is needed to secure, deliver, treat, and distribute water; water is required to develop, process, transport, and utilize energy (Scott et al. 2011). Various driving forces in this synergy process contribute to the changes in EW use. The driving forces in energy are decomposed into five parts: energy intensity effect (ΔE_EI), industrial structure effect (ΔE_S), GDP value-added effect (ΔE_G), income improvement effect (ΔE_Y), and population-scale effect (ΔE_P). Similarly, water intensity effect (ΔW_WI), industrial structure effect (ΔW_S), GDP value-added effect (ΔW_G), income improvement effect (ΔW_Y), and population-scale effect (ΔW_P) drive the variation of water use. On this basis, the contribution levels of different forces to energy consumption and water use, such as ΔI_E and ΔI_W and ΔP_E and ΔP_W, are calculated respectively. Accordingly, the fundamental driving forces that influence the alters of energy-water usage characteristics are captured.

Decomposition model

Decomposition of energy consumption and water use

This study employs Kaya identity to capture the effects of driving forces on sustainable energy and water use changes in China. Based on Kaya's identity, changes in energy use can be decomposed into five components: energy intensity (EI), industrial structure (S_i), GDP value added (G), income improvement (AVY_i), and population scale (P_i). The shift in energy consumption could be decomposed, and the impacts

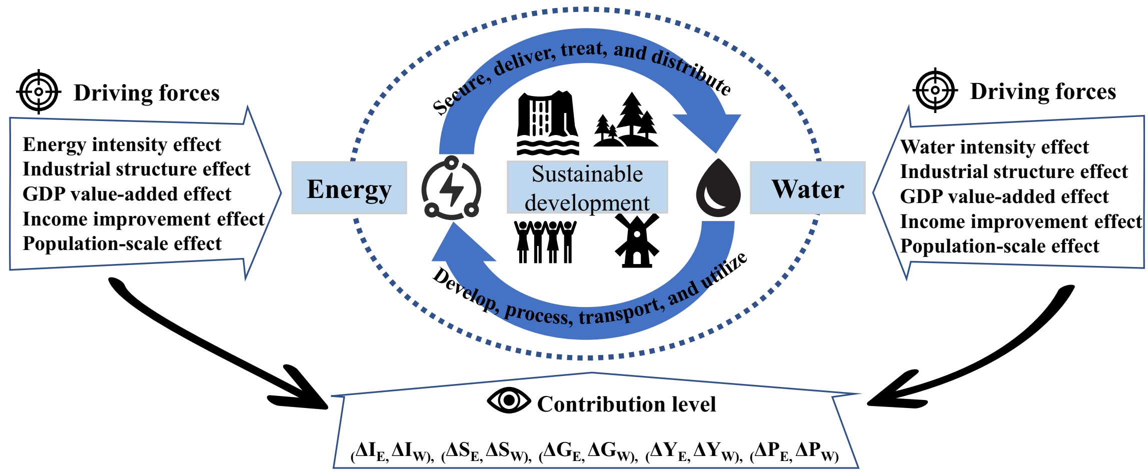


Fig. 1 The conceptual framework for processing the sustainable energy-water development and driving forces

of main driving effects are quantified with the following equations[1,2]:

$$E = \sum_{i=1}^{8} E_i = \sum_{i=1}^{7} \frac{E_i}{G_i} \cdot \frac{G_i}{G} \cdot G + \sum_{i=8} \frac{E_i}{Y_i} \cdot \frac{Y_i}{P_i} \cdot P_i = \sum_{i=1}^{7} EGI_i \cdot S_i \cdot G + \sum_{i=8} EYI_i \cdot AVY_i \cdot P_i \quad (1)$$

where i represents the subsector included in this study (i=1,2,…,8 for agriculture, mining, manufacturing, electric power, construction, transportation, other services, household[3]). In Eq. (1), E represents the total energy consumption; E_i represents the energy consumption by subsector i; G_i represents the industrial value added of subsector i; G represents the entire gross domestic product (GDP); Y_i represents the total disposable income; P_i represents the total population scale in China, indicating the effects of population-scale growth as a determinant for energy consumption, where i=8 denotes the household sector[4]. Moreover, $EI = EGI_i + EYI_i = \frac{E_i}{} G_i + \frac{E_i}{} Y_i$ denotes the energy intensity (technical advancement); $S_i = \frac{G_i}{G}$ denotes the ratio of the value added of various sectors in total GDP, named industrial structure; $AVY_i = \frac{Y_i}{} P_i$ denotes per capita disposable income, named income level. Adopting the additive LMDI method (Ang 2005, Ang 2015), the aggregate changes of energy use for an economy between the base year 0 and target year t can be decomposed into five driving forces: energy intensity effect (ΔE_EI), industrial structure effect (ΔE_S), GDP value-added effect (ΔE_G), income improvement effect (ΔE_Y), and population-scale effect (ΔE_P), as following Eq. (2).

$$\Delta E_{tot}^{(T-0)} = E^T - E^0 = \Delta E\_GI + \Delta E\_S + \Delta E\_G + \Delta E\_YI + \Delta E\_Y + \Delta E\_P \quad (2)$$

The impacts of various driving forces can be quantified as following Eqs. (3)–(8).

$$\Delta E\_GI = \sum_{i=1}^{7} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{EGI_i^T}{EGI_i^0}\right) \quad (3)$$

$$\Delta E\_S = \sum_{i=1}^{7} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{S_i^T}{S_i^0}\right) \quad (4)$$

[1] Energy (or water) consumption is different in the production and residential sectors; thus, it needs to be decomposed respectively when calculating. Specifically, the energy consumption in the production sectors mainly considers the energy consumed for economic activities, through energy intensity effect (ΔE _ GI), industrial structure effect (ΔE _ S), and GDP value-added effect (ΔE _ G), three determinants to measure. The energy consumption in the household sector is consumed to support residents' daily livings; thus, energy intensity effect (ΔE _ YI), income improvement effect (ΔE _ Y), and population-scale effect (ΔE _ P) are crucial components to capture human activities, which is consistent with *Li H, Lin J, Zhao Y, and Kang J-N (2019a): Identifying the driving factors of energy-water nexus in Beijing from both economy- and sector-wide perspectives. Journal of Cleaner Production 235, 1450-1464.*

[2] Due to the difference in energy consumption between the production sectors and the household sector, energy intensity (EI) in production sectors is $EGI_i = \frac{E_i}{} G_i$, representing energy intensity of production sector i, which can be decomposed as the share of energy consumption to value added of production sector i; however, energy intensity in residential sectors is $EYI_i = \frac{E_i}{} Y_i$, representing the energy intensity of the residential sector, which can be decomposed as the share of energy consumption to the per 1000 yuan disposable income of residential sector i. Thus, $EI = EGI_i + EYI_i = \frac{E_i}{} G_i + \frac{E_i}{} Y_i$ denotes the energy intensity. The above explains why the sum of Equation (1) changes from 8 to 7 then back to 8.

[3] Refer to the National Classification of Economic Activities (GB/T 4754-2017), i=1,2,…,7 in this study denotes seven production subsectors, including agriculture, mining, manufacturing, electric power, construction, transportation, and other services; i=8 denotes the household sector.

[4] The energy consumption in the production industries mainly considers the energy consumed for economic activities, and it is calculated by decomposing the industrial added value and GDP rather than population. Thus, the total population scale is decomposed in the household sector to capture resource consumption caused by population-scale growth, referring to Equation (8).

$$\Delta \text{E\_G} = \sum_{i=1}^{7} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{G^T}{G^0}\right) \tag{5}$$

$$\Delta \text{E\_YI} = \sum_{i=8} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{\text{EYI}_i^T}{\text{EYI}_i^0}\right) \tag{6}$$

$$\Delta \text{E\_Y} = \sum_{i=8} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{\text{AVY}_i^T}{\text{AVY}_i^0}\right) \tag{7}$$

$$\Delta \text{E\_P} = \sum_{i=8} L\left(E_i^T, E_i^0\right) \cdot \ln\left(\frac{P^T}{P^0}\right) \tag{8}$$

where $L\left(E_i^T, E_i^0\right) = \frac{E_i^T - E_i^0}{lnE_i^T - lnE_i^0}$ is the logarithmic mean weight.

