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MAPPING THE WATER - ENERGY - GHG NEXUS FROM SUPPLY CHAIN PERSPECTIVE

MAPOVÁNÍ ENERGIE-VODA-SKLENÍKOVÉ PLYNY NEXUS Z HLEDISKA DODAVATELSKÉHO ŘETĚZCE

SHORT VERSION OF DOCTORAL THESIS

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KLÍČOVÁ SLOVA

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Declaration

I declare that I am the author of this doctoral thesis. It has been prepared under the guidance of my supervisors. The reported results are original research which developed based on my knowledge gained during PhD study and consultation with experts. I have quoted all the sources including own publications. The related references are provided at the end of this thesis.

Brno: Xuechao Wang

Abstract

Water utilisation, energy consumption and Greenhouse Gas (GHG) emissions are crucial indicators and very much related for maintaining or achieving the Environmental and social sustainability. This thesis presents the methodologies have been developed and case studies have been conducted to explore and identify the Water-Energy-GHG Nexus (WEGN) from the supply chain perspective. Three methodologies which are based on the application and integration of the Input-Output (IO) model, Geographic Information System (GIS) and Supply Chain Network (SCN) are proposed, for analysing and designing the WEGN network, while also addressing challenges that have previously prevented practical implementation. The applicability of these methodologies is demonstrated by three comprehensive case studies focused on the sectoral environmental efficiency, regional environmental efficiency and critical transmissions of WEGN. My contributions to the field include:

i. IO based assessment tool for identifying regional environmental efficiency in terms of WEGN, especially for the regions that are closely connected by interregional trade.
ii. Integrating the GIS and IO methodologies (GIS-IO) to reveal and map WEGN network, tracking the critical inter-regional and -sectoral WEGN flows, clarifying the regional, sectoral and worldwide patterns of WEGN network, and identifying the associated benefits for different regions.
iii. IO and SCN based assessment approach (IO-SCN) for quantifying the sectoral WEGN coefficients.

Abstrakt

Využití vody, spotřeba energie a emise skleníkových plynů (GHG) jsou rozhodujícími ukazateli a do značné míry souvisí s udržováním nebo dosahováním environmentální a sociální udržitelnosti. Tato práce prezentuje vyvinuté metodiky. Představuje také provedené případové studie, které prozkoumaly a identifikovaly Water-Energy-GHG Nexus (WEGN) z pohledu dodavatelského řetězce. Pro analýzu a návrh sítě WEGN jsou navrženy tři metodiky, které jsou založeny na nové aplikaci a integraci modelu vstup-výstup (IO), geografického informačního systému (GIS) a sítě dodavatelského řetězce (SCN), a zároveň řeší výzvy, které dříve neumožňovali praktické implementace. Použitelnost těchto metod je prokázána třemi komplexními případovými studiemi zaměřenými na odvětvovou environmentální účinnost, regionální environmentální účinnost a kritické přenosy WEGN. Mezi mé příspěvky v této oblasti patří:

i. Nový nástroj pro hodnocení založený na IO pro identifikaci regionální environmentální účinnosti z hlediska WEGN, zejména pro regiony, které jsou úzce propojenyobchodem.

ii. Pokročilá integrace metodik GIS a IO (GIS-IO) za účelem odhalení a mapování sítě WEGN, sledování kritických meziregionálních a sektorových toků WEGN, vyjasnění regionálních, odvětvových a celosvětových vzorců sítě WEGN a určení souvisejících výhod pro různé regiony.

iii. Efektivní metoda hodnocení založená na IO a SCN pro kvantifikaci sektorových koeficientů WEGN.

Contributing Publications

This thesis is been based on the author's publication in several highly recognised international journals (presented in this chapter as follows). The developed methodology and work in Chapter 3 are published in Journal of Cleaner Production (IF: 7.246) [1]. One publication closely related to the work in Chapter 4 is going to be published in Renewable and Sustainable Energy Reviews (IF=12.110, CiteScore=25.5) [2]. The results in Chapter 5 is based on the works accepted in Applied Energy (IF: 8.848) [3]. The other review studies and assessments that make up the thesis or develop the results in Chapter 1 - 5 are published in Renewable and Sustainable Energy Reviews (IF: 12.110), Ecosystem services (IF: 6.330), Journal of Environmental Management (IF: 5.647), Journal of Cleaner Production (IF: 7.246), Ecological Indicators (IF: 4.229), Energies (IF: 2.702), Sustainability (IF: 2.576) and Chemical Engineering Transactions (Scopus Index).

1 **Wang, X.C.**, Klemeš, J.J., Long, X., Zhang, P., Varbanov, P.S., Fan, W., Dong, X., Wang, Y., 2020. Measuring the environmental performance of the EU27 from the Water-Energy-Carbon nexus perspective. Journal of Cleaner Production, p.121832. DOI: 10.1016/j.jclepro.2020.121832. **[IF = 7.246]**

1 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Huisingh, D., Guan, D., Dong, X., Varbanov, P.S., 2020. Unsustainable Imbalances and Inequities in Carbon-Water-Energy Flows across the EU27. Renewable and Sustainable Energy Reviews. **[IF = 12.110] [CiteScore = 25.5]**.

2 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Dong, X., Wei, H., Xu, Z., Varbanov, P.S., 2020. Water-Energy-Carbon Nexus Analysis of China: An Environmental Input-Output Model-Based Approach. Applied Energy, 261, p.114431. DOI: 10.1016/j.apenergy.2019.114431. **[IF = 8.848]**

3 **Wang, X.C.**, Klemeš, J.J., Dong, X., Fan, W., Xu, Z., Wang, Y., Varbanov, P.S., 2019. Air pollution terrain nexus: A review considering energy generation and consumption. Renewable and Sustainable Energy Reviews, 105, 71-85. **[IF = 12.110]**

4 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., 2020. Water-Energy-Carbon Nexus Analysis of the EU27 and China. Chemical Engineering Transactions, 81. **(Scopus Index) (Accepted)**

5 **Wang, X.C.**, Klemeš, J.J., Walmsley, T.G., Wang, Y., Yu, H., 2018. Recent Developments of Water Footprint Methodology. Chemical Engineering Transactions, 70, 511-516. **(Scopus Index)**

6 **Wang, X.C.**, Klemes, J.J., Dong, X., Sadenova, M.A., Varbanov, P.S., Zhakupova, G., 2019. Assessment of Greenhouse Gas Emissions from Various Energy Sources. Chemical Engineering Transactions, 76, 1057-1062. **(Scopus Index)**

Complete Publication List is provided in the full-length thesis

Table of Contents

CHAPTER 1 INTRODUCTION

1.1 General Introduction

The concept of WEGN relies on pathways among these three interdependent sectors from an industrial point of view: the water production, the energy generation and carbon sectors. The utilisation of water and energy in developing and functioning communities and plants generates waste (like GHG emissions) in addition to the services from water and energy consumption. Energy is required for water generation, operation and distribution. Water is also necessary for the generation and operation/conversion of energy as well as manufacturing processes. Energy production and utilisation related human activities are the main contributors to GHG emissions.

Water, energy, and GHG have become crucial indicators of social development and environmental sustainability. The consumptions of water and energy, as well as GHG emissions, are closely related to environmental sustainability achievement via the metabolism of the ecosystem and human society. The confluence of declining water availability, expanding energy demand and quality as well as increasing climate change impacts makes addressing water, energy and GHG issues together with a critical global and regional need. In recent studies, the nexus between these three key factors have been increasingly emphasised, which is pivotal for decreasing environmental footprints.

As shown in Figure 1, water, energy, and Greenhouse Gases (GHG) sectors are represented by a blue ellipse, a red rectangle, and a brown pentagon. Coloured arrows indicate the interactions (such as energy consumption during water withdrawal) among these three sectors. Three main kinds of linkage are illustrated: net forward linkages (arrows begin in a sector), net backward linkages (arrows end in a sector), and internal effect (arrows begin and end in a sector) (Ifaei and Yoo, 2019). All sectors can be appropriately placed in the nexus framework. For example, for the agricultural sector, water is crucial for exploitation and irrigation. Energy is mandatory for pumping and water delivery. Energy can also be directly used for cultivation and harvesting as well as indirectly used for fertilising, weeding, and pesticide application (Zhao et al., 2018). In agricultural activities that involve energy input and land resource exploitation, the atmospheric carbon pool always plays the roles of carbon emission sources and sinks (Zhao et al., 2018).

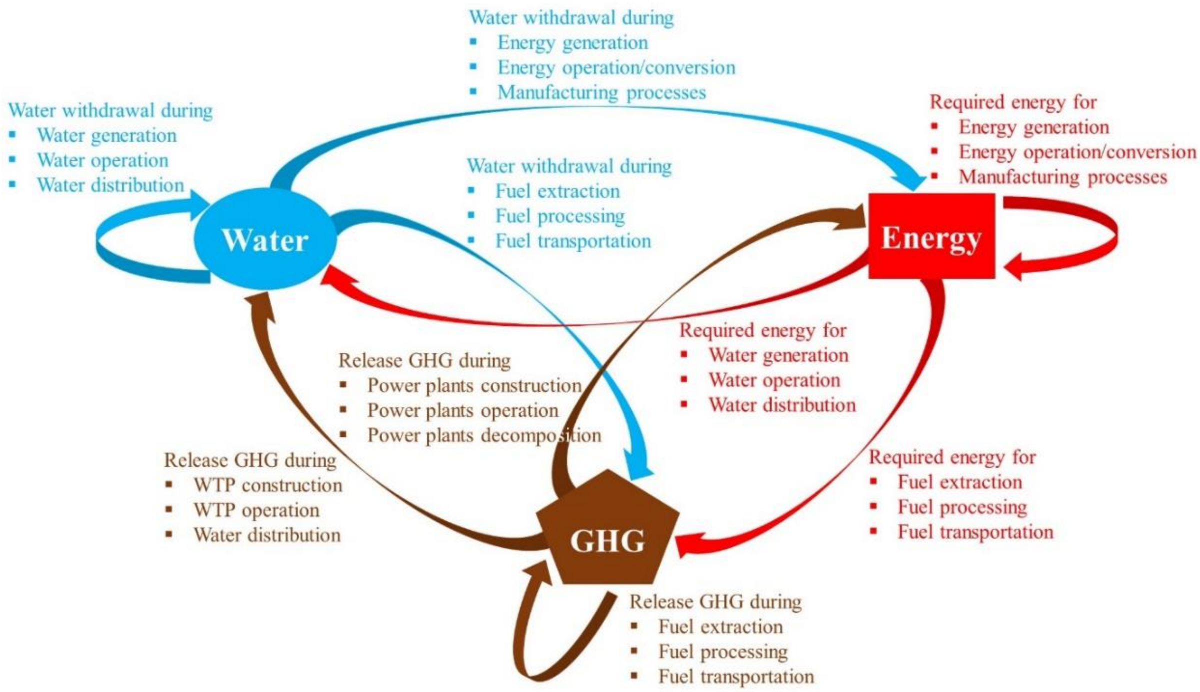

Figure 1 *Water-Energy-GHG Nexus* (Wang et al., 2020b)

A massive amount of production and different kinds of services are shared between different sectors and regions worldwide. It is extremely important to analyse the linkage between water consumption, energy consumption and GHG emissions. An in-depth understanding of the WEGN is pivotal for minimising the environmental footprint (Wang et al., 2020b). Water utilisation, energy consumption, and carbon emissions stand for three significant environmental strategy elements in the EU27, China as well as worldwide (Wang et al. 2019). Li et al. (2020) reviewed the WEGN, including the concepts, research focuses, mechanisms, and methodologies. Because of its extremely significant for regional sustainability and the environment healthy, the WECN has been arousing increasing attention worldwide. The WEGN mechanism for the power generation sector, water service sector, agriculture production sector, and the household sector have also been concluded by Li et al. (2020).

