CHEMICAL ENGINEERING TRANSACTIONS
VOL. 86, 2021
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

ISBN 978-88-95608-84-6; ISSN 2283-9216
DOI: 10.3303/CET2186074

Water-Energy-Carbon Network Critical Transmissions: Case Study of China

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This study seeks to explore the Energy-Carbon-Water nexus of China, identifying the regional transmissions of embodied energy consumption, CO_2 emissions and water consumption in the coastal area of China. Nice provinces are taken into consideration, and the Multi-Region Input-Output model is employed. The critical transmissions of embodied Energy-Carbon-Water among different provinces have been analysed. Results show that: i) Hebei export the most embodied energy and Zhejiang import the most embodied energy; ii) The structure of embodied CO_2 emissions transmissions is similar with that of embodied energy consumption; iii) Guangdong benefits the most from the regional embodied water transmissions system, and Jiangsu contributes the most. This study contributes to a better understanding of the regional embodied Energy-Carbon-Water nexus system, providing a reference for future studies of other regions in the world.

1. Introduction

Increasing strategies, targets, and policies have been setting up and revolve around water use, energy consumption and CO_2 emissions. Regional or sectoral water utilisation, energy consumption, CO_2 emissions, etc., are usually employed for showing the environmental performance, however, which is not the complete picture. As three of the most crucial elements of environmental strategies, water, energy and CO_2 emissions are profoundly entwined in more complicated and invisible ways (Wang et al., 2020a). The critical transmissions of embodied-water-utilisation, -energy-consumption and -CO_2-emissions among multiple economic sectors (Fernando et al., 2021) and multi-region constitute the complicated virtual Energy-CO_2-Water (ECW) network (Wang et al., 2020b). Water, energy and low-CO_2 emissions offer a foundation for the development of the environment, the economy and society. However, global challenges, including water scarcity, energy crises and increasing global warming, threaten sustainable development in many regions worldwide (Xu et al., 2020). Compared with the Paris Agreement (Sumaila et al., 2019) and the United Nation Framework Convention on Climate Change (UNFCCC) (Roe et al., 2019), the 17 UN Sustainable Development Goals (SDGs) provide a more comprehensive goal (THE 17 GOALS, 2021). The more humanity centric holistic approach of the 17 UN SDGs was proposed by the UN together with political leaders globally, where clean water, affordable and clean energy, and climate actions within the context of a sustainable partnership are spelt out so that a sustainable future for all human beings will be built up equitably and in peace.
The key intermedia of the ECW network is inter-regional trade. A massive amount of embodied water utilisation, energy consumption and carbon emissions are transferred (Liu et al., 2017) with the products and services during the inter-sectoral and inter-regional trades (Chen et al., 2019). The accumulation amount of sectoral or regional embodied material consumption or emissions might be much larger or lower than the direct value. For example, the direct water consumption of the agriculture sector is much more than that of embodied amount. Conversely, heavy industry and light industry have much higher values of embodied water and energy consumption (Wang et al., 2021). The resources availability and embodied resources consumption of a specific

Paper Received: 21 October 2020; Revised: 17 February 2021; Accepted: 1 May 2021
Please cite this article as: Wang X.-C., Klemes J.J., Varbanov P.S., 2021, Water-energy-carbon Network Critical Transmissions: Case Study of China, Chemical Engineering Transactions, 86, 439-444 DOI:10.3303/CET2186074

region can be different or even contradictory as well (Lu et al., 2018). It demonstrates that the results from the sectoral-based and supply-chain-based perspectives can be significantly different. Although the embodied ECW net export countries can benefit a lot in terms of economic gain, they significantly bear the consequences of environmental pressure, including water consumption, energy consumption and carbon emissions (Wang et al., 2020b). Conversely, the embodied ECW net import countries can benefit from the inter-regional trade in terms of environmental impacts. The results might be uplifting if from the global perspective as the complicated ECW network contributes to reducing the consumption of water and energy and the CO_2 emissions. For example, while contributing to the equivalent annual economic output, the EU27 consume 6.5 × 10^{10} t less water and 4.9 × 10^{18} J less energy and emit 1.4 × 10^{9} t less CO_2 compared to the rest of the world, which significantly contributes to relieving the environmental pressure (Wang et al., 2020b). The importance is to balance the mutual benefits among all stakeholders. It is crucial to measure the sectoral and regional environmental performance from the supply chain perspective and identify the impact factors (Liang et al., 2016), however, which still needs more in-depth exploration.