Correspondingly, changes in water use can be decomposed, and the effects of determining forces are calculated with the following equations:

$$\begin{aligned} W &= \sum_{i=1}^{8} W_i \\ &= \sum_{i=1}^{7} \frac{W_i}{G_i} \cdot \frac{G_i}{G} \cdot G + \sum_{i=8} \frac{W_i}{Y_i} \cdot \frac{Y_i}{P_i} \cdot P_i \\ &= \sum_{i=1}^{7} \text{WGI}_i \cdot S_i \cdot G + \sum_{i=8} \text{WYI}_i \cdot \text{AVY}_i \cdot P_i \end{aligned} \tag{9}$$

$$\begin{aligned} \Delta W_{tot}^{(T-0)} &= W^T - W^0 \\ &= \Delta \text{W\_GI} + \Delta \text{W\_S} + \Delta \text{W\_G} + \Delta \text{W\_YI} + \Delta \text{W\_Y} + \Delta \text{W\_P} \end{aligned} \tag{10}$$

$$\Delta \text{W\_GI} = \sum_{i=1}^{7} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{\text{WGI}_i^T}{\text{WGI}_i^0}\right) \tag{11}$$

$$\Delta \text{W\_S} = \sum_{i=1}^{7} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{S_i^T}{S_i^0}\right) \tag{12}$$

$$\Delta \text{W\_G} = \sum_{i=1}^{7} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{G^T}{G^0}\right) \tag{13}$$

$$\Delta \text{W\_YI} = \sum_{i=8} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{\text{WYI}_i^T}{\text{WYI}_i^0}\right) \tag{14}$$

$$\Delta \text{W\_Y} = \sum_{i=8} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{\text{AVY}_i^T}{\text{AVY}_i^0}\right) \tag{15}$$

$$\Delta \text{W\_P} = \sum_{i=8} L\left(W_i^T, W_i^0\right) \cdot \ln\left(\frac{P^T}{P^0}\right) \tag{16}$$

where,

$$L\left(W_i^T, W_i^0\right) = \frac{W_i^T - W_i^0}{lnW_i^T - lnW_i^0} \tag{17}$$

$$\Delta \text{W\_WI} = \Delta \text{W\_GI} + \Delta \text{W\_YI} \tag{18}$$

Contributions of various drivers to energy-water use characteristics

The contribution degrees are computed in terms of the multiple factors and the change of energy consumption or water use to measure the impact of different driving forces on sustainable energy-water development. The contribution of various factors in energy consumption could be expressed by Eqs. (19)–(23).

$$\Delta I_E = \frac{\Delta \text{E\_EI}}{\Delta \text{E\_total}} \tag{19}$$

$$\Delta S_E = \frac{\Delta \text{E\_S}}{\Delta \text{E\_total}} \tag{20}$$

$$\Delta G_E = \frac{\Delta \text{E\_G}}{\Delta \text{E\_total}} \tag{21}$$

$$\Delta Y_E = \frac{\Delta \text{E\_Y}}{\Delta \text{E\_total}} \tag{22}$$

$$\Delta P_E = \frac{\Delta \text{E\_P}}{\Delta \text{E\_total}} \tag{23}$$

Correspondingly, the contribution of determining driving forces in water use can be expressed by the following equations:

$$\Delta I_W = \frac{\Delta \text{W\_WI}}{\Delta \text{W\_total}} \tag{24}$$

$$\Delta S_W = \frac{\Delta \text{W\_S}}{\Delta \text{W\_total}} \tag{25}$$

$$\Delta G_W = \frac{\Delta \text{W\_G}}{\Delta \text{W\_total}} \tag{26}$$

$$\Delta Y_W = \frac{\Delta \text{W\_Y}}{\Delta \text{W\_total}} \tag{27}$$

$$\Delta P_W = \frac{\Delta \text{W\_P}}{\Delta \text{W\_total}} \tag{28}$$

In this study, the dimensionless contribution degree of an individual force to EW use change can be coordinated to uncover its impact on EW use changes. For instance, the pair of ΔI_E and ΔI_W can be utilized to capture the effect of technological advancement on energy-water use, while the combination of ΔG_E and ΔG_W shows the effect of economic growth (i.e., GDP value added) on sustainable energy-water development.

Data sources

Annual data spanning from 2000 to 2017 is covered in this study. These data, including GDP, the value added of each subsector, disposable income, and population, are collected from *China Statistical Yearbook* (2001–2018) and the *China Population and Employment Statistical Yearbook* (2001–2018). All the economic data are converted to constant prices based on 2000. The energy consumption data is derived from the China Emission Accounts and Datasets (CEADs, 2000–2015 and 2016–2017) that are authoritative and accurate compared with other databases. The direct water withdrawal data, which is measured in m^3, is first collected from *China Environmental Statistics Yearbook* (CESY, 2018) and Fan et al. (2018) and then aggregated according to our research objectives.

Characteristics of energy consumption and water use in China

As a developing country, the Chinese economy is developing rapidly, and its economic aggregate is increasing during the twenty-first century. Before presenting the decomposition analysis results, it is necessary to analyze the general characteristics of EW use in China during this study period.

Overall energy consumption in China from a sectoral perspective

Figure 2 shows the sectoral energy consumption in China from 2000–2017. There are significant differences in energy consumption among various sectors. The total energy consumption perspective significantly grew from 1466.1 to 4485.2 Mtce over 2000–2017, with an annual growth rate of 6.9%. The changes in energy consumption underwent three stages: 2002–2006 was a rapid expansion period, with an average yearly growth rate of more than 8%; 2006–2012 was a steady growth stage; except for 2013, 2012–2017 was a retarded growth stage. During the set of 2000–2006, the growth rate of energy consumption pronouncedly increased from 2.1 to 8.6%, and the total energy consumption experienced a massive increase by 76.4% compared to the 2000 level. Notably, the highest sequential growth rate was in 2003, reaching 15.1%. In the second stage, energy consumption is increasing steadily, but the growth rate has dropped to 5.9%. Due to the continuous increase in energy conservation and emission reduction, the growth rate is gradually decreasing. When it exceeded 4000 Mtce with a grade of 14.4% in 2013, the total energy consumption tends to increase slowly. The growth rate of energy consumption appears a downward trend, but energy demand is still huge. The main reason is that the implementation of China's 12th Five-Year Plan has promoted economic growth mode transformation and improved the energy efficiency brought by technological progress.

In terms of the direct energy use in subsectors, agriculture, mining, manufacturing, power, construction, transport, and household are the seven main sectors, which had experienced an immediate increase in energy consumption from 2000 to 2017. Energy use in manufacturing and household sectors significantly increased from 807.7 Mtce and 167.0 Mtce in 2000 to 2451.4 Mtce and 576.2 Mtce in 2017. The corresponding average annual growth rates were 6.9% and 8.0%. The construction industry was extending the fastest, with a growth rate of 8.6%. China's investment-driven economic growth mode was accompanied by large-scale infrastructure construction, particularly after the *four trillion investment plan* was carried out in 2008 (China TSCo, 2008). This measure had resulted in a massive growth in energy consumption in the construction industry. The growth rates of energy use in transport, power, agriculture, mining, and other services were 8.2%, 6.0%, 5.1%, 3.1%, and 8.8%.

According to the contribution of various sectors, from 2000 to 2017, the manufacturing industry was the first energy consumer, with an average contribution rate of 57.1%. It was attributed to the high-speed development of the manufacturing scale after China accessed the WTO. Besides, the construction sector contributed the least, with a ratio of 1.6% on average. The contribution of energy consumption by sectors in 2000 was ranked as MFU, HOU, EGW, TRS, MIN, OSE, AGR, and CON and MFU, HOU, TRS, EGW, OSE, MIN, AGR, and CON in 2006 and 2012 and MFU, HOU, TRS, OSE, EGW, MIN, AGR, and CON in 2017, respectively. It indicates that manufacturing and household were the top two contributors, while the proportions of energy consumed by agriculture and construction sectors were relatively low during this study period. Notably, even though the secondary industry is still the leading energy consumer, the proportion of energy use in the tertiary industry has increased. After the *Twelfth Five-Year Plan*, not only has China optimized its consumption structure and improved the energy intensity of energy-sensitive sectors, but the share of the tertiary industry in the national economy has continued to grow. Furthermore,