Severe challenges of energy high-efficiency utilisation, water resource-saving, and low-carbon emissions have been big pressure on the regional and global sustainable development. The climate change further aggravates water scarcity and consequently negatively influence environmental sustainability. The sets of related issues have been contributing to global warming along with degradation in human well-being, ecosystem health, economic development, etc. (Yang et al., 2017). The WEGN characteristics of different sectors can provide a new perspective for relieving challenges of environmental pressure.

1.2 Thesis Aim and Scope

The overall aim of the research is to investigate and develop methods for exploring and identifying the WEGN from the supply chain perspective by integrating the IO model, Geographic Information System and Supply Chain Network. Robust engineering design and comprehensive assessment framework in facilitating the planning to identify WEGN mechanism are proposed. All economic sectors in all countries of EU27 and different regions of China are the targets, and case studies have been developed related to these sectors and regions to demonstrate the developed methodologies. Three novel methodologies are proposed and applied to three comprehensive case studies. The scope of the study is divided into the following main sections:

i. **IO based assessment tool for identifying environmental efficiency in terms of WEGN.**

To extend the methodology of IO for assessing and understanding the regional environmental performance, where interregional trade, serving as an important basis for future considerations or planning for policymakers, closely connects different regions.

<u>Case Study: Integrated Regional Environmental Efficiencies and Coefficients Identification</u>

The water and energy efficiencies and carbon emission intensity of different countries in the EU27 are analysed. The embodied water consumption coefficients, embodied energy consumption coefficients and embodied CO_2 emission coefficients (ECEC) are identified. Both the direct and indirect values of the above indicators are explored. Water efficiency, energy efficiency and CO_2 emission index per capita are calculated as well. It can contribute to understanding the environmental performance in the EU27, and provide a reference for future studies of other regions in the world.

ii. **GIS and IO methodologies to reveal and map WEGN network**

To integrate the GIS and IO methodologies for tracking the inter-regional and -sectoral WEGN flows, clarifying the regional, sectoral and worldwide patterns WEGN network, and identifying the associated benefits for different regions.

<u>Case Study: Disparities and Drivers of Carbon-Water-Energy Flows</u>

Regional sustainability should be considered from the global and multi-sector level, instead of regional single-sector basis, especially in terms of climate change, and the

WEGN trilemma. The study quantified the WEGN flows of EU27 from three angles: regional patterns, sectoral patterns and global patterns. The exploration revealed apparent disparities between different countries within EU27, different sectors, as well in the EU27 as a block of nations compared and the rest of the world.

iii. IO and supply chain network based assessment tool for quantifying WEGN coefficients

To integrate the IO and Supply Chain Network methodologies for identifying the sectoral environmental performance from the supply chain perspective, where different sectors are closely connected, especially in a big economy.

<u>Case Study: Integrated Sectoral Environmental Performance Assessment</u>

The embodied water and energy consumption and embodied carbon emissions are assessed. The water and energy consumption coefficients and CO_2 emission coefficients are analysed. All of these indicators include the entire process from raw material production to final product manufacturing, and this usually includes the processes of several different sectors. The indicators can represent the significance of the life cycle water and energy requirements as well as carbon emissions estimates. The sectoral environmental performance has also been analysed, as indicated by the consumption and emissions coefficients as well as the indexes.

CHAPTER 2 IO BASED ASSESSMENT TOOL FOR IDENTIFYING ENVIRONMENTAL EFFICIENCY IN TERMS OF WEGN

2.1 Brief Abstract

The European Union (EU) has been one of the most significant water users, energy consumers and CO_2 emitters. Understanding the Water-Energy-Carbon (WEC) nexus of the EU member countries (EU27) is vital for regional and worldwide sustainable development. This research aims to investigate the WEC nexus in the EU27. The Environmental Input-Output (EIO) model has been employed. The Embodied Water Consumption Coefficients (EWCC), Embodied Energy Consumption Coefficients (EECC) and embodied CO_2 emission coefficients (ECEC) are calculated. Both the direct and indirect values of the above indicators are explored. Water efficiency, energy efficiency and CO_2 emission index per capita are calculated as well. The results identify the water and energy efficiencies, and carbon emission intensity of different countries in the EU27. It can contribute to understanding the environmental performance in the EU27, and provide a reference for future studies of other regions in the world.

2.2 Environmental Input-Output (EIO) model

Table 1 The format of the EIO table (Wang et al., 2020).

		Intermediate demand 1, 2, …, n	Final demand	Total output
Intermediate input	1	z_{ij}	f_i	x_i
	2			
	…			
	n			
Value-added		v_j		
Total input		x_j		
Water input		w_j		
Energy input		e_j		
CO_2 emissions		c_j		

The EIO model (Yang et al., 2018a) was developed based on economic input-output (IO) model. EIO is a practical approach to analyse and calculate the supply chain characteristics between different regions and different sectors. The EIO model involves environmental factors, which is a widely applied method for exploring economic activities environmental issues, like energy consumption, GHG emissions, water utilisation (Wang et al., 2020). In this study, all countries are treated as different sectors in the EIO model. The EIO model is employed in this study for exploring the performances of energy consumption, water use and CO_2 emission in the 27 EU member countries. It is based on a consumption-based method of environmental assessment. Table 1 shows the format of the EIO table. z_{ij} is the intermediate use of region/sector *j* demand from region/sector *i*. f_i indicates the final demand of region/sector *i*. x_i means the total output of sector *i*. v_j is the added value of sector *j*. x_j means the total input of sector *j*. w_j means the direct water consumpted by sector *j*. e_j is the direct energy consumption amount by sector *j*. c_j means the CO_2 emission be sector *j*.

2.2.1 Embodied Water Consumption

Based on the EIO table profile, the direct consumption coefficients can be calculated by:

$$a_{ij} = x_{ij}/x_j, (i = 1, 2, 3, \dots, n;\ j = 1, 2, 3, \dots, n). \quad (1)$$

The direct water use coefficients are given as:

$$a_j^w = w_j/x_j, (j = 1, 2, 3, \dots, n), \quad (2)$$

where all parameters are introduced in section 3.2.

The embodied water consumption is given as:

$$w^{em} = A^w(I - A)^{-1}F, \quad (3)$$

where A^w means the matrix of direct EWCC with elements a_j^w. *I*, *A* and F^{diag} have the same meaning that has been explained in section 2.3.1.

2.2.2 Embodied Energy Consumption

The direct EECC of different counties are given as:

$$a_j^e = e_j/x_j, (j = 1, 2, 3, \dots, n), \quad (4)$$

The embodied energy consumption E^{em} can be obtained as follow:

$$E^{em} = A^e(I - A)^{-1}F, \tag{5}$$

where A^e is the matrix of direct energy consumption Coefficients with elements a_j^e; I is the identity matrix; A means the matrix of direct consumption Coefficients with elements a_{ij}; F represents the diagonal matrix, which is transformed from the total output matrix.

2.2.3 Embodied CO_2 Emissions

The embodied CO_2 emission is given by:

$$C^{em} = A^c(I - A)^{-1} F , \tag{6}$$

where A^c means the direct CO_2 emission matrix with the elements a_j^c, which is the direct CO_2 emission coefficients can be defined as:

$$a_j^c = c_j / x_j , (j = 1, 2, 3, \ldots, n). \tag{7}$$

2.2.4 Environmental Pressures Assessment

The EWCC, EECC and ECEC are calculated in this research for reflecting the environmental performance of the EU27. Following formulas are given:

$$E^w = A^w(I - A)^{-1}, \tag{8}$$

$$E^e = A^e(I - A)^{-1}, \tag{9}$$

$$E^c = A^c(I - A)^{-1}, \tag{10}$$

where E^w means the national EWCC; E^e represents the national EECC and E^c is the national ECEC.

The indirect EWCC, EECC and ECEC can be given as:

$$R^w = E^w - A^w, \tag{11}$$

$$R^e = E^e - A^e, \tag{12}$$

$$R^c = E^c - A^c. \tag{13}$$

2.3 Results and Discussions

2.3.1 Embodied Water Consumption

Figure 2 shows the EWCC of the EU27. Figure 3 shows the direct and indirect EWCC of the EU27. The EU27 average value (27 m^3/k€) is much lower than that of the average world value (75 m^3/k€). It means the water efficiency of EU27 is much higher than the average world level, and the relevant technology of EU27 is much better than the average level worldwide. However, there are still more than half of EU27 countries have higher embodied consumption coefficients than the EU27 average value, which means that these countries have lower water utilisation efficiency.