As the largest developing, the ECW network is propped up by economic supply chains, which have been properly identified by existing works (Li et al., 2021). Inter-regional and inter-sectoral trades result in major displacements of environmental impacts, accompanying by the transmissions of a large amount of flows of embodied water utilisation, energy consumption and CO_2 emissions (Wiedmann and Lenzen, 2018). The embodied materials have been increasingly transferred from developing to developed countries because of the booming international trade (Peters et al., 2011). Inter-regional trade can well explain the regional consumption of water and energy and CO_2 emissions, standing for the importance of identifying the regional or even global shaping factors and critical transmissions of the ECW network. It is crucial for accurately recognising the key impact factors of shaping the sectoral and regional environmental performance (Zhang et al., 2020). It is also important for identifying the key nodes to improve production efficiency and reduce the environmental impacts from the supply chain perspective. However, sectors that serve as shaping factors and intermedia in the embodied ECW network are usually overlooked.

As a result of the large population, along with the rapid economic development, China is facing different kinds of environmental pressure, such as intensive CO_2 emissions, water scarcity, water uneven distribution and energy crisis (Wang et al., 2021). China contributes to 27 % of global CO_2 emissions, which is higher than any of other single country (Ritchie and Roser, 2017). China aims to hit peak emissions by 2030 and pledges to go carbon emissions neutral by 2060 (Climate Change, 2021). Reducing CO_2 emissions or mitigating climate change have been at the core of all strategies and measures of China. China is also facing the serious challenge of water resource shortage due to uneven water distribution and water scarcity. The proportion of the population facing water shortages has increased fourfold worldwide during the past two centuries (Kummu et al., 2016), and around one-third of the population in China are residing in the areas with serious water stress under the increasing national water demand (Wang et al., 2019).

For narrowing the research gaps mentioned above, this paper aims at exploring the regional transmissions of embodied water-energy-carbon system, taking the coastal area of China as a case. The critical transmissions of embodied water consumption, energy consumption and carbon emissions have been identified among different regions in the coastal area of China.

2. Data

In this study, nine provinces in the coastal area of China are involved, including Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian and Guangdong. All data used in this study are consistent with the year 2015, as the latest Multi-Region Input-Output (MRIO) database of China is of 2015 (CEADs, 2021).

The energy consumption, CO_2 emissions and water consumption data of different regions were collected and processed from the China Statistical Yearbook of the Environment (National Bureau of Statistics of China, 2021) and the CEADs database (CEADs, 2021). All data used in this study are public and are available from China's National Bureau of Statistics. All data can be downloaded for free.

3. Method

The Multi-Region Input-Output (MRIO) is used in this study. Although the MRIO depends on big sets of consistent and systematic data, which are usually slightly lagging, it is a widely used and effective method with good robustness for handling economic and environmental data from the supply chain perspective. It is a useful tool for solving similar issues. The framework is shown in Figure 1, where Ind means Industries, Com is commodities, FD is final demand, VA means value added (also called primary inputs), Indicators are from satellite indicator accounts of the MRIO model, documenting nonmonetary inputs to production, IIOT is the Industry by Industry input-output (IO) tables; CIOT means the Commodity by Commodity IO table.