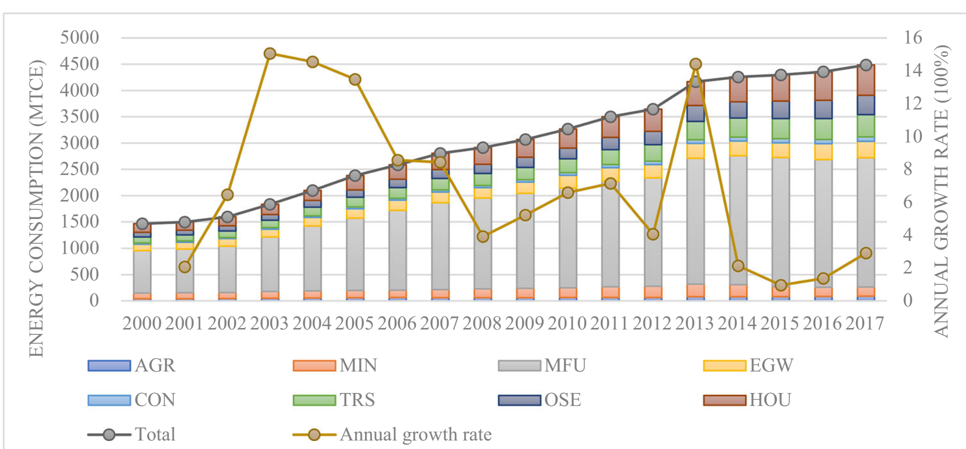


Fig. 2 Energy consumption in China during 2000–2017

the transport sector's contribution rose from 7.7% in 2000 to 8.2% in 2017. It was due to the rapid development of logistics demand, including storage and postal services.

Overall water use in China from a sectoral perspective

The results of sectoral water use from 2000 to 2017 are illustrated in Fig. 3. Unlike energy consumption, China's water use had only slightly increased, with an annual growth rate of only 0.4% and negative growth in some years. Water use in China has grown from 554.2 billion m^3 in 2000 to 578.6 billion m^3 in 2006 and 590.1 billion m^3 in 2017, which is far lower than the growth rate of energy consumption during the same time interval. 2004 was the year with the most insufficient water use, which was 524.9 billion m^3, a 4.7% decrease from 2003; on the contrary, the highest water consumption was recorded in 2013, reaching 607.7 billion m^3 during the study period.

The changes in water use experienced three different stages. During the 2001–2006 phase, water consumption was unstable. Since China joined the WTO in 2001, most industries with high water consumption had developed rapidly to pursue GDP growth, resulting in large amounts of water use. After 2006, the *11th Five-Year Plan* outlined a binding index for cutting down the water consumption per unit of industrial added value by 30%. During 2007–2013, the overall water withdrawal kept increasing. The main reason is the low utilization rate of industrial and agricultural water and the severe water waste for urban residents. At the stage of 2013–2017, the growth rate of water use was slow, and the total usage was relatively stable with a slight decline. The crucial driving forces are the urgent demand for upgrading the industrial structure, stricter environmental laws and regulations, and reducing the costs for potential resources or ecological crisis.

In terms of the water consumption by different sectors, agriculture accounted for the largest share, with over 64% on average, because China was a major agricultural producer and required large amounts of water for irrigation. The proportion of the secondary industry (including MIN, EGW, MFU, CON) was about 23% of total use, whereas the construction sector consumed less than 0.3%. The tertiary industry (including TRS, OSE, HOU) contributed 12.3% of full water use, and the household sector occupied almost 10–12% of consumption. Moreover, the transportation sector contributed less water use among the eight different sectors.

Regarding the changing trend of water use, the proportion of agricultural sectors was decreasing, and water use in the household sector kept increasing. The share of the agricultural sector declined from 68.4% in 2000 to 63.8% in 2017. The decline in freshwater withdrawal for the agriculture sector can be attributed to the changes in irrigation methods and water recycling. Correspondingly, the proportion of the household sector's water use increased from 9.8% in 2000 to 13.1% in 2017. The rapid development of industrial scale and service industries were the decisive factors for the growth of water demand in the tertiary industry. Also, the proportion of water used in the secondary industry increased first and then decreased, which reached 24.9% in 2006 and 22.0% in 2017. The government implemented measures to improve water use efficiency in the secondary industry after the *11th Five-Year Plan*, such as eliminating high water-consuming industries, adopting stepwise water prices, and utilizing reclaimed water.

Relationship of energy consumption and water use in China

The relationship between total energy consumption and water use is displayed in Fig. 4. From the perspective of overall consumption, both energy and water have increased from 2000 to 2017. Besides, the two resources maintain a similar change characteristic. During 2006–2012, the consumption of all two resources maintained a fast growth speed. After 2013,

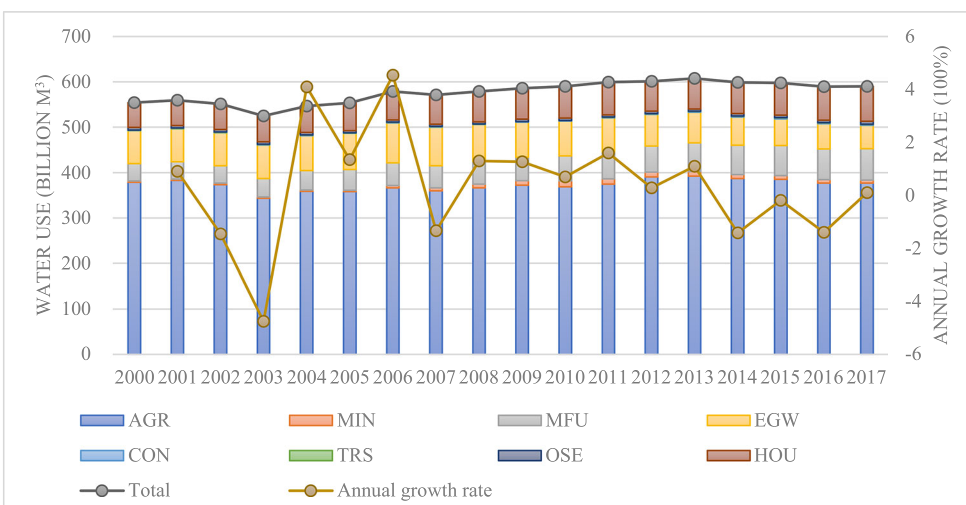


Fig. 3 Water use in China during 2000–2017

energy consumption slowed down, and water use showed a downward tendency, which should be achieved by implementing the *12th Five-Year Plan* to build an energy-saving and water-saving society.

Additionally, we performed a simple linear fitting to explore the EW relationship, and the results in Fig. 5 show that water use and energy consumption are highly positively correlated. Assuming that total energy consumption increases by 1 billion tce, the corresponding water use shall reach 538.17 billion m^3; conversely, when energy consumption appears negative or slow growth, water use will also drop accordingly. Thus, energy consumption limitations will help realize water use goals during the study period. Implementing energy policies will help achieve water conservation and contribute to the dual impacts on energy consumption and water use. In particular, it is critical to explore which factors drive sustainable EW management. The result is consistent with Alun et al. (2016). Furthermore, the influence of crucial driving forces on its characteristics will be in-depth discussed in the "Results and discussion" section.

Results and discussion

In this section, we explore the roles and uncover the reasons for various driving forces on China's sustainable energy-water development characteristics. The EW use can be characterized by decomposing the influences of crucial drivers on energy consumption and water use, consistent with Li et al. (2019b). First, we decomposed the quantity effects of five driving forces on energy consumption and water use. Next, the contributions of key driving forces were integrated together to capture their influences on sustainable energy-water development in three different time-intervals: 2000-2006, 2006-2012, and 2012-2017. Finally, the effect changes of every driving force in three different stages were further discussed.