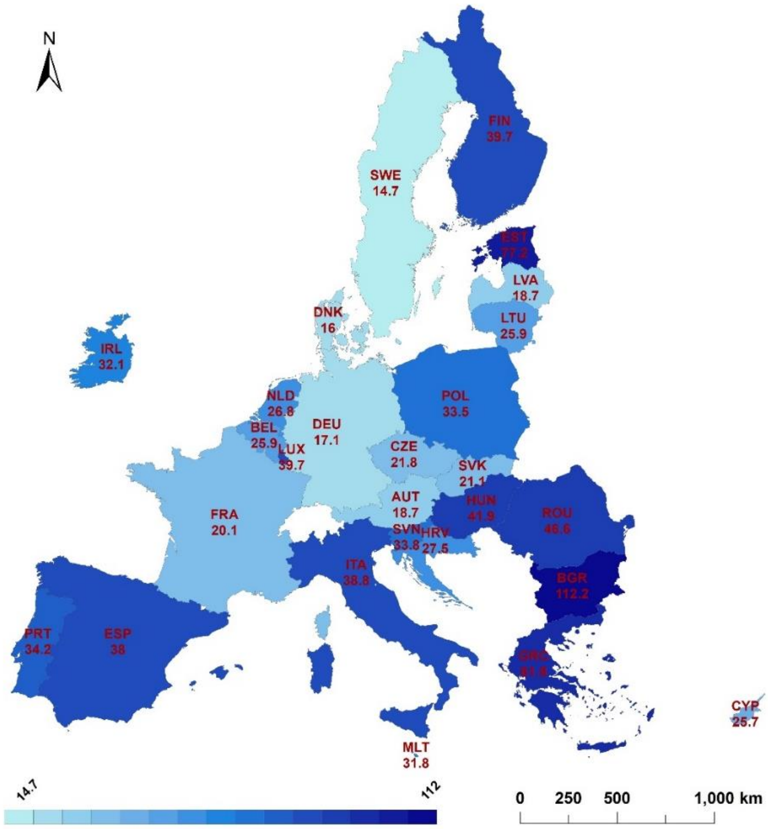

Figure 2 EWCC of the EU27 (m^3/k€)

When the indirect EWCC is considered, Bulgaria has the biggest number at 54 m^3/k€, followed by Luxembourg (39 m^3/k€), Estonia (35 m^3/k€) and Ireland (30 m^3/k€). These countries have plenty of indirect embodied water consumption because they seriously relay on the upstream countries outputs (Wang et al., 2020). It means that plenty of the embodied water of these countries come from the upstream countries during international trade. The water pressure and environmental performances of these countries highly depend on the upstream countries from the perspective of the supply chain. The situation might be even worse for countries with higher indirect embodied water consumption than that of direct, like Luxembourg. On the other hand, it also indicates that these countries might benefit from transferring environmental pressures to the upstream countries, by importing semi-finished products or finished products and leaving the primary processes that with high environmental risk in upstream countries.

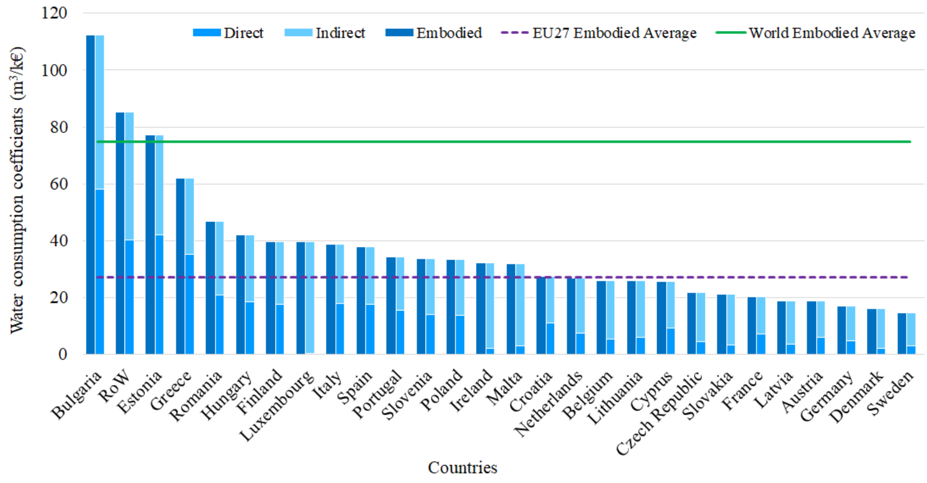

Figure 3 Direct and Indirect EWCC

Figure 4 shows the embodied water consumption per capita in the EU27 countries in 2014, as well as the EU27 average value (1,332 m^2) and average world value (1,248 m^2). Eleven members of EU27 are with a higher value than the EU27 average number, and the other 16 countries consume less embodied water per capita. The industrial sector, especially the steel sector is still the key contributors to the economy of Luxembourg except banking (The World Factbook, 2020).

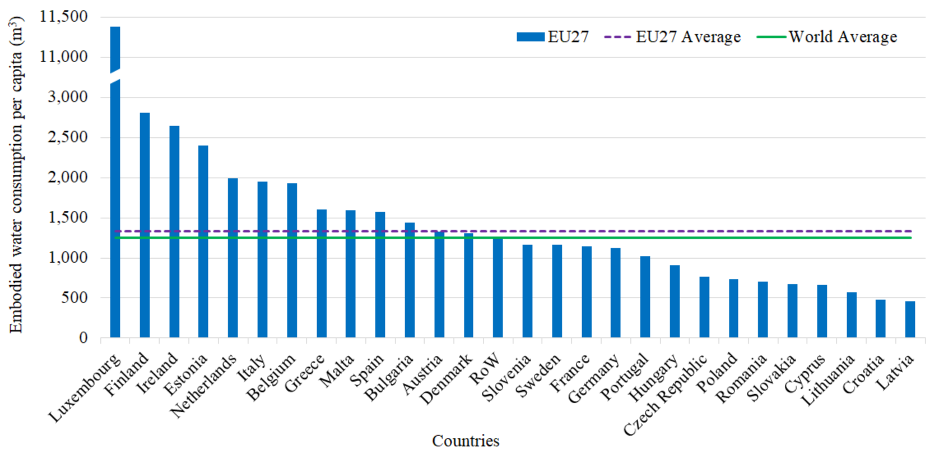

Figure 4 Embodied Water Consumption Per Capita

2.3.2 Embodied Energy Consumption

Figure 5 shows the EECC of the EU27. Figure 6 shows the direct and indirect EECC of EU27, as well as the EU27 average value and average world value. The average world value (13.9 MJ/€) is much higher than that of EU27 (8.8 MJ/€), which means the energy efficiency and relevant technologies of EU27 are much better than the worldwide average level. When taken the EU27 into consideration, there are 19 countries of EU27 have higher energy consumption coefficients than the EU27 average value. The 8 most energy-efficient countries worldwide are in Europe, and 6 of them are in the EU27, they are Germany, Ireland, Denmark, France, Austria and Italy Cashman (Cashman, 2015).

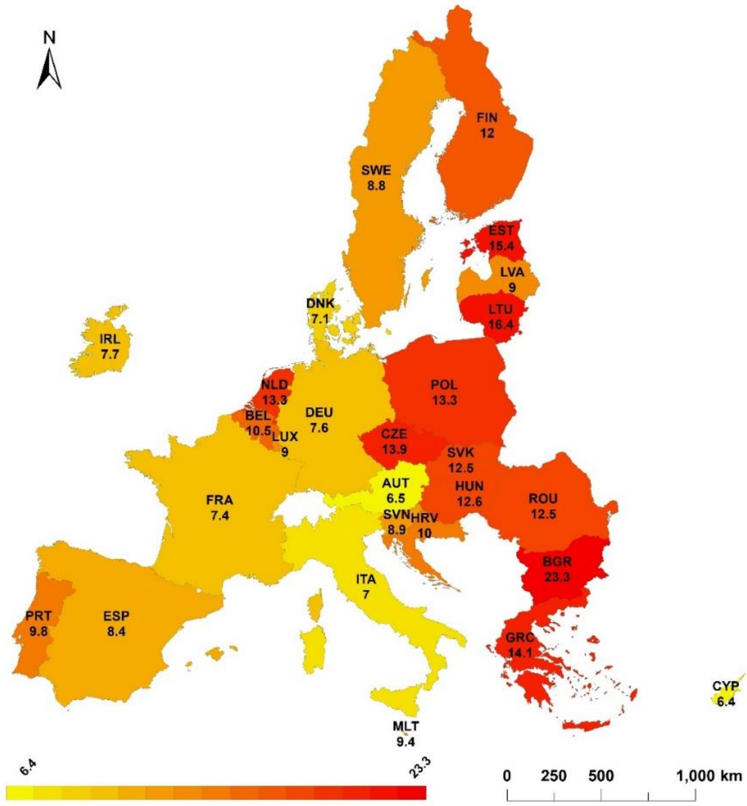

Figure 5 EECC of the EU27(MJ/€)

When the indirect EWCC is considered, Bulgaria (11.2 MJ/€), Luxembourg (8.1 MJ/€), Czech Republic (7.7 MJ/€), Estonia (7.7 MJ/€), and Slovakia (7 MJ/€) are the top five countries in the EU27. It means that these countries import a huge amount of embodied energy from upstream countries or regions during international trade. They significantly relay on the upstream countries outputs to be as their inputs.

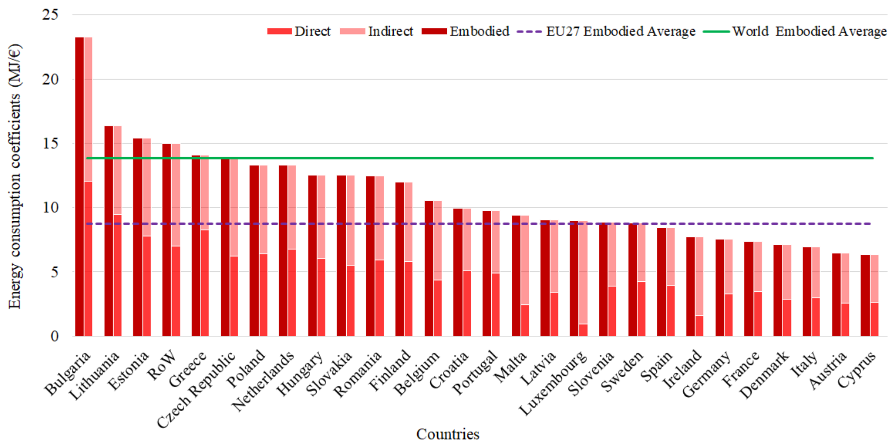

Figure 6 Direct and Indirect EECC

Figure 7 shows embodied energy consumption per capita in the EU27 in 2014, as well as the EU27 average value (0.43 TJ) and average world value (0.23 TJ). The EU27 average value is much higher than the average world value because the most of EU27 countries are developed countries with high industrial level and a large amount of energy consumption, which is opposite to the situation of energy consumption coefficients.

