Energy-Water Nexus Analysis Based on Input-Output Model: A Case Study of Fujian Province, China

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Abstract: Energy and water are inextricably linked to each other. In this study, an input-output model (IOM) is advanced to analyze the consumption relationship between various energy-related water and water-related energy. IOM can not only confirm the mixture energy consumption and mixture water consumption, but also reflect the mixture energy and mixture water flow between sectors. Our major findings are: (i) Man (manufacture) is the main sector in terms of direct energy and water consumption; (ii) Agr (Agriculture) is the dominant direct water dedicator and Psp (Production and supply of electric, heating and gas) is the highest energy-related water consumption sector; (iii) energy consumption in water extraction processes is greatest (reaching up to 88.97%); (iv) water consumption of hydroelectric, thermal, nuclear and other forms of power generation is the heaviest consumption (reaching up to 96.52%); (v) Man (manufacture) is the main energy outflow and inflow sector (outflow: 2.01×10¹¹ kwh, inflow: 2.56×10¹¹ kwh); (vi) Agr is the largest provider of mixture water (outflow: 7.55×10⁹ m³), Man (manufacture) is the largest receiver of mixture water sector (inflow: 9.88×10⁹ m³).

1. Introduction

Water and energy are important material for human survival, economic development, and social progress, and they are inextricably linked; with the growth of population and rapid urbanization, water and energy consumption have greatly increased [1]. Fujian Province not only is the starting point of the historical Maritime Silk Road, but also is a distribution centre of maritime commerce. The consumption of energy and water is huge, nowadays, there is still a lack of separate analysis on the study of the relationship between energy and water in Fujian Province.

Water resource system is a complex system which consist of interconnected water resources in various water bodies within a certain time and space range. And energy from the development to the use of the process, through the production of energy, transport, processing, conversion, storage, distribution, and many other links [2]. There are dependencies, constraints and synergies between water and energy [3]. In nature, water forms a natural water cycle under the action of natural forces such as solar precipitation energy [4]. In order to make water resources fully meet the needs of production, life and economic development, water is in constant motion within the hydrosphere, connecting individual bodies of water. The natural water cycle that forms allow for the permanent existence, constant renewal, and dynamic adjustment of water bodies [6].

Input-output model (IOM) has been widely applied to energy and water research. IOM reflects the relationship between different sectors through the input-output relationship, which can be used to calculate the implied resource consumption generated by the whole national economic system. For
example, Zheng et al. used IOM to study Chongqing’s water resources management policy from producer and consumer[6]. Zhang et al. used a method that combined IOM and factorial analysis to identify crucial sectors in Kyrgyzstan, which also can measure the influence of virtual water metabolism network [7]. In addition, Liu et al. also explored an extended IOM method to study the life-cycle environmental impacts of different sectors in Saskatchewan, Canada[9]. Liu et al. set an assessment framework of water-energy nexus for virtual and embodied energy[9].

The aim of study is to explore the key sectors that are high consumption of mixture energy and water consumption in Fujian Province. The model can provide policy makers with sector-oriented suggestions for energy conservation and water saving.

2. Methodology
First, direct energy and water consumption across sectors is calculated that based on the type of energy and water. Energy is divided into coal, oil, natural gas, heat, electricity, and other energy sources that based on the energy balance table. Water resources consist of agricultural water, industrial water, construction water and tertiary industry water usage according to sector classification.

\[ F_i^e = \sum_{k=1}^{s} e_{ik} \]  
\[ F_i^w = \sum_{k=1}^{s} w_{ik} \]  

Where the direct energy consumption of sector \( i \) represents \( F_i^e \), the \( k \) direct energy consumption of sector \( i \) represents \( e_{ik} \); the direct water consumption of sector \( i \) represents \( F_i^w \), the \( k \) direct energy consumption of sector \( i \) represents \( w_{ik} \). According to the water cycle process, the mixture energy consists of 5 parts, issue concerning water, the mixture water consists of 4 parts. There is the calculation process as follows:

\[ e_{i\text{ nexus}} = e_{i\text{ wax}} + e_{i\text{ wsx}} + e_{i\text{ web}} + e_{i\text{ wtx}} \]  
\[ w_{i\text{ nexus}} = w_{i\text{ cox}} + w_{i\text{ ox}} + w_{i\text{ oxy}} + w_{i\text{ oxy}} \]  