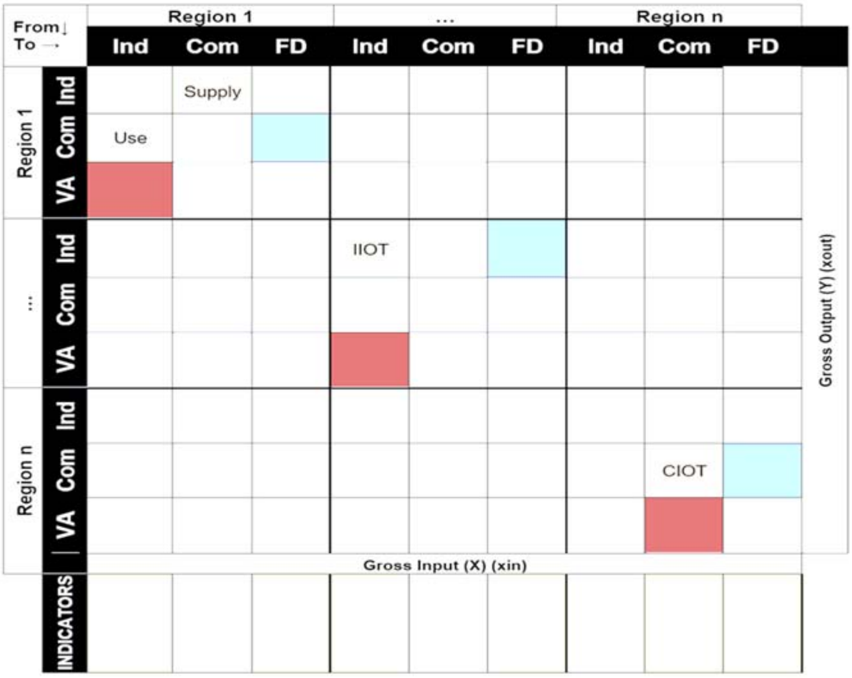

Figure 1: The framework of the MRIO model

Nine regions and 42 economic sectors are considered in this study. Based on the MRIO model, the following equations are employed in this study. The water-relevant indicators, ε_j^s and ε_i^r, are took as examples to show the calculating processes, and introduce the following notations:

$$L = [(\varepsilon_1^1 \quad \cdots \quad \varepsilon_{42}^1) \quad \cdots \quad (\varepsilon_1^9 \quad \cdots \quad \varepsilon_{42}^9)] \tag{1}$$

$$E = [(e_1^1 \quad \cdots \quad e_{42}^1) \quad \cdots \quad (e_1^9 \quad \cdots \quad e_{42}^9)], \tag{2}$$

$$Z = \begin{bmatrix} \begin{pmatrix} z_{1,1}^{1,1} & \cdots & z_{1,56}^{1,1} \\ \vdots & \ddots & \vdots \\ z_{42,1}^{1,1} & \cdots & z_{42,42}^{1,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{9,1} & \cdots & z_{1,42}^{9,1} \\ \vdots & \ddots & \vdots \\ z_{42,1}^{9,1} & \cdots & z_{42,42}^{9,1} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{1,1}^{1,9} & \cdots & z_{1,56}^{1,9} \\ \vdots & \ddots & \vdots \\ z_{42,1}^{1,9} & \cdots & z_{42,42}^{1,9} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{9,9} & \cdots & z_{1,9}^{9,9} \\ \vdots & \ddots & \vdots \\ z_{56,1}^{9,9} & \cdots & z_{42,42}^{1,9} \end{pmatrix} \end{bmatrix} \tag{3}$$

$$Y = \begin{bmatrix} \begin{pmatrix} \sum_{s=1}^{9}\sum_{j=1}^{42} z_{1,j}^{1,s} + \sum_{s=1}^{9}\sum_{k=1}^{5} f_{1,k}^{1,s} & & \\ & \ddots & \\ & & \sum_{s=1}^{9}\sum_{j=1}^{42} z_{42,j}^{1,s} + \sum_{s=1}^{9}\sum_{k=1}^{5} f_{42,k}^{1,s} \end{pmatrix} & & \\ & \ddots & \\ & & \begin{pmatrix} \sum_{s=1}^{9}\sum_{j=1}^{42} z_{1,j}^{9,s} + \sum_{s=1}^{9}\sum_{k=1}^{5} f_{1,k}^{9,s} & & \\ & \ddots & \\ & & \sum_{s=1}^{9}\sum_{j=1}^{42} z_{42,j}^{9,s} + \sum_{s=1}^{9}\sum_{k=1}^{5} f_{42,k}^{9,s} \end{pmatrix} \end{bmatrix} \tag{4}$$

where ε_j^s indicates the embodied water intensity of sector *j* in province *s*, $z_{j,i}^{r,s}$ indicates the intermediate flow from sector *j* in province *r* to sector *i* in province *s*, $f_{i,k}^{r,s}$ means the final demand of term *k* in the province *s* from sector *i* in province *r*, (*k* = 1, 2, 3, 4, 5, indicate final consumption expenditures by households, non-profit organisations serving households and government, as well as changes in inventories and valuables and the gross fixed capital formation).