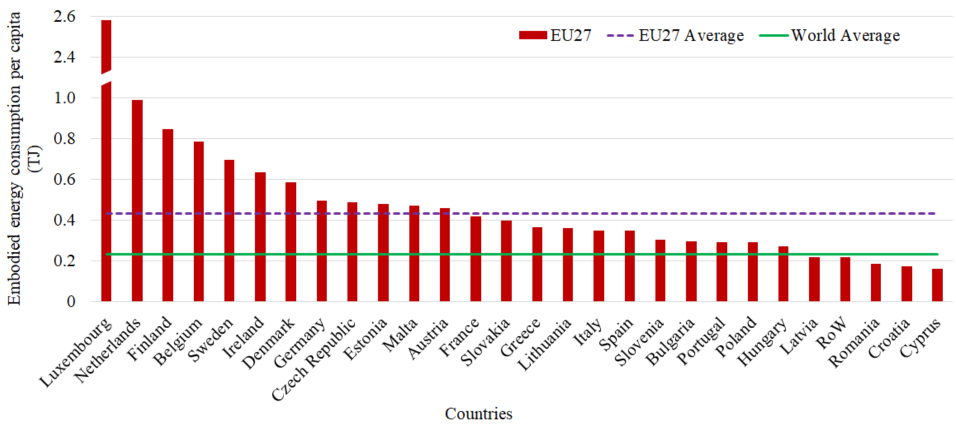

Figure 7 Embodied Energy Consumption Per Capita

2.3.3 Embodied CO_2 Emission

Figure 8 shows the EECC of the EU27. Figure 9 shows the direct and indirect EECC of EU27, as well as the EU27 average value and average world value. The EU27 average value, 285 t/M€, is much lower than the average world value, 637 t/M€. It indicates that the fossil fuel efficiency per monetary of EU27 is much higher than the average world value because of its higher lever technological development. However, there are three countries with an even higher value than the average world number, which are Bulgaria (914 t/M€), Estonia (825 t/M€) and Poland (647 t/M€). They are the least productive fossil fuel consumers in the EU27.

Figure 10 shows the embodied CO_2 emission per capita in the EU27 in 2014, as well as the EU27 average value (10.6 t) and average world value (14.1 t). The largest values of EU27 are in Luxembourg (115 t), followed by Ireland (30 t), Demark (26 t), Estonia (26 t), etc. Several countries perform even worse than the world average level. The best situations exist in Croatia (6.4 t), Romania (7.1 t), Hungary (8.6 t), Portugal (8.7 t). Compared with the embodied energy consumption per capita (Figure 7), it was evident that France, Sweden, Lithuania and Portugal are with higher embodied energy consumption amount, however with lower CO_2 emission value, because of their higher renewable energy consumption proportion.

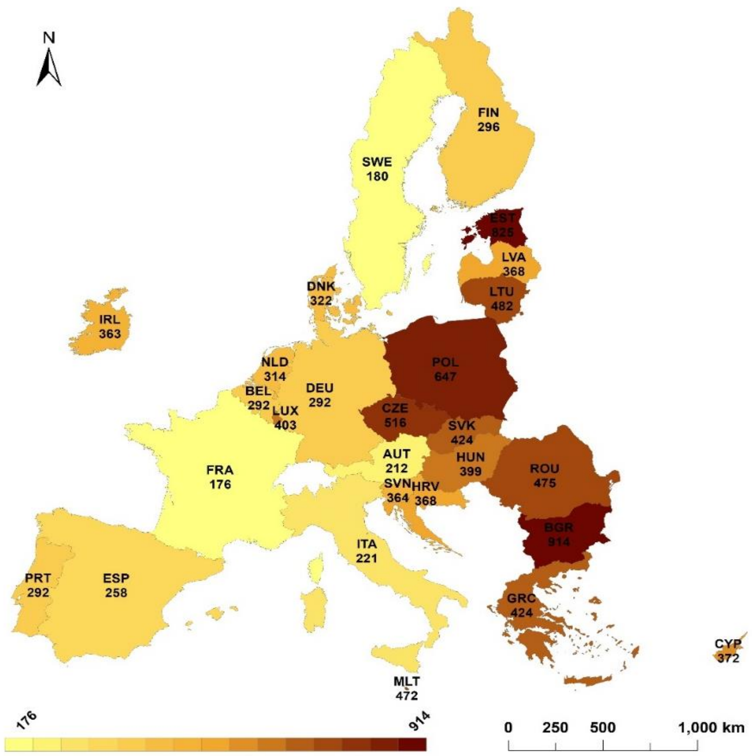

Figure 8 EECC of the EU27(t/M€)

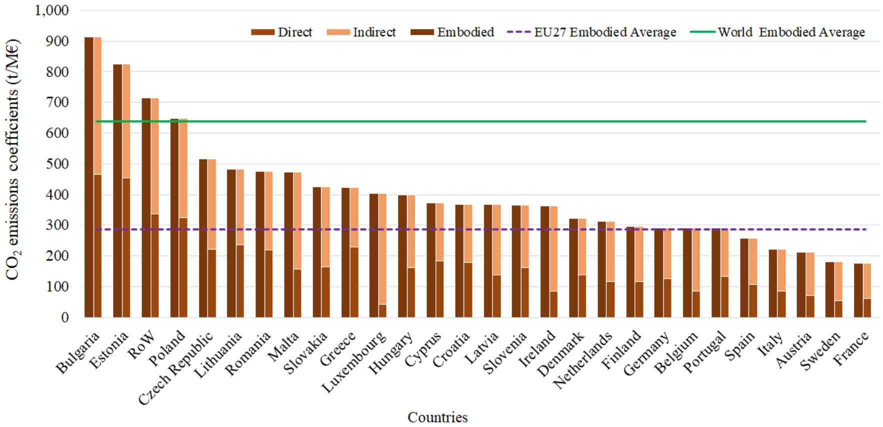

Figure 9 Direct and Indirect EECC

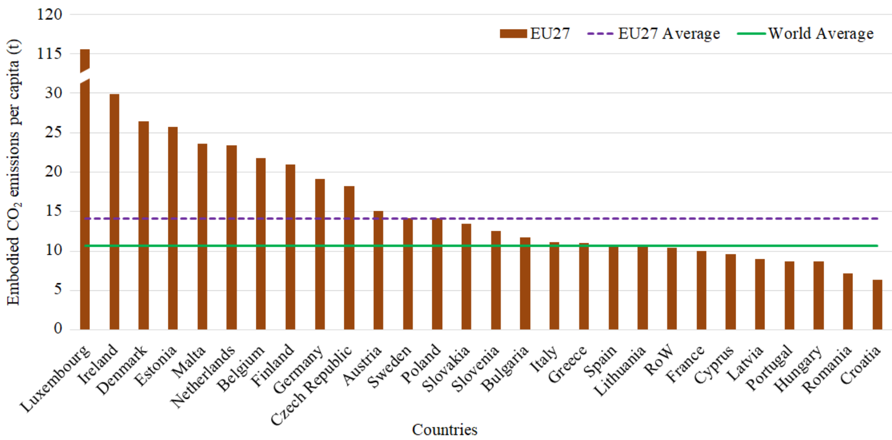

Figure 10 Embodied CO_2 Emission Per Capita

2.4 Implications and Suggestions

The international trade, economic development, policies, industrial structure, etc. are the most essential impact factors for WEC nexus of different countries. The embodied resource consumptions assessment offer a better idea for calculating the amount in the viewpoint of the supply chain. It contributes to better understand the input-output embodied resources. Direct and indirect EWCC, EECC and ECEC indicate the real source of national embodied resources. Proper policies or strategies should be made and applied according to the situations of different countries, for maximising water efficiency and energy efficiency as well we minimising carbon emission and environmental footprints.

2.5 Conclusion and Suggestions

The WEC nexus of the EU27 has been analysed in this study. The EIO approach is employed for calculating the EWCC, EECC and ECEC. The international trade, economic development, policies, industrial structure, etc. are the most essential impact factors for WEC nexus of different countries. The embodied resource consumptions assessment offer a better idea for calculating the amount in the viewpoint of the supply chain. It contributes to better understand the input-output embodied resources. Direct and indirect EWCC, EECC and ECEC indicate the real source of national embodied resources. Proper policies or strategies should be made and applied according to the situations of different countries, for maximising water efficiency and energy efficiency as well we minimising carbon emission and environmental footprints.

CHAPTER 3 GIS-IO METHODOLOGY TO REVEAL AND MAP WEGN NETWORK

3.1 Brief Abstract

The EU27 countries exert significant influence on the global pattern of CO_2-Emissions-Water-Energy (CWE) network. However, whether the associated benefits are similar for all countries is unclear. Here we constructed a EU27 multiregional input-output model at a sector level, to identify the inter-regional and -sectoral CWE flows, and clarify the regional, sectoral and worldwide patterns of EU27 CWE network. The results revealed an environmental inequality across the EU27 and impacts on the rest of the world. The EU27 countries contributed 1.4 Gt less CO_2 emissions, 64.5 Gm^3 less water utilisation and 4.9×10^4 PJ less energy consumption, compared to the rest of the world, while generating the equivalent economic output in 2014. This has a dramatic effect on the global environment. Germany, France and Italy are the biggest beneficiaries in the CWE network in the EU27.

3.2 Method

3.2.1 GIS

GIS has been wildly used for supporting environmental assessing and modelling, and being able to store, analysis/manage and visualise large spatial, non-spatial and temporal datasets. It has been the most efficient tool for dealing with geometric and alphanumerical data (Rossetto et al., 2018). GIS can help to identify and visualise WEGN data and the network flows visualisation, supporting decision-making, at sectoral and regional scale. This approach can manage location-based information, linking WEGN information databases among different countries to spatial maps to create visually displays (Torabi Moghadam et al., 2018). GIS method is employed to map the WEGN flows and visualise the WEGN in the EU27.

3.2.2 MOIO

An MRIO database for 28 economies (Format as shown by Table 2), including the EU27 countries and the rest of the world, was complied. There are 56 economic sectors and five final demand sectors for each economy. In the MRIO table, $z_{i,j}^{r,s}$ indicates the intersectoral monetary flow from sector *i* in economy *r* to sector *j* in economy *s*. $f_{i,k}^{r,s}$ means the final demand of term *k* in the economy *s* from sector *i* in economy *r*, (*k* = 1, 2, 3, 4, 5, indicate final consumption expenditures by households, final consumption expenditures by non-profit organisations serving households, final consumption expenditures by government, gross fixed capital formation, and changes in inventories and valuables). x_i^r is the total output of sector *i* in economy *r*. v_j^s indicates the added value of sector *j* in economy *s*. x_j^s is the total input of sector *j* in economy *s*. e_j^s is the direct energy input of sector *j* in economy *s*. w_j^s is the direct water input of sector *j* in economy *s* for both intermediate input and final demand. c_j^s are the direct CO_2 emissions from sector *j* in economy *s*.