Where \( e_{i\text{ nexus}} \) is the water-related energy of sector \( i \), \( e_{i\text{ nexus}} \) is the energy consumption in water intake process of sector \( i \), the energy consumption of water supply and distribution process represents \( e_{i\text{ wsx}} \), the energy consumption of water use process represents \( e_{i\text{ wtx}} \), the energy consumption in wastewater treatment; where the energy-related water of sector \( i \) represents \( w_{i\text{ nexus}} \), the water consumption in oil represents \( w_{i\text{ ox}} \), the water consumption in coal of sector \( i \) represents \( w_{i\text{ cox}} \), the water consumption in oil represents \( w_{i\text{ ox}} \), \( w_{i\text{ electric}} \) is the water consumption in electric.

\[ e_{i\text{ total}} = F_i^e + e_{i\text{ nexus}} \]  
\[ w_{i\text{ total}} = F_i^w + w_{i\text{ nexus}} \]  

Where the mixture energy of sector \( i \) represents \( e_{i\text{ total}} \), the energy-related water of sector \( i \) represents \( w_{i\text{ total}} \). Due to the differences in the expression units of each energy, all energy units are unified for kwh in order to unify the calculation.

The total water and energy consumption of each sector combined with the intensity of water and energy based on the economic input-output table, all economic flows are transformed into energy and water flows, and the final use of energy and water is also obtained. The energy and water intensity

Calculation equation is as follows:

\[ \varepsilon = E(U - H)^{-1} \]  

In the formula, \( \varepsilon \) is the energy(water) intensity, \( \varepsilon = [\varepsilon_{ij}]_{n \times n} \) represents \( n \) sectors. \( E \) is energy(water) consumption by sector, \( E=[E_{ij}]_{n \times n}; U=[u_{ij}] \), when \( i = j, U_{ij} = x_j \), else \( U_{ij} = 0; H \) is the economic value flow matrix. \( H=[h_{ij}]_{n \times n}, h_{ij}=x_{ij}, x_{ij} \) represents the economic investment of sector \( i \) in sector \( j \).
3. Case study

3.1. Study area
Fujian Province is located in Southeast China, which occupy 124,000 square kilometres in total land area. According to the National Bureau of Statistics in 2017, the gross domestic product (GDP) of Fujian Province reaches 321.82 billion yuan, which ranks tenth in the country; the energy consumption reaches 12.89 million tce. Among them, raw coal consumption accounts for 45.90%. There is 19.20 billion m³ of total water consumption, which takes up 3.18% of the total national water consumption. Among them, agricultural water consumption takes up 47.52% of the total water consumption, industrial water consumption accounts for 33.53%, thermal and nuclear power water consumption accounts for 5.52%. The water of coal, oil and natural gas production and supply is less consumption. Similarly, water extraction and use are inseparable from the energy consumption. Therefore, the study of water-energy relationship is more conducive to local resource management.

3.2. Data sources
This data is composed of four parts: (i) the input-output table of Fujian Province in 2017 is from the National Bureau of Statistics of China; (ii) direct energy consumption data from China Energy Statistics Yearbook; (iii) direct water data from China Environmental Statistics Yearbook; (iv) Water-related energy intensity and energy-related water intensity data from literature[10]. According to the energy balance table, the original Input-output table has 42 sectors, they are divided into 9 sectors, including: agriculture (Agr); mining (Min); manufacturing (Man); production and supply of power, electricity, and heat (Psp); water supply (Wa); construction (Con); transport (Tr); wholesale food (Wh) and service (Se).

4. Result and Discuss

4.1. Energy consumption and water consumption
Figure 1 shows the direct energy and water consumption in Fujian Province in 2017. The results show that the largest direct energy is consumed by Man (266.51×10⁹ kwh); Psp is the second direct energy-consumption sector (125.89×10⁹ kwh); Se is the third energy-consumption sector (20.84×10⁹ kwh). According to water-related energy consumption, Man consumes the most energy (1.53×10⁹ kwh), Se is the second energy-consumption sector (0.85×10⁹ kwh); The third water-related energy consumption is consumed by Con (0.23×10⁹ kwh). The ranking of energy consumption is the same as that of GDP. This shows that there is a positive correlation between energy and GDP growth. Therefore, in order to maximize the energy saving effect, Fujian Province should not only pay attention to Man, Psp and Se, which have the largest direct energy consumption, and Man, Se and Con, who consumes the most water.