Based on the MRIO model, there is a balance in the MRIO table:

$$E + LZ = LY \tag{5}$$

Then the import embodied water consumption (IEW_i^r) and export embodied water consumption (EEW_i^r) of sector *i* in province *r* can be given as:

$$IEW_i^r = \sum_{j=1}^{42} \varepsilon_j^s \times z_{j,i}^{r,s}, (r \neq s) \tag{6}$$

$$EEW_i^r = \sum_{j=1}^{42} \varepsilon_i^r \times z_{i,j}^{r,s}, (r \neq s) \tag{7}$$

The import embodied *water* consumption (IEE^r) and export embodied water consumption (EEE^r) of province *r* can be obtained:

$$IEW^r = \sum_{i=1}^{42} IEW_i^r \tag{8}$$

$$EEW^r = \sum_{i=1}^{42} EEW_i^r \tag{9}$$

4. Results

4.1 Regional Transmissions of Embodied Energy Consumption

Table 1 shows the regional transmissions of embodied energy consumption in the coastal area of China. Hebei exports the most embodied energy at 1,975 PJ, followed by Jiangsu and Shandong. Hebei is the largest steel-producing province in China, accounting for around one-third of iron and steel products in China and one-eighth of worldwide (Wang et al., 2021). A huge amount of steel products is transported from Hebei to other regions in China or even the world. Regarding the total import amounts, Zhejiang province import the most embodied energy, which is 1,861 PJ, followed by Guangdong and Jiangsu. These three provinces have an import value that higher than 1,000 PJ. they are big economic provinces in China and have higher GDP than most other regions. They import the most embodied energy from Hebei province main because of the steel production trade.

Table 1: Regional Transmissions of Embodied Energy Consumption, (PJ)

	Tianjin	**Hebei**	**Liaoning**	**Shanghai**	**Jiangsu**	**Zhejiang**	**Fujian**	**Shandong**	**Guangdong**	**Total Export**
Tianjin		27	34	50	97	87	14	40	104	**454**
Hebei	78		113	166	575	537	55	102	349	**1,975**
Liaoning	52	63		156	181	233	22	66	149	**922**
Shanghai	20	49	47		109	181	33	65	187	**691**
Jiangsu	95	83	161	219		411	77	44	517	**1,608**
Zhejiang	32	29	39	101	127		23	38	117	**507**
Fujian	17	14	23	63	58	79		23	93	**369**
Shandong	41	77	72	149	262	228	39		229	**1,096**
Guangdong	26	30	39	81	114	104	21	33		**448**
Total Import	**362**	**371**	**529**	**983**	**1,524**	**1,861**	**284**	**411**	**1,745**	

4.2 Regional Transmissions of Embodied CO_2 Emissions Water Consumption

Table 2 presents the regional transmissions of embodied CO_2 emissions across the coastal provinces of China. The structure of embodied CO_2 emissions transmissions is similar to that of embodied energy consumption, as energy consumption related activities are the main contributors of CO_2 emissions. Regions of Zhejiang, Guangdong and Jiangsu, lead the list of total embodied CO_2 emissions import at 164 Mt, 156 Mt and 142 Mt. The main embodied CO_2 import source of them is Hebei province, importing 44 Mt, 29 Mt and 48 Mt. This is mainly due to importporing a large number of steel products from Hebei. During the regional trade, they transfer significant environmental pressure to Hebei as well. Regarding the total export amount, Hebei, Jiangsu and Shandong export the most embodied CO_2 emissions at 166 Mt, 147 Mt and 122 Mt. They export lots of products to other regions and benefit from the economy; however, they are also under big environmental pressure.

Table 2: Regional Transmissions of Embodied CO_2 emissions, (Mt)

	Tianjin	Hebei	Liaoning	Shanghai	Jiangsu	Zhejiang	Fujian	Shandong	Guangdong	Total Export
Tianjin		2.3	3.0	4.2	8.7	7.3	1.3	3.4	8.7	**38.9**
Hebei	6.9		9.6	14.0	48.2	44.6	4.7	9.1	29.2	**166.3**
Liaoning	5.4	5.4		13.7	14.5	18.1	1.7	8.2	12.1	**79.0**
Shanghai	1.7	4.2	3.8		9.8	14.9	2.8	5.3	15.3	**57.7**
Jiangsu	8.7	7.5	14.6	20.1		37.5	7.0	4.3	47.4	**147.1**
Zhejiang	3.8	2.9	3.6	11.1	12.3		2.2	6.4	10.7	**52.9**
Fujian	2.0	1.4	2.0	6.4	5.1	6.8		3.4	8.1	**35.3**
Shandong	4.3	8.5	7.7	16.6	31.4	24.8	4.5		24.6	**122.4**
Guangdong	3.3	3.4	3.9	9.1	11.9	10.3	2.1	5.4		**49.4**
Total Import	**36.2**	**35.6**	**48.1**	**95.2**	**141.8**	**164.3**	**26.3**	**45.5**	**156.0**	