Table 2 The format of MRIO table

From \ To			Intermediate Input					Final Demand			Total Output
			Economy 1		…	Economy 28		Economy 1	…	Economy 28	
			Sector 1	…	…	Sector 1	…				
Intermediate Output	Economy 1	Sector 1	$z_{i,j}^{r,s}$					$f_{i,k}^{r,s}$			x_i^r
		…									
	…	…									
	Economy 28	Sector 1									
		…									
Value-added			v_j^s								
Total Input			x_j^s								
Energy Input			e_j^s								
Water Input			w_j^s								
CO_2 Emissions			c_j^s								

Two types of balance in the MRIO table: i) Rest of world balance given by Equation (14); ii) input-output balance as shown by Equations (15), (16) and (17), which represent energy input-output balance, water input-output balance and CO_2 emission input-output balance.

$$x_i^r = \sum_{s=1}^{28} \sum_{j=1}^{56} z_{i,j}^{r,s} + \sum_{s=1}^{28} f_{i,k}^{r,s}, \tag{14}$$

$$e_j^s + \sum_{s=1}^{28} \sum_{j=1}^{56} \varepsilon_j^s \times z_{j,i}^{r,s} = \varepsilon_i^r \times (\sum_{s=1}^{28} \sum_{j=1}^{56} z_{i,j}^{r,s} + \sum_{s=1}^{28} \sum_{k=1}^{5} f_{i,k}^{r,s}), \tag{15}$$

where ε_j^s is the embodied energy intensity of sector *j* in economy *s*, $z_{j,i}^{r,s}$ indicates the intermediate flow from sector *j* in economy *r* to sector *i* in economy *s*, ε_i^r means the embodied energy intensity of sector *i* in economy *r*.

$$w_j^s + \sum_{s=1}^{28} \sum_{j=1}^{56} \omega_j^s \times z_{j,i}^{r,s} = \omega_i^r \times (\sum_{s=1}^{28} \sum_{j=1}^{56} z_{i,j}^{r,s} + \sum_{s=1}^{28} \sum_{k=1}^{5} f_{i,k}^{r,s}), \tag{16}$$

where ω_j^s is the embodied water intensity of output from sector *j* in economy *s*, $z_{j,i}^{r,s}$ indicates the intermediate flow from sector *j* in economy *r* to sector *i* in economy *s*, ω_i^r means the embodied water intensity of output from sector *i* in economy *r*.

$$c_j^s + \sum_{s=1}^{28}\sum_{j=1}^{56}\theta_j^s \times z_{j,i}^{r,s} = \theta_i^r \times (\sum_{s=1}^{28}\sum_{j=1}^{56} z_{i,j}^{r,s} + \sum_{s=1}^{28}\sum_{k=1}^{5} f_{i,k}^{r,s}), \quad (17)$$

where θ_j^s is the embodied CO_2 emission intensity of output from sector *j* in economy *s*, $z_{j,i}^{r,s}$ indicates the intermediate flow from sector *j* in economy *r* to sector *i* in economy *s*, θ_i^r means the embodied CO_2 emission intensity of output from sector *i* in economy *r*. Here we take the energy-relevant indicators, ε_j^s and ε_i^r, as examples, to show the calculating processes, and introduce the following notations:

$L = [(\varepsilon_1^1 \quad \cdots \quad \varepsilon_{56}^1) \quad \cdots \quad (\varepsilon_1^{28} \quad \cdots \quad \varepsilon_{56}^{28})]$,

$E = [(e_1^1 \quad \cdots \quad e_{56}^1) \quad \cdots \quad (e_1^{28} \quad \cdots \quad e_{56}^{28})]$,

$$Z = \begin{bmatrix} \begin{pmatrix} z_{1,1}^{1,1} & \cdots & z_{1,56}^{1,1} \\ \vdots & \ddots & \vdots \\ z_{56,1}^{1,1} & \cdots & z_{56,56}^{1,1} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{28,1} & \cdots & z_{1,56}^{28,1} \\ \vdots & \ddots & \vdots \\ z_{56,1}^{28,1} & \cdots & z_{56,56}^{28,1} \end{pmatrix} \\ \vdots & \ddots & \vdots \\ \begin{pmatrix} z_{1,1}^{1,28} & \cdots & z_{1,56}^{1,28} \\ \vdots & \ddots & \vdots \\ z_{56,1}^{1,28} & \cdots & z_{56,56}^{1,28} \end{pmatrix} & \cdots & \begin{pmatrix} z_{1,1}^{28,28} & \cdots & z_{1,28}^{28,28} \\ \vdots & \ddots & \vdots \\ z_{56,1}^{28,28} & \cdots & z_{56,56}^{1,28} \end{pmatrix} \end{bmatrix},$$

$$Y = \begin{bmatrix} \begin{pmatrix} \sum_{s=1}^{28}\sum_{j=1}^{56} z_{1,j}^{1,s} + \sum_{s=1}^{28}\sum_{k=1}^{5} f_{1,k}^{1,s} & & \\ & \ddots & \\ & & \sum_{s=1}^{28}\sum_{j=1}^{56} z_{56,j}^{1,s} + \sum_{s=1}^{28}\sum_{k=1}^{5} f_{56,k}^{1,s} \end{pmatrix} & & \\ & \ddots & \\ & & \begin{pmatrix} \sum_{s=1}^{28}\sum_{j=1}^{56} z_{1,j}^{28,s} + \sum_{s=1}^{28}\sum_{k=1}^{5} f_{1,k}^{28,s} & & \\ & \ddots & \\ & & \sum_{s=1}^{28}\sum_{j=1}^{56} z_{56,j}^{28,s} + \sum_{s=1}^{28}\sum_{k=1}^{5} f_{56,k}^{28,s} \end{pmatrix} \end{bmatrix}$$

Then the Equation (15) can be transformed into:

$$E + LZ = LY \quad (18)$$

The $(\mathrm{Y} - \mathrm{Z})$ reversible, then L can be gained based on Equation (18):

$$L = \mathrm{E}(\mathrm{Y} - \mathrm{Z})^{-1} \quad (19)$$

Based on the notation L and Equation (6), we can obtain the ε_j^s and ε_i^r. Then the import embodied energy consumption (IEE_i^r) and export embodied energy consumption (EEE_i^r) of sector *i* in economy *r* can be given as:

$$IEE_i^r = \sum_{j=1}^{56} \varepsilon_j^s \times z_{j,i}^{r,s}, (r \neq s) \quad (20)$$

$$EEE_i^r = \sum_{j=1}^{56} \varepsilon_i^r \times z_{i,j}^{r,s}, (r \neq s) \quad (21)$$

If both r and s belong to the EU27, then we can obtain the embodied energy consumption of EU27 countries that import from the EU27 members. Otherwise, we get the total value of embodied energy consumption that EU27 countries import from the whole world. The proportions can be obtained as well. Based on Equations (20) and (21), we can obtain the import embodied energy consumption (IEE^r) and export embodied energy consumption (EEE^r) of economy r:

$$IEE^r = \sum_{i=1}^{56} IEE_i^r \tag{22}$$

$$EEE^r = \sum_{i=1}^{56} EEE_i^r \tag{23}$$

The net value can be given as:

$$DEE^r = IEE^r - EEE^r \tag{24}$$

The import embodied water consumption (IWE^r), export embodied water consumption (EWE^r), import/export difference for embodied water (DWE^r), import embodied CO_2 emission (ICE^r), export embodied CO_2 emission (ECE^r), and the import/export difference for embodied CO_2 emissions (DCE^r), of economy r are allocated in the same way. The coefficients of embodied CO_2 emissions, water utilisation and energy consumption are from our previous publication (Wang et al., 2020a), in which the data is consistent with that of this study. Because the coefficients of EU27 average coefficients are lower than the worldwide average value, we assume if the same amount of GDP is generated, EU27 can emit less GHG emissions and consume less water and energy. There should be a considerable difference or reduction. Based on the above equations, we can obtain the amount of embodied-CO_2 emissions, -water and -energy that EU27 import from the rest of the world, given as D. Then the reduction amount (R) by EU27 can be given as:

$$R = D(A_{WO}/A_{EU} - 1) \tag{25}$$

3.3 Regional Patterns of EU27 CWE Network

This study quantified the embodied CO_2 emissions chain (Figure 11), water chain (Figure 12) and energy chain (Figure 13) among the EU27 countries. The CO_2 emissions chain of the embodied CO_2 emissions flows among the EU27 countries during interregional trade, the water chain as the embodied water flows, and the energy chain as the embodied energy flows was defined. The net value of the embodied CO_2 flows revealed the role different countries play in international trade varied widely. Negative means that the country exported more embodied CO_2 and positive indicates that the country imported more embodied CO_2 than it exported. The countries with negative values of embodied CO_2 emissions imports were victims in this CO_2 emissions chain of EU27 interregional trade (Figure 11). Whereas countries with positive embodied CO_2 values were beneficiaries. Beneficiaries leave massive embodied CO_2 emissions with the victims (i.e. upstream countries) during interregional trade, via importing semi-finished or finished products (Wang et al., 2020a). Although the upstream countries obtain considerable economic benefits with access to the downstream countries' economies, they bear the consequences of environmental pressures.