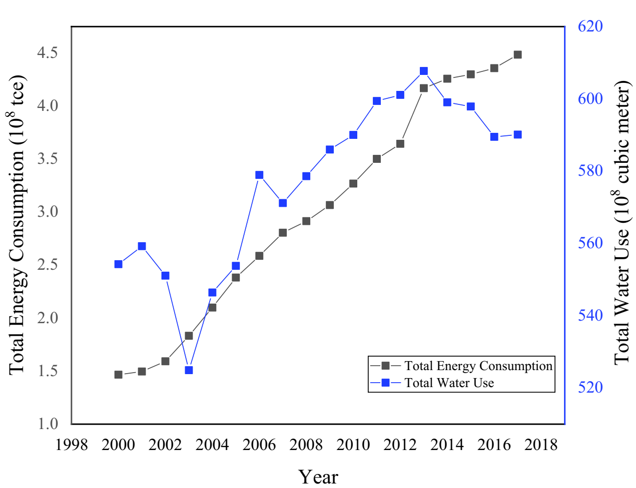


Fig. 4 The total energy consumption and water use

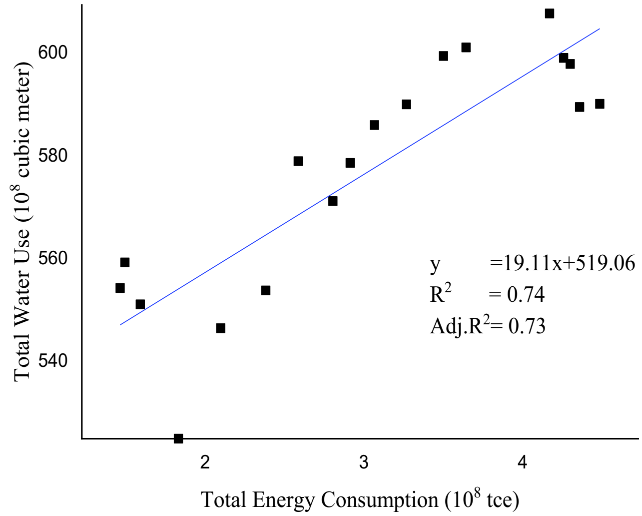


Fig. 5 Relationship of energy consumption and water use

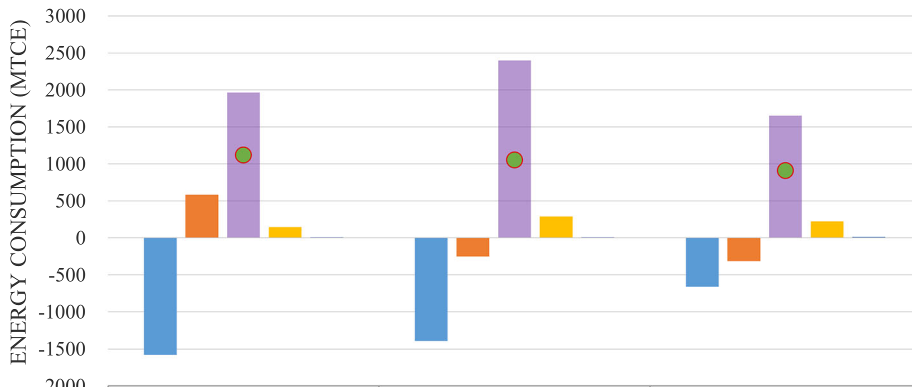
Effects of various driving forces on energy consumption and water use in China

Effects of five driving forces on energy consumption

Figure 6 shows the results of various driving forces on China's energy consumption from three periods: 2000–2006, 2006–2012, and 2012–2017. Energy consumption dropped from 1120.6 to 912.0 Mtce during the study period. We select five variables of ΔE_EI, ΔE_S, ΔE_G, ΔE_Y, and ΔE_P to measure their effects on energy consumption. The figure above shows that the maximum observed factor is ΔE_G, and the minimum is ΔE_P. In other words, GDP growth is the main factor in energy consumption increase. Because of the economic aggregate's fast growth in the twenty-first century, energy consumption had risen significantly from 1963.2 Mtce in 2000–2006 to 2399.0 Mtce in 2006–2012. After 2012, Chinese economic development had experienced a new normal, and the effect of ΔE_G has dropped to 1651.3 Mtce. However, it still contributes far higher than other factors. Notably, income improvement (ΔE_Y) has always positively affected energy consumption, although minor. The population-scale effect (ΔE_P) played a slightly positive role in energy consumption.

In contrast, the energy intensity effect (ΔE_EI) contributed the most to restrain energy consumption growth. It reduced energy use by 1579.0 Mtce in 2000–2006, 1389.8 Mtce in 2006–2012, and 660.5 Mtce in 2012–2017. It should be noted here that the energy intensity effect is declining year by year due to the adoption of energy conservation and emission reduction and the advancement of energy-related technologies. Fantastically, from 2000 to 2006, the industrial structure effect (ΔE_S) positively increased energy consumption to 583.7 Mtce, while it played a negative role after 2006, that is with −252.3 Mtce in 2006–2012 and −316.1 Mtce energy consumption in 2012–2017, respectively.

Fig. 6 Effects of various forces on China's energy consumption from three periods: 2000–2006, 2006–2012, and 2012–2017. Note: Abbreviation is defined as follows: ΔE_total represents the cumulative effect of five forces on energy consumption.



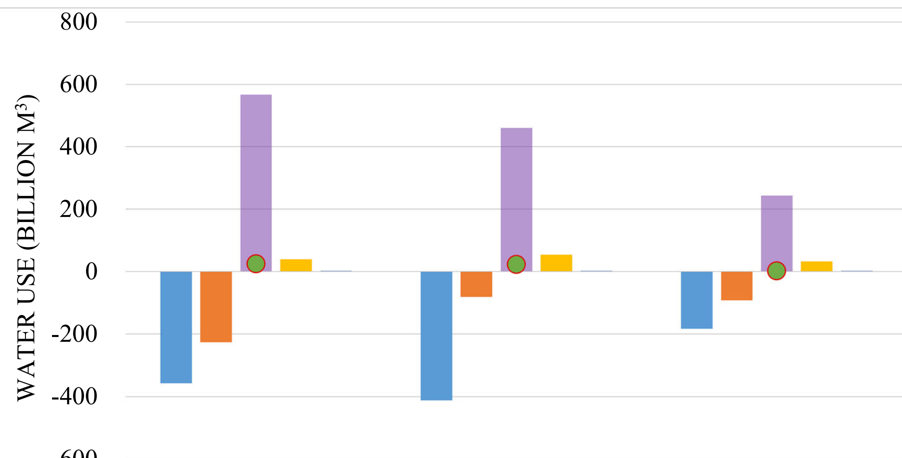
	2000-2006	2006-2012	2012-2017
ΔE_EI	-1579.0	-1389.8	-660.5
ΔE_S	583.7	-252.3	-316.1
ΔE_G	1963.2	2399.0	1651.3
ΔE_Y	144.5	289.7	223.1
ΔE_P	8.2	10.3	14.2
ΔE_total	1120.6	1057.0	912.0

Overall, from 2000 to 2006, 2006 to 2012, and 2012 to 2017, the cumulative effects of five factors (ΔE_total) on energy consumption reached 1120.0 Mtce, 1057.0 Mtce, and 912.0 Mtce, respectively. The cumulative effect positively increased energy use, but the contributions showed a decreasing tendency during the study period. In other words, various driving forces had varied roles in energy consumption. While the GDP value-added effect resulted in a significant increase in energy consumption, the energy intensity effect was the primary driving force to inhibit energy consumption. Other forces had comparatively minor effects on energy consumption in China during three time intervals (Tables 2, 3, 4, 5, and 6 in Appendix).

Effects of five driving forces on water use

The data intermissions are divided into three sub-intervals to capture the impacts of different driving forces on water use in China, and the results are presented in Fig. 7. From these results, GDP value-added effect (ΔW_G), income improvement

Fig. 7 Effects of various factors on water use in China from three periods: 2000–2006, 2006–2012, and 2012–2017. Note: Abbreviation is defined as follows: ΔW_total represents the cumulative effect of five forces on water use



	2000-2006	2006-2012	2012-2017
ΔW_WI	-357.5	-411.6	-183.9
ΔW_S	-226.5	-81.8	-91.7
ΔW_G	567.6	459.8	243.4
ΔW_Y	38.9	53.9	32.1
ΔW_P	2.2	1.9	2.0
ΔW_total	24.7	22.2	2.0

effect (ΔW_Y), and population-scale effect (ΔW_P) increase the water use, while water intensity effect (ΔW_WI) and industrial structure effect (ΔW_S) decrease the water use. The absolute value ordering of these five driving forces is ΔW_G>ΔW_WI>ΔW_S>ΔW_Y>ΔW_P.

