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Interactions of energy technology development and new energy exploitation with water technology development in China

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ABSTRACT

Interactions of energy policies with water technology development in China are investigated using a hybrid input-output model and scenario analysis. The implementation of energy policies and water technology development can produce co-benefits for each other. Water saving potential of energy technology development is much larger than that of new energy exploitation. From the viewpoint of proportions of water saving co-benefits of energy policies, energy sectors benefit the most. From the viewpoint of proportions of energy saving and CO_2 mitigation co-benefits of water technology development, water sector benefits the most. Moreover, economic sectors are classified into four categories concerning co-benefits on water saving, energy saving and CO_2 mitigation. Sectors in categories 1 and 2 have big direct co-benefits. Thus, they can take additional responsibility for water and energy saving and CO_2 mitigation. If China implements life cycle materials management, sectors in category 3 can also take additional responsibility for water and energy saving and CO_2 mitigation. Sectors in category 4 have few co-benefits from both direct and accumulative perspectives. Thus, putting additional responsibility on sectors in category 4 might produce pressure for their economic development.

1. Introduction

China is currently one of the world's largest energy consumers and carbon dioxide (CO_2) emitters. China's energy demands and CO_2 emissions are expected to keep growing in future [1]. Energy-related CO_2 emissions are mains reasons for global climate changes. In addition, water shortage is a big problem for Chinese regions [2–4]. Thus, China established targets for reducing energy and water demands in the eleventh and twelfth five-year plans. CO_2 mitigation is also considered in China's twelfth five-year plan. Policies such as industrial structure changes, energy technology development, new energy exploitation and water technology development are proposed to achieve these targets.

Along with intensified attention on global climate changes, lots of studies on energy conservation and CO_2 mitigation in China are conducted. China's energy intensity fluctuation is mainly due to technology development and industrial structure changes [5,6] and partly due to the heterogeneity and imperfect substitutability among various energy types during the last decade [7]. Economic growth have resulted in high energy demands, while technology development contributes to energy saving [8–10]. Moreover, China's accelerated marketization has greatly contributed to energy efficiency improvement since 1993 [11]. In order to deal with energy shortage, China's energy demands must follow a sustainable way to coordinate the economy growth, social development, and environmental protection [12], which may need a life cycle viewpoint of the whole society [13]. For the improvement of energy efficiency, China should reduce coal demands and increase coal efficiency as well as upgrade economic structure [14]. Moreover, China's urbanization process should be optimized to reduce energy demands [15]. China should also deepen energy-pricing mechanism reform and increase energy prices reasonably, as higher energy prices will decrease industrial energy consumption without reducing economic outputs in the long run [16].

In addition, the decline in energy-related CO_2 emissions and CO_2 intensity is mainly caused by technology development [17–23], while economic growth contributes the most to increased CO_2 emissions [19,21–24]. Moreover, China has large potentials of reducing CO_2 emissions by improving technical levels of production and consumption systems [25]. Low-carbon development policies, such as building management system for CO_2 reduction and mastering core technologies for exploiting renewable energy sources, should be enhanced [26,27]. China should also optimize the structure of final demands [20].

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Water is also a strategic resource for socioeconomic development. There are interactions between water resource and energy sources. Thus, water-energy nexus are studied to save energy and water resources simultaneously. Energy demands of water supply and water reuse are analyzed [28–30], and water demands for energy production are also investigated [30]. In addition, energy can be recovered in wastewater treatment to achieve sustainable water cycle [31,32].

Current studies on interactions between energy and water sources mainly focus on energy production, water supply and reuse and wastewater treatment activities. Economic sectors connect with one another through input–output relations [33]. Energy technology development in a particular sector can influence the production of other sectors that have relationships with it. Furthermore, changes in the production of sectors will influence their water demands. Thus, not only energy production but also energy demands of other sectors will influence water demands of the whole economy. Similarly, not only water production but also water demands of other sectors have impacts on the whole economy's energy demands and CO_2 emissions. Impacts of other sectors' water and energy demands on the whole economy's energy and water demands, however, are not considered. Investigating impacts of each sector's energy technology development and energy structure changes on water demands of the whole economy and impacts of each sector's water technology development on energy demands and CO_2 emissions of the whole economy can contribute to the reduction of energy and water demands and CO_2 emissions simultaneously, providing information for decision makers. Thus, this study mainly contributes to analyzing interactions of energy technology development and new energy exploitation with water technology development in China.

2. Methodology

Input–output (IO) models can capture input-output relations among economic sectors [33]. Technology development and material consumption structure changes are indicated by changes of direct requirement matrix and pollutant emission intensity of input-output models. Adjusting direct requirement matrix of traditional monetary input-output model is complicated, due to the interference of sector prices [34]. The physical input-output model can describe the physical reality of the economy [35], and its direct requirement matrix can be easily adjusted to reflect technology development of resource utilization. The compilation of physical input-output model, however, is a challenging job [36], due to its large data demands. Thus, a hybrid input-output (HIO) model is used in this study.