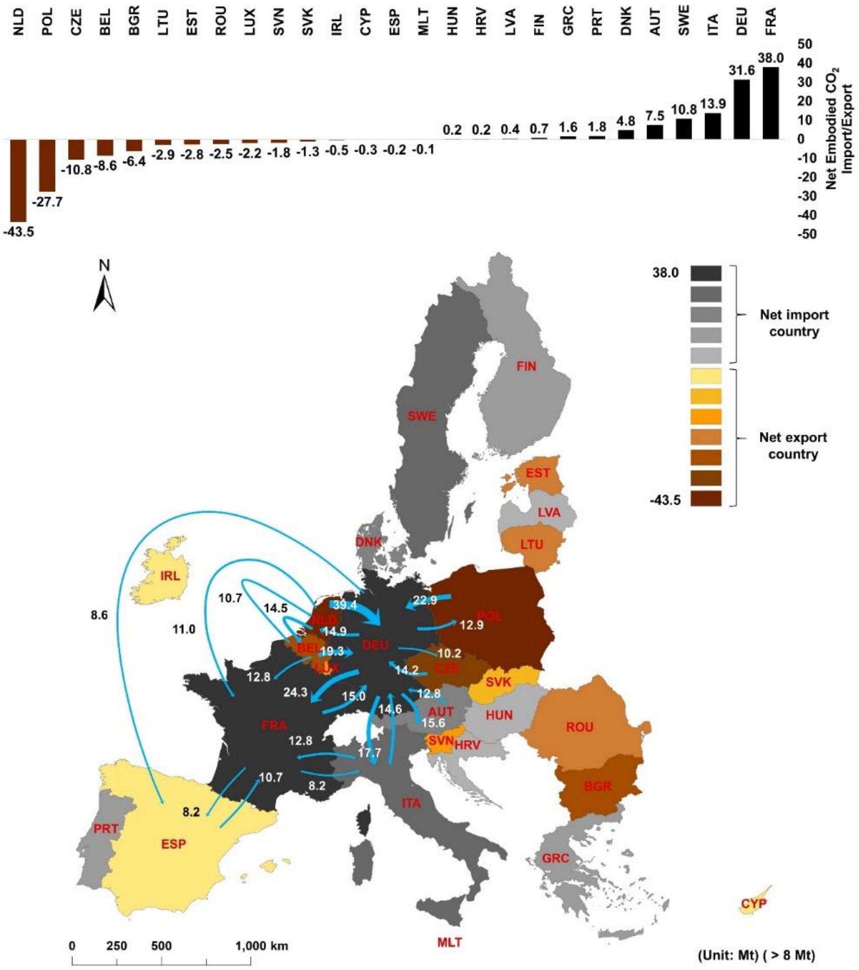

Figure 11 Embodied CO_2 Emissions Chain (> 8 Mt) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (brown) or importers (black). The chains are listed in terms of flows to other countries for amounts greater than 8 Mt.

Europe uses about 243 Gm^3 of water annually in economic activity (European Environment Agency, 2018). Agriculture accounts for the largest amount of water consumption at 50% with energy production using a further 28% of water annually (European Environment

Agency, 2020). The Netherlands has the most net outflow value in the water chain of EU27 (Figure 12), which is -3,502 Mm^3, followed by Italy at -2,717 Mm^3, which together, account for 62.7% of total net outflow amount within EU27. Comparatively, Germany and France have the highest net import flow values in the water supply chain, which are 4,127 Mm^3 and 2,931 Mm^3, accounting for 41.6% and 30.0% of the total amount within EU27.

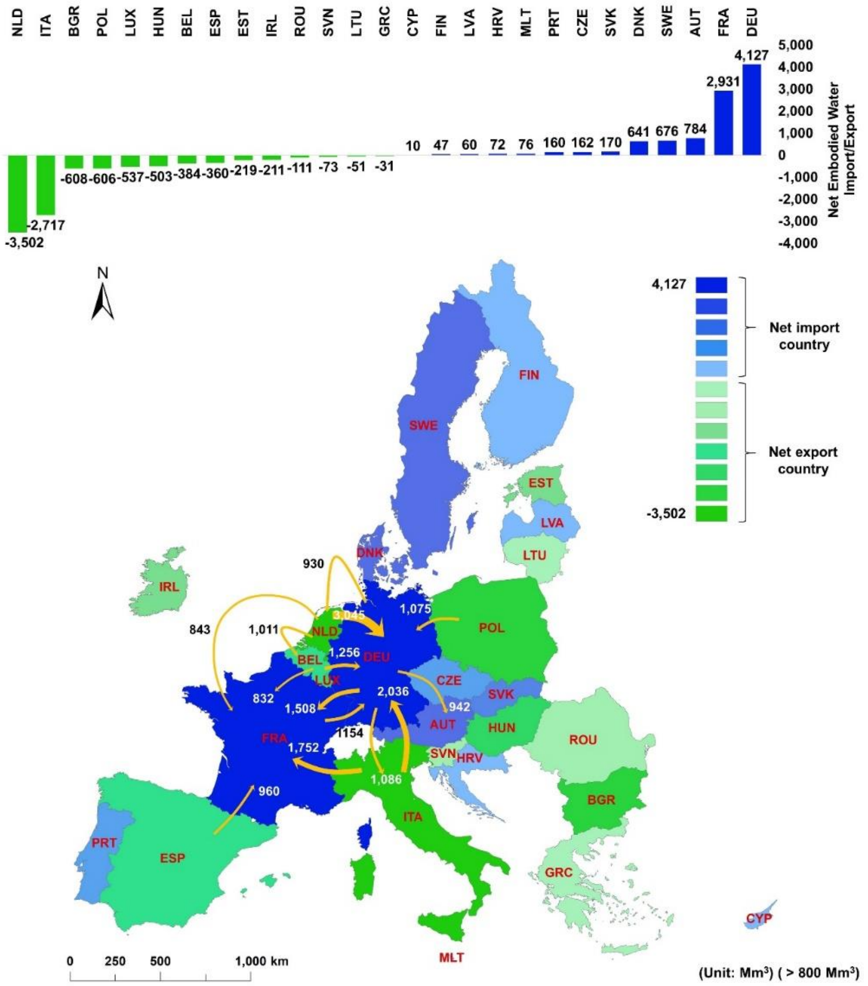

Figure 12 Embodied Water Chain (> 800 Mm^3) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (green) or importers (blue). The chains are listed in terms of flows to other countries with the amount greater than 800 Mm^3.

The Netherlands leads the list of net embodied energy outflows (Figure 13), -3.5×10^3 PJ in the EU27, which is much higher than the total amount of other EU27 countries. It serves as the key supplier to Germany (2.5×10^3 PJ), Belgium (7.1×10^2 PJ), France (6.5×10^2 PJ) and Italy (4.8×10^2 PJ), in total account for 86.1% of its embodied energy export. This is due to the fact that the Rotterdam super port in the Netherlands with its large refining and petrochemicals sector and pipeline connections to neighbouring refineries in Belgium and Germany is a key energy hub for North-West Europe. Germany dominates the list of net import embodied energy import, with 2.4×10^3 PJ, followed by France at 1.2×10^3 PJ. These two countries have more than 1 ×10^3 PJ net import embodied energy.

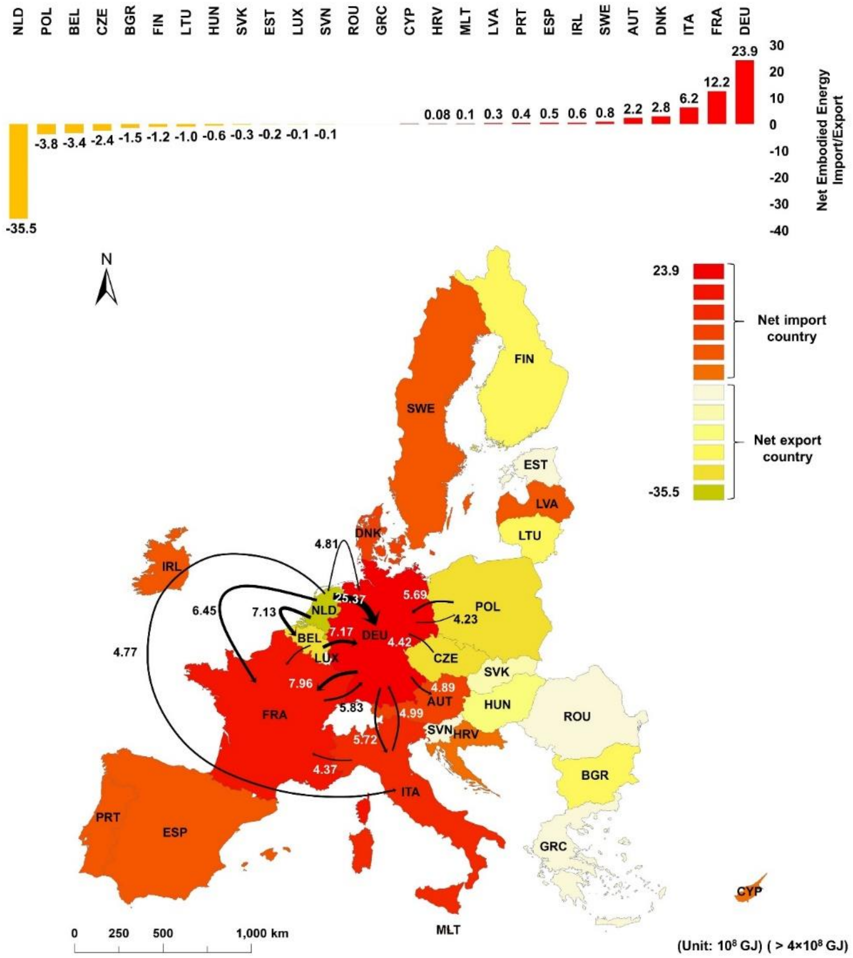

Figure 13 *Embodied Energy Chain (> 4×10^8 GJ) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (yellow) or importers (red). The chains are listed in terms of flows to other countries, with the amount greater than 4×10^8 GJ.*

Quantifying the import and export of embodied CWE flows can help in obtaining insights into the regional patterns of CWE network. The interregional trade structure of EU27 directly causes its CWE nexus. The bigger economies, usually have larger CO_2 emissions, water and energy flows. The structure of the embodied CWE import/export (Figure 14) is roughly consistent with the GDP size of EU27 in 2014 (GDP European countries, 2020). Germany, France and Italy dominate the lists of embodied CWE imports understandably.

Trade relevant embodied CO_2 imported within the EU27 is 736 Mt in total (Figure 14a). Germany, France and Italy together account for 46.3% of that, in which Germany shared 24.8%, followed by France at 12.5% and Italy at 8.9%. Unlike the import structure, the top embodied CO_2 export country is Germany at 151 Mt, with 20.5% of total export embodied CO_2 of EU27, followed by the Netherlands at 89.4 Mt at (12.2%), Belgium at 62.1 Mt (8.4%) and Poland at 60.4 Mt (8.2%). This illustrates why France has the most net value of embodied CO_2 import, and the Netherlands is the opposite with a net export of the most embodied CO_2 (Figure 11). The Netherlands is one of the most CO_2-intensive (per capita) countries in the EU27 (Amores et al., 2019). This is positive because it exports the most embodied CO_2 to downstream countries that have higher efficiency.

Trade relevant embodied water demand within EU27 was 52,461 Mm^3 in total (Figure 14b), of which Germany, France and Italy contribute 13,278 Mm^3 (25.3%), 7,185 Mm^3 (13.7%) and 4,552 Mm^3 (8.7%), with 47.7% of the total amount. The Netherlands and Italy have higher net embodied water outflows, and have higher embodied water consumption per capita (Wang et al., 2020a), which means they have lower embodied water efficiencies. Agricultural water-intensive EU27 countries in Southern and Eastern Europe are expected to suffer more hardships with increasing extreme weather events and higher summer temperatures associated with global warming.