Based on the decomposition results, the most influential driver of the increase in water use was ΔW_G, reaching 567.6 billion m^3 in 2000–2006, 459.8 billion m^3 in 2006–2012, and 243.4 billion m^3 in 2012–2017, respectively. Nevertheless, the effect of ΔW_G was going down because of the dropping of the annual economic growth rate. Simultaneously, the income improvement effect drove an additional demand for water use, reaching 38.9 billion m^3 in 2000–2006, 53.9 billion m^3 in 2006–2012, and 32.1 billion m^3 in 2012–2017. As China's population entered a steady growth stage, the population-scale effect is merely a minor effort to raise water use. Conversely, water use was significantly reduced by the water intensity effect. The composed water intensity effect decreased 357.5 billion m^3 in 2000–2006, 411.6 billion m^3 in 2006–2012, and 189.3 billion m^3 in 2012–2017. The industrial structure effect is another force for reducing water use, with 226.5 billion m^3 in 2000–2006 and 91.7 billion m^3 in 2012–2017. The absolute value of these two forces averaged 61.9 times the total effects, which directly show that both have

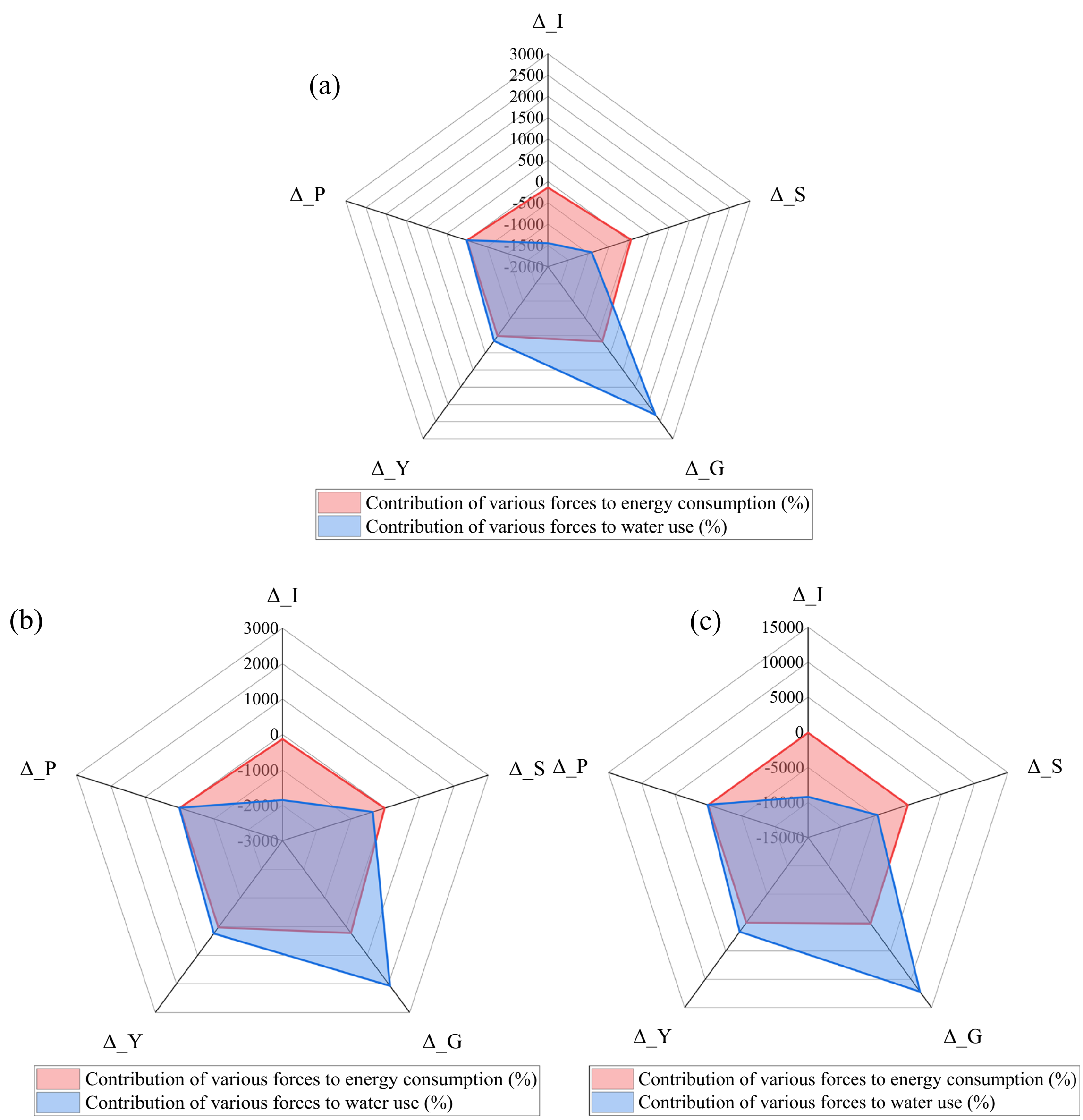


Fig. 8 **a** Contributions of various forces to the sustainable EW development from 2000 to 2006. **b** Contributions of various forces to the sustainable EW development from 2006 to 2012. **c** Contributions of various forces to the sustainable EW development from 2012 to 2017. Note: Abbreviations are defined as follows: Δ_G devotes to GDP value-added effect on total EW use; Δ_Y devotes to income improvement effect on total EW use; Δ_P devotes to population-scale effect on total EW use; Δ_S devotes to industrial structure effect on total EW use; Δ_I devotes to intensity (efficiency) effect on total EW use

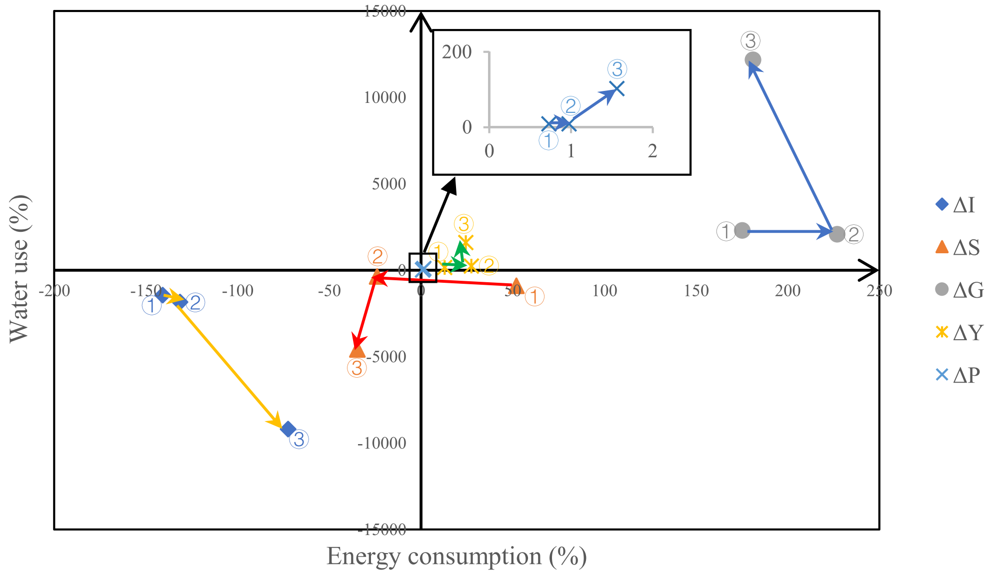


Fig. 9 Changes of five driving forces' contributions in three time intervals: 2000–2006, 2006–2012, and 2012–2017. Note: The numbers on this figure are defined as follows: ①, the first stage (2000–2006); ②, the second stage (2006–2012); and ③, the third stage (2012–2017)

inhibitory impacts on the increase in water consumption, but the contribution of ΔW_WI was more significant compared to ΔW_S. Thus, the water efficiency effect was the main driving factor for the decline in water needs.

Moreover, the total effect of the five driving forces was positive, which meant that the values of water intensity effect and industrial structure effect were lower than the contribution of GDP value added, income improvement, and population scale over the period. Notably, the actual value of the total effect was down rapidly from 24.7 to 2.0 billion m^3, with a decrease of 22.7 billion m^3, benefit from the industrial structure transformation and water use efficiency improvement.

Contributions of various driving forces to the changes of sustainable energy-water use

Contributions of various driving forces to sustainable EW use during 2000–2006, 2006–2012, and 2012–2017

The contributions of crucial driving forces on energy consumption and water use are united to capture their impacts on sustainable EW development in China. The study period is divided into three sub-intervals: 2000–2006, 2006–2012, and 2012–2017. According to Eqs. (19)–(28), the changes in EW use are decomposed into five driving forces, namely Δ_S, Δ_G, Δ_Y, Δ_P, and Δ_I; and the contribution ratios of determining forces on EW use are illustrated in Fig. 8.