Figure 2 indicates the consumption of energy-related water and direct water in Fujian Province in 2017. The results show that the largest water consumption is Agr (91.25 × 10⁶ m³); Se is the second direct water-consumption sector (32.78 × 10⁶ m³); Tr is the third water-consumption sector (23.76 ×10⁶ m³); Psp is the highest water consumption (5.25 × 10⁶ m³); Different from other provinces, Se has become the second largest water consumption sector in Fujian Province, the main reason is that tourism in service industry is one of the economic sources of Fujian Province. Based on energy-related water consumption, Man is the highest water consumption (3.15×10⁶ m³); Se becomes the second high water-consumption sector (1.58×10⁶ m³). In short, in terms of water saving, Agr and Se are the most potential water saving sectors, followed by Tr; the emphasis of water saving sector is Psp, Man, Se.
4.2. Proportion of different types of water-related energy and energy-related water

Figure 3 shows the proportion of various types of water consumption. The energy consumption of water consumption process accounts for 88.97%, energy consumption of water intake process is the most, which includes the energy consumption of domestic water, agricultural water and industrial water. Energy consumption for water supply and distribution accounts for 7.63%, energy consumption in water extraction process accounts for 2.53%, and energy consumption of wastewater treatment process accounts for 0.87%.

Figure 4 shows the proportion of various types of water consumption. As the follow picture can be seen from the figure, energy-related water 3 represents water consumption of electricity, thermal, nuclear, and other forms of power generation, which accounts for 96.52%, hydropower is the most important consumption mode in energy-related water 3; energy-related water 2 represents water consumption of oil, accounting for 3.32%; energy-related water 1 represents water consumption of coal, accounting for at least 0.16%.

4.3. Mixture water and energy flows among sectors

Figure 5 shows the mixture energy flow among economic sectors. Based on the width of the flow, we identify the proportion of the flow of each sector in the total flow of the designated sector. The axis value on the circle represents the proportion and value of mixed energy inflow or outflow in each sector. For example, Man is the largest energy outflow and inflow sector, energy outflow is $201.00 \times 10^9$ kwh, energy inflow is $256.00 \times 10^9$ kwh; Min is the largest energy providing sector of Man, followed by Psp.
and Agr; the largest outflow sector of Man is Con, followed by Tr and Se; Tr is a relatively energy-balanced sector, the energy outflow is $95.40 \times 10^9$ kwh, and energy inflow is $88.70 \times 10^8$ kwh.

Figure 5. Mixture energy flow among sectors.

Figure 6 shows the mixture water flow among economic sectors. It is obvious that Agr is the largest mixed water outflow sector. More than 92% (7.55×$10^9$ m$^3$) of the water flows out to the others. Man is still the largest mixed water inflow sector (reaches to 9.88×$10^9$ m$^3$); Wa occupies the smallest percentage of the total mixed water flow. Con is almost dependent on mixed water inflow by other sectors, it flows to 95% of the mixture water inflow; Min is the most outflow sector of mixed water, the proportion of outflow reaches 90%.

Figure 6. Mixture water flow among sectors.
6. Conclusions
This study discovers the quantitative relationship between water and energy consumption through using the Fujian’s input-output table in 2017. Results can reveal the direct consumption of energy and water in Fujian, as well as reflect the proportion of various types of water consumption. The second aim is to reveal the relationships of mixture water and mixture energy among sectors in Fujian Province, it also reveals the proportion of inflow or outflow among sectors.

Some major findings can be summarized as follows: (i) Man is the primary contributor of direct energy and water consumption; (ii) Agr is the main contributor of direct water, and Psp is the largest water consumption sector; (iii) energy consumption is the largest in the water intake process; (iv) water consumption of exergy, thermal, nuclear and other forms of power generation is the largest consumption; (v) Man is the largest energy outflow and inflow sector; (vi) Agr is the largest provider of mixture water, Man is the largest receiver of mixture water sector.

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