Trade relevant embodied energy imports within EU27 was 2.6×10^4 PJ in total, of which Germany (7.2×10^3 PJ), France (3.4×10^3 PJ) and Italy (2.4×10^3 PJ) account for 49.9%. Inversely, Netherlands and Germany export most embodied energy. But the Netherlands has lower energy efficiency in both monetary units and per capita units (Wang et al., 2020a). The current situation, with the Netherlands exporting more embodied energy, means it should improve its efficiency. In planning for future energy flows and energy security in Europe, the EU27 are looking to sector coupling with the electrification of transport and heating and cooling loads.

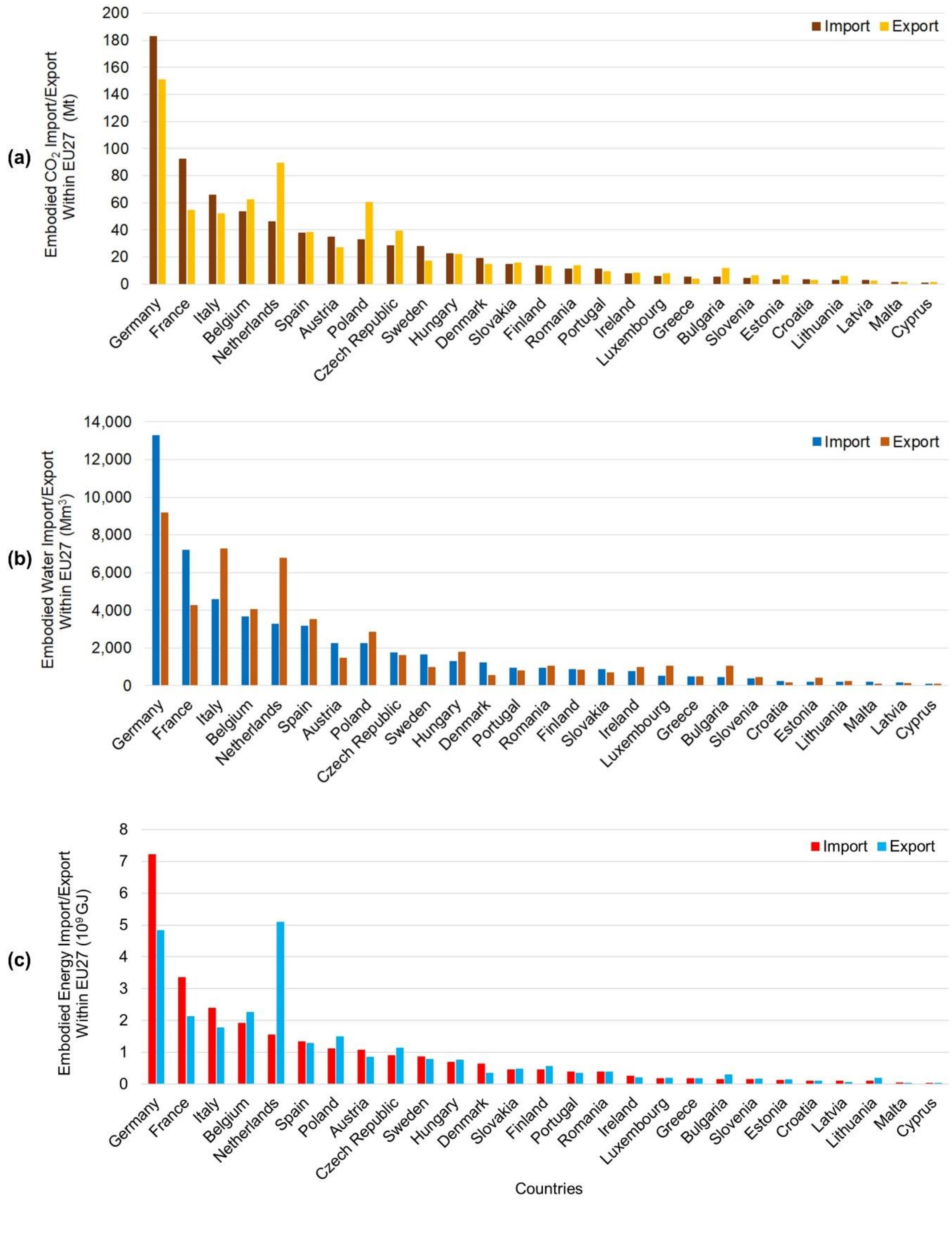

Figure 14 Embodied CWE Import/Export within EU27.

3.4 Sectoral Patterns of EU27 CWE Network

The CO_2 chain within EU27 is mainly shaped by MAN, SOC and CON sectors (Figure 15a), accounting for 82.1% of the total trade relevant embodied CO_2. Manufacturing contributed 451.3 Mt embodied CO_2, where 34.1% is from the net upstream countries (with net negative values), and the remainder (65.9%) is from downstream countries. This underscores the large impacts of trade among the net downstream countries (with net positive values), although, the net upstream countries supply massive resources, they do not benefit much from the commercial chain. All ten sectors showed a similar structure, with lower share by net upstream countries than by the net downstream countries.

The important question here for these countries and the other more industrialised EU27 countries (e.g. the Netherlands, Austria, Denmark, Sweden, Belgium, Ireland and Poland) is what do they all gain from EU membership. In reality, a bigger bargaining power in trade agreements and a larger market. The UK is still charting unknown waters in terms of reaching an individual trade agreement with the different trading pacts (e.g. North American Free Trade Agreement (NAFTA), World Trade Organization (WTO), the Association of South-East Asian Nations (ASEAN) etc.). Based on the experience of Switzerland, this will be an unknown, long and windy road for the UK. This is putting the UK under further pressure to decarbonise.

In the EU27's water chain (Figure 15b), MAN and SOC contribute 83.7% of the total trade-related embodied water. Manufacturing contributed 32,091 Mm^3, embodied water consumption, where 40.2% (12,892 Mm^3) is from net upstream countries, and the remaining 59.8% (19,199 Mm^3) is from the net downstream countries. The second key sector is SOC, with 7,798 Mm^3 trade-related embodied water, where 45.2% is from net upstream countries and 54.8% from net downstream countries. For the CON sector, 40.9% of trade relevant embodied water is from net upstream countries and the remaining, 59.1%, is from downstream countries. In contrast, the WAS and WAT sectors have a higher share from net upstream countries than from net downstream countries, although these two sectors account for only 2% of the total amount.

In the energy chain (Figure 15c), the key transmission sector is MAN, contributing 1.7×10^4 PJ and accounting for 64.1%, which is much higher than the total amount of the remaining sectors. Of the MAN relevant, 40% is from net upstream countries, and 60% is from downstream countries. The key sectors are SOC and CON, accounting for 12.1% and 7.2% of flows in the energy chain. This indicates that the above three sectors significantly shape the energy supply chain structure in the EU27.

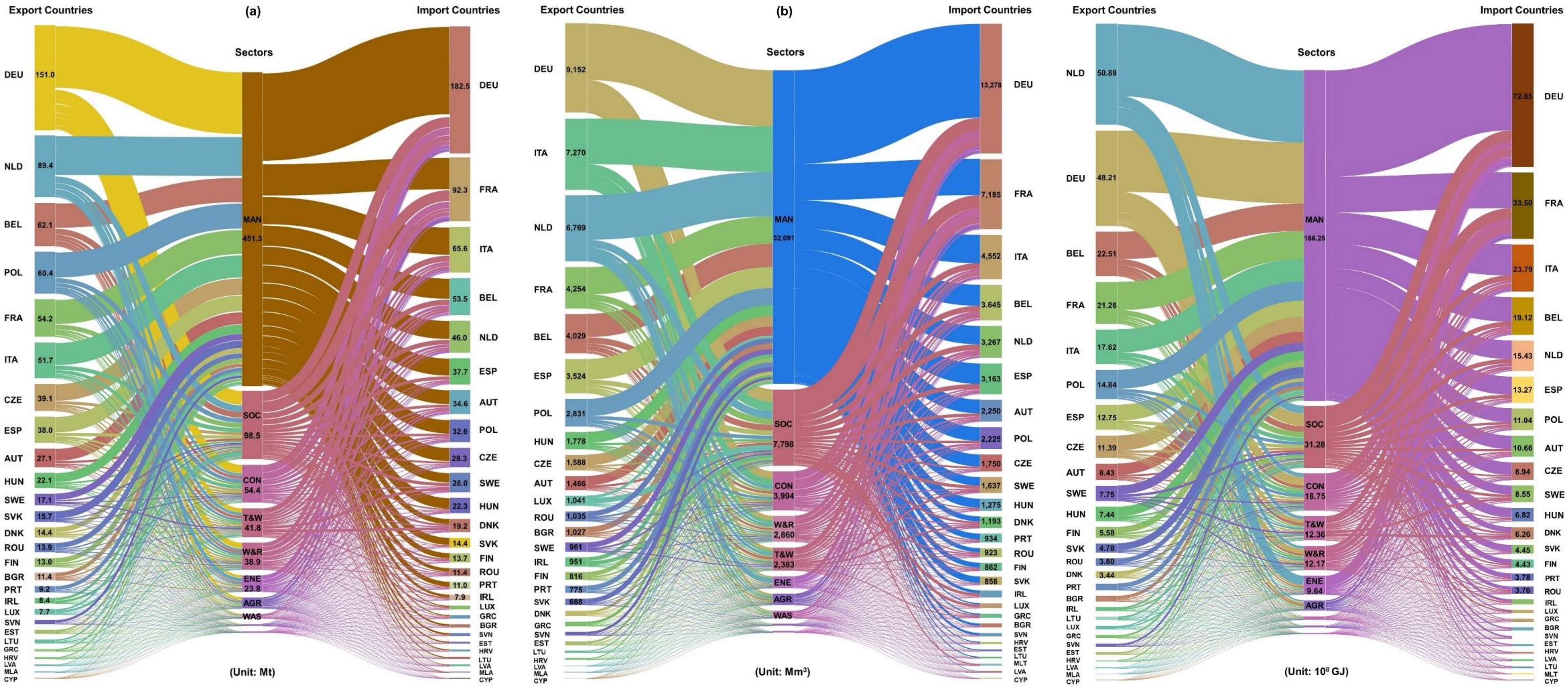

Figure 15 CWE Chain in Sector Level of EU27.

Agriculture (AGR), mining and quarrying (M&Q), manufacturing (MAN), energy supply (ENE), water supply (WAT), waste management (WAS), construction (CON), wholesale and retail trade (W&R), transport and warehousing (T&W), social services (SOC).