During the 2000–2006 stage, the absolute value ordering of the contributions of these driving effects to energy consumption and water use was Δ_G>Δ_I>Δ_S>Δ_Y>Δ_P, as shown in Fig. 8a. It indicates that the contribution of various driving forces to energy consumption and water use kept a similar inclination. It means that the synergies of critical driving forces in energy conservation and water reduction occurred during the 2000–2006 stage. Notably, the increase of EW use was caused by the GDP-added value effect, income improvement effect, and population-scale effect, while energy/water intensity declined the energy and water use. Interestingly, Δ_S had positive[5] contributions to increase energy consumption but strongly negative to water use, 52.1% and −917.1%, respectively. However, the contribution degrees of driving forces varied significantly. Δ_G accounted for a large proportion of energy consumption growth of 175.2% and water consumption of 2298.2%, while ΔI significantly contributed to a 140.9% drop in energy consumption and 1447.4% water use. In other words, Δ_I was the only driving force that promoted the simultaneous decline of energy consumption and water use, thereby weakening the dependence of other factors on it. The contribution of Δ_P was relatively small as the contribution rates are 0.7% and 8.9%, respectively. Moreover, the contribution ratios of total forces to the increase in water use were much more extensive than energy consumption.

During the 2006–2012 time interval, Fig. 8 b displayed the contributions of different driving forces on EW use. Following these results, we found that Δ_G, Δ_Y, and Δ_P increased energy-water use, which enlarged the difference of dependence on it, while ΔI and ΔS played an essential role in decreasing EW use and weakened the dependence. As the contribution degrees of various forces remained in the exact effect directions, this explained the synergy of key drivers in energy-saving and water-saving. Primarily, increased energy and water use were mainly caused by Δ_G, with 227.0% for energy consumption and 2071.2% for water use, respectively; and Δ_I was still the primary force for energy-saving and water-saving, reaching −131.5% and −1854.2%, respectively.

[5] "Positive" in this section only represents "+" in mathematics and means greater than zero; similarly, "negative" represents "-" and means less than zero.

Table 2 Definition of variables in this study

Variable	Definition	Unit
E	The total energy consumption	Mtce
E_i	Energy consumption by sector i	Mtce
Gi	The industrial value added of production sector i	Billion yuan
G	GDP	Billion yuan
Y_i	Disposable income of household sector i	Billion yuan
P_i	The total population of China	Million persons
EI	Energy intensity	-
EGI_i	$EGI_i = E_i/G_i$, the share of energy consumption to value added of production sector i, representing energy intensity of production sector i	tce/1000 yuan
EYI_i	$EYI_i = E_i/Y_i$, the share of energy consumption to the disposable income of residential sector i, representing the energy intensity of residential sector i	tce/1000 yuan
S_i	$S_i = G_i/G$, the share of value added of sector i to GDP, representing the industrial structure	%
AVY_i	$AVY_i = Y_i/P_i$, per capita disposable income, denoting the income level of sector i	1000 yuan/person
$\Delta E_{tot}^{(T-0)}$	A total change of energy use during base year 0 to target year T	Mtce
ΔE_GI	Energy intensity effect, denoting the changes of energy consumption from energy efficiency improvement in the production sector	Mtce
ΔE_S	Industrial structure effect, denoting the changes of energy consumption from industrial structure adjustment	Mtce
ΔE_G	GDP value-added effect, denoting the changes of energy consumption from GDP	Mtce
ΔE_YI	Energy intensity effect, denoting the changes of energy consumption from energy efficiency improvement in the household sector	Mtce
ΔE_Y	Income improvement effect, denoting the changes of energy consumption from income improvement	Mtce
ΔE_P	Population-scale effect, denoting the changes of energy consumption from population expansion	Mtce
ΔP_W	Contribution ratios of population-scale effect to water use	%
W	The total water use	Million m^3
W_i	Water use by sector i	Million m^3
$\Delta W_{tot}^{(T-0)}$	A total change of water use during base year 0 to target year T	Million m^3
WGI_i	$WGI_i = W_i/G_i$, the share of water use to value added of production sector i, representing water intensity of production sector i	t/1000 yuan
WYI_i	$WYI_i = W_i/Y_i$, the share of water use to the disposable income of residential sector i, representing the water intensity of residential sector i	t/1000 yuan
ΔW_GI	Water intensity effect, denoting the changes of water use from water efficiency improvement in the production sector	Million m^3
ΔW_S	Industrial structure effect, denoting the changes of water use from industrial structure adjustment	Million m^3
ΔW_G	GDP value-added effect, denoting the changes of water use from GDP	Million m^3
ΔW_YI	Water intensity effect, denoting the changes of water use from water efficiency improvement in the household sector	Million m^3
ΔW_Y	Income improvement effect, denoting the changes of water use from income improvement	Million m^3
ΔW_P	Population-scale effect, denoting the changes in water use from population expansion	Million m^3
ΔI_E	Contribution ratios of energy intensity effect to energy consumption	%
ΔS_E	Contribution ratios of industrial structure effect to energy consumption	%
ΔG_E	Contribution ratios of GDP value-added effect to energy consumption	%
ΔY_E	Contribution ratios of income improvement effect to energy consumption	%
ΔP_E	Contribution ratios of population-scale effect to energy consumption	%
ΔI_W	Contribution ratios of water intensity effect to water use	%
ΔS_W	Contribution ratios of industrial structure effect to water use	%
ΔG_W	Contribution ratios of GDP value-added effect to water use	%
ΔY_W	Contribution ratios of income improvement effect to water use	%

Δ_P had a minor influence on energy and water use, consistent with the results from 2000 to 2006. Notably, Δ_S had transferred to reduce energy use, which was different from 2000 to 2006. The reason behind this was that through the utilization of high technology to transform traditional industries to establish a stable, economical, clean, and safe environmental protection system, the industrial structure is being upgraded during the *Eleventh Five-Year Plan* period, such as developing new fuel vehicles and exploring renewable energies.

During the decade of 2012–2017, the contribution of five driving forces to sustainable EW development was illustrated in Fig. 8c. The growth of energy consumption and water use was mainly attributed to Δ_G, reaching 181.1% and 12171.2%, respectively. As economic development entered the new normal, the promotion of Δ_G on water and energy use had declined, but it was still much higher than other driving forces' contribution. Δ_Y and Δ_P were other important forces to increase energy and water use. Conversely, Δ_I and Δ_S promoted the most to energy-saving and water-saving. This influence tendency was in line with the results in the 2006–2012 time interval. ΔI reduced significantly by 72.4% in energy consumption and 9193.3% in water use. As for Δ_S, EW use was also considerably decreased by 34.7% and 4586.7%, respectively. This sub-period in China's industrial structure was characterized by the integrated development of the modern service industry and advanced manufacturing and the elimination of backward production capacity (Chen et al. 2019). Moreover, covering the *Twelfth Five-Year Plan* period, the government proactively pointed that water use per unit of industrial value added should be down by 30% and that of energy consumption per unit of GDP should be down by 16%. These points explained that Δ_I and Δ_S brought about a considerable drop in water use.

Further discussion of five driving forces' changes in three time intervals

The influence changes of five driving forces that contribute to energy consumption and water use in three different stages are shown in Fig. 9. The points located in the first and third quadrants were the most, which showed that these factors had synergy influences on energy and water use. All of Δ_G, Δ_Y, and Δ_P occurred in the first quadrant, which meant increased energy consumption and water use during the study period. Conversely, points of Δ_I were located in the third quadrant, which shows a synergy on energy-saving and water-saving and weakened the dependence of other forces on the EW use at the same time. The effect directions of these factors were coordinated and synergistic, but different ratios of contributions characterized them. Notably, the first point of Δ_S had included in the fourth quadrant. This phenomenon meant that the industrial structure adjustment not only had the influence of synergistic energy-saving and water-saving but also generated the risk of conflicts during 2000–2006. In fact, China's economic structure has been gradually adjusted and optimized after 2006, so another two points were included in the third quadrant. In short, from the perspective of calculation results, the absolute value of these driving forces' contribution ratios affected much more water use than energy consumption. Because the positive effect of Δ_G on energy consumption was too large to be offset by other factors, the contributions of various factors on energy were relatively unobvious. Although both are declining, ΔW_total was much lower than ΔE_total because the growth rate of water use in China increased very slightly. For example, Δ_G contributed 12171.2% to water use during 2012–2017, but it was offset by Δ_I with 9193.3%. Thus, policymakers should pay more attention to energy conservation than water reduction.