4.3 Regional Transmissions of Embodied Water Consumption

Table 3 shows the regional transmissions of embodied water consumption. Different from the patterns of embodied energy consumption and CO_2 emissions, Guangdong import the most embodied water from other regions, at 63×10^8 m^3, followed by Zhejiang and Jiangsu at 54×10^8 m^3 and 36×10^8 m^3. Guangdong has the biggest GDP amount in China, with the most developed economy. It imports a large number of products from the other regions of China every year, with a large amount of embodied water. Regarding the total export amount, Jiangsu export the most embodied water at 74.7×10^8 m^3, and the biggest gainer is Guangdong at 22.4×10^8 m^3, followed by Zhejiang at 17.3×10^8 m^3. The 2nd place of total export list is Shandong province at 37.1×10^8 m^3, which is much less than that of Jiangsu.

Table 3: Regional Transmissions of Embodied Water consumption, (10^8 m^3)

	Tianjin	Hebei	Liaoning	Shanghai	Jiangsu	Zhejiang	Fujian	Shandong	Guangdong	Total Export
Tianjin		0.8	1.2	1.2	2.7	2.0	0.8	0.7	3.2	**12.6**
Hebei	3.2		2.2	2.9	8.4	8.1	1.3	10.5	9.8	**46.5**
Liaoning	1.9	1.9		2.4	3.6	4.7	0.6	6.6	5.1	**26.6**
Shanghai	0.6	1.3	1.3		2.9	4.5	0.9	1.6	4.8	**18.0**
Jiangsu	5.1	4.1	7.0	8.8		17.3	3.3	6.8	22.4	**74.7**
Zhejiang	1.2	1.0	1.5	2.8	4.1		0.8	1.5	4.1	**17.1**
Fujian	1.0	0.9	2.1	2.6	2.8	4.5		1.3	5.8	**21.0**
Shandong	2.3	2.3	4.0	4.3	7.3	7.6	1.4		7.8	**37.1**
Guangdong	1.5	1.6	2.9	3.8	5.1	5.4	1.0	1.3		**22.6**
Total Import	**16.8**	**13.8**	**22.0**	**28.8**	**36.9**	**54.1**	**10.1**	**30.3**	**63.2**	

5. Conclusions

This study identified the regional transmissions of embodied energy-carbon-water system, taking the coastal area china as cases. The critical transmissions of embodied energy consumption, CO_2 emissions and water consumption among nine provinces have been calculated. Main contributions include:

(i) Hebei exports the most embodied energy at 1,975 PJ, as it is the largest steel-producing province in China, accounting for around one-third of iron and steel products in China and one-eighth of worldwide. It exports a large number of steel products to other regions every year. Regarding the total import amounts, Zhejiang province benefits the most, importing 1,861 PJ of energy, followed by Guangdong and Jiangsu. These three provinces have an import value that higher than 1,000 PJ. Hebei province is their biggest contributor.

(ii) The structure of embodied CO_2 emissions transmissions is similar to that of embodied energy consumption, which is because that energy consumption related activities are the main contributors of carbon emissions. Zhejiang, Guangdong, and Jiangsu import the most embodied CO_2 emissions at 164 Mt, 156 Mt and 142 Mt. They transfer big environmental pressures to the upstream regions from the supply chain perspective. Hebei is the biggest contributor as a large number of steel products are traded from Hebei to these three provinces. Hebei, Jiangsu and Shandong export the most embodied CO_2 emissions.

(iii) The pattern of embodied water consumption transmission is different from that of energy consumption and CO_2 emissions. Guangdong import the most embodied water at 63×10^8 m^3, followed by Zhejiang and Jiangsu at 54×10^8 m^3 and 36×10^8 m^3. They are with the most developed economy in China, importing a large number of products from the other regions of China Jiangsu export the most embodied water at 74.7×10^8 m^3, and the biggest gainer is Guangdong at 22.4×10^8 m^3.

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