Assume that the economic system contains n categories of sectors. Rows representing m energy sectors are expressed in energy units, and rows representing k water sectors are expressed in mass units. Moreover, rows representing the other $(n - m - k)$ sectors are expressed in monetary units.

Each sector's total outputs equal to the sum of its intermediate deliveries and final demands. Calculations of direct requirement matrix $\boldsymbol{A}$, Leontief inverse matrix $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ and total requirement matrix $\boldsymbol{B}$=$(\boldsymbol{I} - \boldsymbol{A})^{-1}$−$\boldsymbol{I}$ in the HIO model are described in Miller and Blair's studies [37]. $\boldsymbol{I}$ is a $n \times n$ identity matrix. Let $\boldsymbol{x}$, a $n \times 1$ column vector, represent each sector's total outputs, direct and accumulative energy and water inputs required to produce total outputs can be expressed by equation (1).

$$\begin{aligned} \text{Direct inputs} &= A\hat{x} \\ \text{Accumulative inputs} &= \left[(I-A)^{-1} - I\right]\hat{x} \end{aligned} \tag{1}$$

where $\hat{x}$ indicates the diagonal matrix for $\boldsymbol{x}$.

CO_2 emissions are treated as physical multipliers of the intermediate delivery matrix. Let the matrix $\boldsymbol{E} = (e_j)_{1\times n}$ indicate each sector's CO_2 emission intensity per unit total outputs. Direct and accumulative CO_2 emissions can be calculated by equation (2).

$$\begin{aligned} \text{Direct emissions} &= E\hat{x} \\ \text{Accumulative emissions} &= E(I-A)^{-1}\hat{x} \end{aligned} \tag{2}$$

According to balances of the HIO model (as shown in equation (3)), we can calculate each sector's total outputs $\boldsymbol{x}$ (a column vector) and each sector's CO_2 emissions (a row vector) $\boldsymbol{c}$, when each sector's final demands $\boldsymbol{y}$ (a column vector) and technology development are known. Technology development is illustrated by changes in elements of direct requirement matrix and pollutant emission intensity matrix.

$$\begin{aligned} x &= (I-A)^{-1}y \\ c &= E(I-A)^{-1}\hat{y} \end{aligned} \tag{3}$$

where the matrix $\hat{y}$ indicates the diagonal matrix for $\boldsymbol{y}$.

Before applying the IO model for the prediction of future possibilities, we must carry out both behavior and structural validity of the IO model.

The behavior validity mainly aims to compare the model-generated behavior with the observed behavior of the real system [38,39]. There are already many studies using the IO models for predictions. For instance, Klafszky discussed the theoretical prediction of the IO model [40]. Studies on input-output predictions for the Netherlands [41–44] and the United States [45] are conducted. Moreover, Xu and co-authors predicted China's future material metabolism possibilities using the IO model [46]. Liang and co-authors used the IO model to predict future material metabolism in cities and industrial parks [47–49]. In addition, Bezdez and Shapiro tested the accuracy of input-output forecasts [50]. The IO model is found to perform as well as and usually better than any of alternative forecasting techniques considered [50]. Thus, Bezdez and Shapiro's study has proved the behavior validity of the IO model.

For the structural validity of the IO model, we use the method proposed by Qudrat-Ullah and Seong [38]. (1) Boundary adequacy: The IO model aims to calculate total outputs, resource demands and pollutant emissions according to final demand changes and technology development. Final demands (the column vector $\boldsymbol{y}$), technical levels (the matrix $\boldsymbol{A}$ and the matrix $\boldsymbol{E}$), total outputs (the column vector $\boldsymbol{x}$), resource demands (elements in the intermediate delivery matrix $\boldsymbol{Z}$ of the IO model) and pollutant emissions (the row vector $\boldsymbol{c}$) are all endogenous to the model. (2) Structure verification: The structure of the IO model is consistent with relevant descriptive knowledge of the economy. The economy comprises production and consumption (which is final demand) activities. Production activities correspond to the intermediate delivery matrix $\boldsymbol{Z}$ of the IO model, and consumption activities correspond to final demands (the column vector $\boldsymbol{y}$) of the IO model. (3) Dimensional consistency: Each equation in the IO model dimensionally corresponds to the real system. The main equations of the IO model describe its row balances. Elements in rows representing energy and water sectors are all described in physical units, while elements in rows representing the other sectors are all described in monetary units. (4) Parameter verification: Parameters describing final demand changes are estimated according to published data and documents of Chinese government, parameters describing technology development are calculated according to sector cleaner production standards of China. (5) Extreme conditions: The IO model exhibits a logical behavior when final demand changes and technology development are assigned extreme values. For instance, if