Δ_G was the leading force in increasing the EW use, which meant all values were always positive. Notably, the effect on energy consumption was most evident in the second stage (2006–2012) than that of water use in the third stage (2012–2017). ΔY was the second promoting factor influencing sustainable energy-water development, and it kept coordinated development during the study period. Notably, the influence on water use increased year by year, while it is on energy reached the maximum in the second stage and stabilized in the third stage. The upgrading in living standards and infrastructure drove more consumption on energy-sensitive water supply facilities, such as shower, dishwasher, and swimming pool. Meanwhile, the high economic and income growth also drives people to pay more attention to the energy and water crisis. Thus, the government may implement local measures to encourage people to switch to a low-consumption lifestyle in the expected future.

Δ_P played a small role in contributing to the increase in energy consumption and water use, with its points in the first quadrant and near the origin. The improvement in living standards makes people consume more energy and water resources. Although the values were minimal, its role in water use was still larger than energy consumption. Hence, more measures should be taken to residents' domestic water consumption, and various policies should be adopted to develop daily water-saving habits, such as step water pricing mechanisms, purchase subsidies, and water-saving appliances. Future regulatory policies also need to guide and encourage energy and water conservation in residents' daily lives.

On the contrary, Δ_I was the primary determinant inhibitor resulting in energy-saving and water-saving. Its energy-saving effect gradually became smaller, and that of the water-saving was more extensive year by year. This result shows that water-saving technology progress is more remarkable than energy-saving and indicates that energy-saving is more challenging than water-saving tasks. It is necessary to increase the R&D investment and promotion of energy-saving technologies. Simultaneously, in technology evaluation and selection, priority should be given to the utilization of production technologies to realize energy-saving and water-receiving synergy. Thus, future regulation and control policies should focus on the R&D and adoption of energy-saving and water-saving production technologies.

More importantly, Δ_S had the hugest difference in the effects of EW use and was the main driving force to be weighed. It is evident that the effect of Δ_S on energy consumption was different from that of water use during 2000–

2006, which is not synergistic. It positively affects energy consumption and negatively affects water use because the previous industrial structure's adjustment process has a see-saw effect. The reduction in the proportion of high water-consuming sectors may cause an increase in high-energy-consuming sectors and vice versa. However, after 2006, Δ_S showed synergy with energy conversation and water reduction, and its contributions to water-saving were gradually increasing. Future adjustment of the industrial structure requires to wholly concern the tradeoff of energy and water conservation to keep a win-win goal.

Conclusions and policy implications

This study captures the contributions of five driving forces to sustainable energy-water development in China during 2000–2017. A theoretical framework is integrated to demonstrate the driving forces of EW use. The general characteristics of energy consumption and water use in China are investigated from the sectoral perspective, which may offer new directions to track environmental issues in specific sectors in future research. Then, five crucial driving forces, the EW intensity effect, industrial structure effect, GDP value-added effect, income improvement effect, and population-scale effect, were further identified by the LMDI model to explore their influences on the energy consumption and water use from three time intervals: 2000–2006, 2006–2012, and 2012–2017. Additionally, a comparison of their contributions in three differential time intervals was conducted to propose future measures.

The analysis in this study leads to four critical findings regarding the influences of driving forces above. These include the following: first, the total water use and energy consumption are highly positively correlated; the total energy consumption significantly increased, whereas manufacturing and construction sector was the most extensive and lowest energy consumer; the entire water use in China increased very slightly, while agriculture took up the largest share, but it kept a decreasing tendency during the study period. Second, the cumulative effects played an essential role in increasing energy consumption, but the contribution was dropping, while the GDP value-added effect led to a significant increase, and the energy intensity effect was the primary driving force to inhibit energy consumption. Third, the pooled effects of five factors on water use were positive but down drastically, whereas the most influential driving force of the increase in water use was GDP value-added effect, and water use was significantly reduced by the water intensity effect. Finally, these driving forces have a more prominent role in water use than that of energy consumption; GDP value-added effect, income improvement effect, and population-scale effect positively increased the EW use in the whole three time intervals; EW intensity effect inhibited and weakened the dependence of other forces on it; industrial structure effect led to some degree of the tradeoff between energy and water resources use during 2000–2006, and population-scale effect has the minor effect on EW use. Therefore, to achieve the national energy and water conservation targets, policymakers should pay more attention to energy conservation than water reduction, particularly technological progress and industrial structure optimization.

Based on the above conclusions, several potential policy recommendations to achieve the coordinated and sustainable development of energy and water resources in China can be proposed. First, the intensity/efficiency effect is the crucial driver responsible for EW use reduction. Therefore, reducing energy and intensity, especially in the production sectors, is critical to limiting energy-water use in China. The government needs to invest more R&D expenditures into encouraging scientific studies on improving the usage and conversion efficiency of energy and water. Besides, optimizing the water and energy structure in high resource-consuming industries is also vital to speed up building a more sustainable energy-water ecosystem. Second, the effectual adjustment of industrial structure to develop a low-carbon economy is still essential for achieving sustainable energy-water development. Since agriculture accounted for the significant share in China's water use, transferring from the high EW-consuming primary industry to the low EW-consuming secondary and tertiary industry will continue to play an essential role in reducing the energy-water pressure in developing countries. The government should encourage enterprises to adopt new energy-saving and water-saving products and eliminate old and high-energy-consuming industries. Finally, economic growth and income improvement are still the primary drivers of energy-water use. Thus, it is necessary to control the growth rate of end consumption and encourage green technology development to improve resource utilization. For production sectors, policymakers may link the switch to a more sustainable energy consumption development pattern and environment-friendly society with more job opportunities; for residential sectors, the government may implement local measures to encourage people to switch to a low-consumption lifestyle. For instance, the plastic ban leads consumers to select more environmentally friendly packaging. However, the population scale is not the main force that drives the increase of energy-water consumption, which indicates that the control of the population size would have minor effects on sustainable energy-water management.

Some limitations need to be broken through in future research. This study mainly focuses on the influence mechanism of energy consumption and water use in China, but the discussion on the coupling relationship between energy and water is not deep enough. The nexus mechanism in terms of how energy-water use interacts within sectors and countries should be identified for sustainable management resources. Furthermore, additional work will be conducted on the regional and sectoral perspectives, and more wide factors and resources' interaction may be discussed in our further research.

Appendix

Table 3 Contributions of various forces to the changes of total EW use from 2000 to 2006 (unit: %)

Driving forces	Contribution of various forces to energy consumption (%)	Contribution of various forces to water use (%)
Δ_I	−140.9	−1447.4
Δ_S	52.1	−917.1
Δ_G	175.2	2298.2
Δ_Y	12.9	157.4
Δ_P	0.7	8.9

Table 4 Contributions of various forces to the changes of total EW use from 2006 to 2012 (unit: %)

Driving forces	Contribution of various forces to energy consumption (%)	Contribution of various forces to water use (%)
Δ_I	−131.5	−1854.2
Δ_S	−23.9	−368.6
Δ_G	227.0	2071.2
Δ_Y	27.4	242.8
Δ_P	1.0	8.6

Table 5 Contributions of various forces to the changes of total EW use from 2012 to 2017 (unit: %)

Driving forces	Contribution of various forces to energy consumption (%)	Contribution of various forces to water use (%)
Δ_I	−72.4	−9193.3
Δ_S	−34.7	−4586.7
Δ_G	181.1	12171.2
Δ_Y	24.5	1604.8
Δ_P	1.6	102.5

Table 6 Changes of five driving forces' contributions in three time intervals: 2000–2006, 2006–2012, and 2012–2017 (unit: %)

Time interval	Δ_I	Δ_S	Δ_G	Δ_Y	Δ_P
2000–2006	(−140.9, −1447.4)	(52.1, −917.1)	(175.2, 2298.2)	(12.9, 157.4)	(0.7, 8.9)
2006–2012	(−131.5, −1854.2)	(−23.9, −368.6)	(227.0, 2071.2)	(27.4, 242.8)	(1.0, 8.6)
2012–2017	(−72.4, −9193.3)	(−34.7, −4586.7)	(181.1, 12171.2)	(24.5,1604.8)	(1.6, 102.5)

Acknowledgements Additional thanks are extended to editors and reviewers for their careful and constructive suggestions on this paper.

Author contribution Conceptualization, all authors; formal analysis, LW and WW; software, LW; supervision, EX; visualization, LW and ZW; writing—original draft, LW; writing—review and editing, all authors. All authors read and approved the final manuscript.

Funding This study was supported by the National Science Foundation of China (No. 71572012).

Data Availability The data analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Alun G, Fei T, Zhiqiang L (2016) Exploring the nexus between water saving and energy conservation: insights from industry sector during the 12th Five-Year Plan period in China. Renewable and Sustainable Energy Reviews 59:28–38. https://doi.org/10.1016/j.rser.2015.12.285

Ang BW (2005) The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33:867–871

Ang BW (2015) LMDI decomposition approach: a guide for implementation. Energy Policy 86:233–238

Arthur M, Liu GY, Hao Y, Zhang LX, Liang S, Asamoah EF, Lombardi GV (2019) Urban food-energy-water nexus indicators: a review. Resources Conservation and Recycling 151:104481

Bazilian M, Rogner H, Howells M, Hermann S, Arent D, Gielen D, Steduto P, Mueller A, Komor P, Tol RSJ (2011) Considering the energy, water and food nexus: towards an integrated modelling approach. Energy Policy 39:7896–7906

Chao Z, Lijin Z, Jiao W (2018) Decoupling between water use and thermoelectric power generation growth in China. Nature Energy 3: 792–799

Chen C, Zhao T, Yuan R, Kong Y (2019) A spatial-temporal decomposition analysis of China's carbon intensity from the economic perspective. Journal of Cleaner Production 215:557–569

Chen M, Luo Y, Shen Y, Han Z, Cui YJAWM (2020) Driving force analysis of irrigation water consumption using principal component regression analysis. 234:106089

Chen S, Chen B (2016) Urban energy–water nexus: a network perspective. Applied Energy 184:905–914

Chen S, Zhu F (2019) Unveiling key drivers of urban embodied and controlled carbon footprints. Applied Energy 235:835–845

China M (2020) Announcement on the release of the assessment results of the strictest water resources management system in 2019

China TSCo (2008) The executive meeting of the state council to study and deploy financial policies and measures to promote economic development

Crompton P, Wu YJ (2005) Energy consumption in China: past trends and future directions. 27, 195-208

Ding T, Liang L, Zhou K, Yang M, Wei Y (2020) Water-energy nexus: the origin, development and prospect. Ecological Modelling 419: 108943

Dong F, Yu B, Pan YJ (2019): Examining the synergistic effect of CO2 emissions on PM2. 5 emissions reduction: Evidence from China. 223, 759-771

Fan J-L, Kong L-S, Zhang X (2018) Synergetic effects of water and climate policy on energy-water nexus in China: a computable general equilibrium analysis. Energy Policy 123:308–317

Fan L, Gai L, Tong Y, Li RJ (2017): Urban water consumption and its influencing factors in China: evidence from 286 cities. 166, 124-133

Fang D, Chen B (2017) Linkage analysis for the water–energy nexus of city. Applied Energy 189:770–779

Fang D, Hao P, Yu Q, Wang JJAE (2020) The impacts of electricity consumption in China's key economic regions. 267, 115078

Fang D, Yu BJEP (2021): Driving mechanism and decoupling effect of PM2. 5 emissions: empirical evidence from China's industrial sector. 149, 112017

Gu A, Teng F, Wang Y (2014) China energy-water nexus: assessing the water-saving synergy effects of energy-saving policies during the eleventh Five-year Plan. Energy conversion and management 85: 630–637

Kahrl F, Roland-Holst D (2008) China's water–energy nexus. Water Policy 10:51–65

Kong Y, He W, Yuan L, Zhang Z, Gao X, Degefu DMJEI (2021) Decoupling economic growth from water consumption in the Yangtze River, China. Economic Belt 123:107344

Li H, Lin J, Zhao Y, Kang J-N (2019a) Identifying the driving factors of energy-water nexus in Beijing from both economy- and sector-wide perspectives. Journal of Cleaner Production 235:1450–1464

Li H, Lin J, Zhao Y, Kang J-N (2019b) Identifying the driving factors of energy-water nexus in Beijing from both economy- and sector-wide perspectives. Journal of Cleaner Production. 235:1450–1464

Li H, Zhao Y, Lin J (2019c) A review of the energy-carbon-water nexus: concepts, research focuses, mechanisms, and methodologies. Wiley Interdisciplinary Reviews-Energy and Environment

Li H, Zhao Y, Kang J, Wang S, Liu Y, Wang H (2020) Identifying sectoral energy-carbon-water nexus characteristics of China. Journal of Cleaner Production 249:119436

Liang Y, Liang S, Xu L, Feng C, Qi J, Yang X, Li Y, Li K, Li H, Yang Z (2020) Socioeconomic drivers of water withdrawals driven by provincial energy demand in China. Journal of Cleaner Production 120971

Liao X, Chai L, Ji J, Mi Z, Guan D, Zhao X (2019) Life-cycle water uses for energy consumption of Chinese households from 2002 to 2015. Journal of Environmental Management 231:989–995

Liu YF, Hu YC, Su MR, Meng FX, Dang Z, Lu GN (2020) Multiregional input-output analysis for energy-water nexus: a case study of Pearl River Delta urban agglomeration. Journal of Cleaner Production 262:121255

Schmidt JJ, Matthews N (2018) From state to system: financialization and the water-energy-food-climate nexus. Geoforum 91:151–159

Scott CA, Pierce SA, Pasqualetti MJ, Jones AL, Montz BE, Hoover JH (2011) Policy and institutional dimensions of the water–energy nexus. Energy Policy 39:6622–6630

Shi Y, Han B, Han L, Wei Z (2019a) Uncovering the national and regional household carbon emissions in China using temporal and spatial decomposition analysis models. Journal of Cleaner Production 232:966–979

Shi YY, Han BT, Zafar MW, Wei ZX (2019b) Uncovering the driving forces of carbon dioxide emissions in Chinese manufacturing industry: an intersectoral analysis. Environmental Science and Pollution Research 26:31434–31448

Siddiqi A, Anadon LD (2011) The water-energy nexus in Middle East and North Africa. Energy Policy 39:4529–4540

Song Y, Huang J, Zhang Y, Wang ZJRP (2019) Drivers of metal consumption in China: an input-output structural decomposition analysis. 63, 101421

Wang C, Li P, Liu Y (2018) Investigation of water-energy-emission nexus of air pollution control of the coal-fired power industry: a case study of Beijing-Tianjin-Hebei region, China. Energy Policy 115: 291–301

Wang Q, Jiang X-t, Yang X, Ge SJ (2020) Comparative analysis of drivers of energy consumption in China, the USA and India–a perspective from stratified heterogeneity. 698, 134117

Wang S, Li R (2018) Toward the coordinated sustainable development of urban water resource use and economic growth: an empirical analysis of Tianjin City, China. Sustainability 10:1323

Xiang X, Jia S (2019) China's water-energy nexus: assessment of water-related energy use. Resources, Conservation and Recycling 144:32–38

Yang P, Liang X, Drohan PJJES, Research P (2020) Using Kaya and LMDI models to analyze carbon emissions from the energy consumption in China. 27, 26495-26501

Yang X, Yi S, Qu S, Wang R, Wang Y, Xu M (2019) Key transmission sectors of energy-water-carbon nexus pressures in Shanghai, China. Journal of Cleaner Production 225:27–35

Yang XC, Wang YT, Sun MX, Wang RQ, Zheng PM (2018) Exploring the environmental pressures in urban sectors: an energy-water-carbon nexus perspective. Applied Energy 228:2298–2307

Yao L, Xu J, Zhang L, Pang Q, Zhang CJSCI, Systems (2019): Temporal-spatial decomposition computing of regional water intensity for Yangtze River Economic Zone in China based on LMDI model. 21, 119-128

Yu B, Fang D, Dong FJE (2020): Study on the evolution of thermal power generation and its nexus with economic growth: evidence from EU regions. 205, 118053

Yu B, Fang DJEI (2021) Decoupling economic growth from energy-related PM2. 5 emissions in China: a GDIM-based indicator decomposition. 127, 107795

Zhang C, Anadon LD (2013) Life cycle water use of energy production and its environmental impacts in China. Environmental Science & Technology 47:14459–14467

Zhang PP, Zhang LX, Chang Y, Xu M, Hao Y, Liang S, Liu GY, Yang ZF, Wang C (2019) Food-energy-water (FEW) nexus for urban sustainability: a comprehensive review. Resources Conservation and Recycling 142:215–224

Zhang X-P, Cheng X-M (2009): Energy consumption, carbon emissions, and economic growth in China. 68, 2706-2712

Zhao C, Chen BJ (2014) Driving force analysis of the agricultural water footprint in China based on the LMDI method. 48, 12723-12731