3.5 Global Patterns of EU27 CWE Network

EU27 imported significant resources from the whole world in 2014, including CWE. Quantification of the global patterns of EU27 CWE network (Figure 16) is crucial for understanding the impact that the EU27 has on the whole world in terms of climate change, water scarcity and energy consumption. The EU27 countries transferred 38.7% of embodied CO_2 within the EU27 (Figure 16a) while it imported 61.3% from the rest of the world. It was assumed in this analysis that if the same amount of GDP is generated, the EU27 could emit 1.4 Gt less CO_2 than the rest of the world. Austria Hungary, the Czech Republic, Estonia and Slovakia are the only countries that import more embodied CO_2 from the EU27 than from the rest of the world in 2014. In contrast, all other 22 EU27 countries import more embodied CO_2 from the rest of the world than from the EU27.

Approximately 32% of the imported embodied water of EU27 countries is from the EU27 (Figure 16b). The remaining 68% is from the rest of the world, which is 111 Gm^3. If the same amount of GDP generated is assumed, then EU27 could consume 64.5 Gm^3 less water than the rest of the world. Austria is the only country of EU27 that imported less embodied water from the rest of the world than from EU27 countries.

For EU27 countries, 48.5% imported embodied energy is from the EU27 (Figure 16c). The rest 51.5% is from the rest of the world, which is 2.8×10^4 PJ. If the same amount of GDP generated is assumed, then the EU27 will consume 4.9×10^4 PJ less energy than the rest of the world, because of the higher efficiency of EU27 based on our previous results (Wang et al., 2020a). Thirteen EU27 countries imported more embodied energy from the EU27 than from the rest of the world (e.g. Austria to Croatia), mainly due to lack of infrastructure and historical links to neighbours. The other 14 countries imported more from the rest of the world than from the EU27.

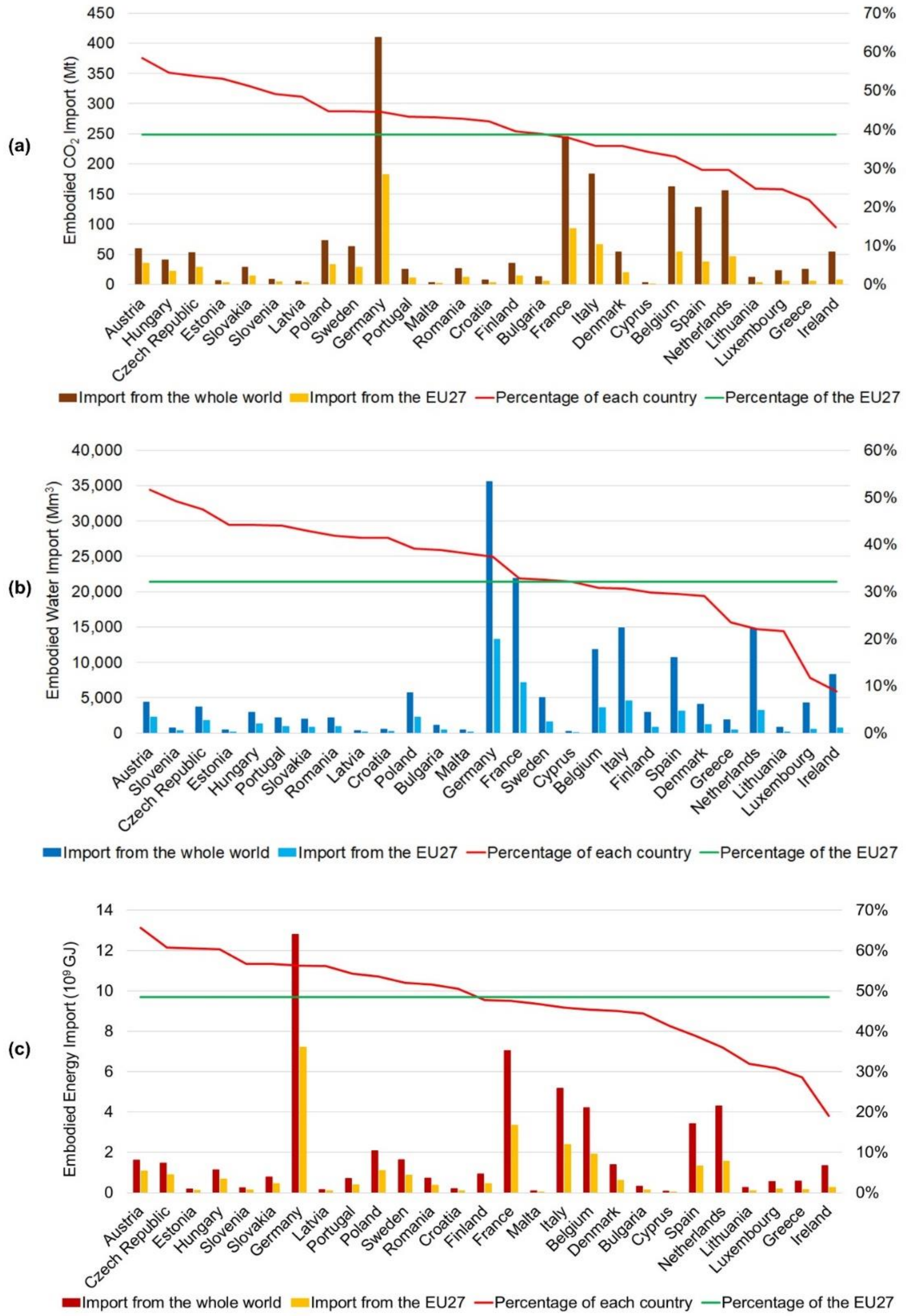

Figure 16 Importation Sources Distribution of Embodied-CO_2 (a), -Water (b), -Energy (c) of EU27. Import from the world: the total amount of embodied resource imports of a specific country; Import from the EU27: the total amount of embodied resource that imported from the EU27 countries; Percentage of each country: the ratio of "import from the EU27" to "import from the world"; Percentage of the EU27: the ratio of the total import of EU27 countries from EU27 to the total import of EU27 countries from the whole world.

3.6 Conclusions and Discussions

With rapid globalisation, regional sustainability should be considered from the global and multi-sector level, instead of regional single-sector basis, especially in terms of climate change, and the CWE trilemma. The study quantified the CWE flows of EU27 from three angles: regional patterns, sectoral patterns and global patterns. The exploration revealed apparent disparities between different countries within EU27, different sectors, as well in the EU27 as a block of nations compared and the rest of the world. Reducing CO_2 emissions, and improving water and energy efficiency are key drivers for making progress in transitioning to a more environmentally conscious economy in line with the UNSDGs at local, regional and global levels. Disappointingly, the CWE chain in the EU27 is imbalanced and inequitable, and the disparities in CWE flows across the EU27 are significant. Although the population, economy size and GDP of different EU27 countries are very different, there is a clear difference in the efficiencies of CO_2 emissions, water utilisation and energy consumption of different EU27 countries related to products and goods.

The CWE nexus should be examined in a holistic approach by the EU27 and other larger trading region to battle climate change, environmental degradation, species diversity losses and economic inequities. This should be undertaken in tandem with a careful examination of the ten key sectors considering the existing NAFTA, WTO, ASEAN trading pacts so that any targets are implemented equitably on a global stage in line with the UN Sustainable Development Goals. In conclusion, industry, the banking sector and geopolitical stability should be carefully managed in the rebalance of the CWE virtual footprint flows as part of a new global UN Sustainable Development Goals deal as never before have the cards of our political leaders been stronger because the COVID-19 pandemic as currently the flow of money and the wheels of industry are unusually dependent on the goodwill of the civic consciousness of mankind.

CHAPTER 4 IO-SCN ASSESSMENT TOOL FOR QUANTIFYING WEGN COEFFICIENTS

4.1 Brief Abstract

China has one of the fastest-growing economies worldwide, consuming large amounts of resources but also experiencing significant environmental issues. Water, energy, and carbon play significant roles in regional sustainable development. It is critical to understand the Water-Energy-Carbon Emissions nexus, and this study explores the nexus using the Environmental Input-Output model. The embodied water and energy consumption and embodied carbon emissions are assessed. The water and energy consumption coefficients and CO_2 emission coefficients are analysed. The main results are: 1) The Water-Energy-Carbon Emissions nexus characteristics of light industry, heavy industry, and service industry were similar: water-intensive, energy-intensive, and carbon-emission-intensive; 2) Agriculture consumed 64.38% of the national water supply; however, the water utilisation efficiency was only 32%; 3) Agriculture had much higher water consumption and direct water consumption coefficients. Light industry, service industry, and heavy industry were the top three sectors in terms of indirect water consumption coefficients; 4) Heavy industry, light industry, and service industry were the top three sectors with the highest indirect energy consumption coefficients and carbon emission coefficients. The consumption (water and energy) and CO_2 emission coefficients can provide significant support for sustainable development strategies. This study provides a better understanding of the Water-Energy-Carbon Emissions nexus in China.

4.2 Method - EIO Model

The general framework of the EIO model is shown in Table 3. In the model, X_{ij} is the flow from sector *i* to sector *j*; F_i is the final demand of sectors *i;* V_j represents the added value of sector *j*; X_i is the total output of sector *I;* X_j is the total input of sector *j;* E_{kj} is the amount of energy type k directly consumed by sector *j;* W_j means the direct water consumption by sector *j*. C_j represents direct carbon emissions of sector j. X_{ij}, F_i, X_i, X_j X_j, and V_j are expressed in monetary units. E_{kj}, W_j, and C_j are measured in physical units.

Table 3 The input-output table of the EIO model, adopted and developed from (Yang et al., 2018b).

		Intermediate demand 1, 2, …, n	Final demand	Total output
Intermediate input	1 2 … n	X_{ij}	F_i	X_i
Value-added		V_j		
Total input		X_j		
Energy input	1 2 … n	E_{kj}		
Water input		W_j		
Carbon emissions		C_j		

4.2.1 Sectoral Embodied Water Consumption

The direct water consumption coefficient c_j^w and the direct consumption coefficients c_{ij} are mandatory for assessing the sectoral embodied water consumption:

$$c_j^w = W_j / X_j \, , (j = 1, 2, 3, \dots, n) \tag{26}$$

$$c_{ij} = X_{ij} / X_j , (i = 1, 2, 3, \dots, m; \; j = 1, 2, 3, \dots, n) \, , \tag{27}$$

where the variables W_j, X_j, X_{ij}, and X_j have been explained in Table 3.

The row vector of embodied water consumption W^{em} is calculated as follows:

$$W^{em} = C^w (I - C)^{-1} F^{diag} \, , \tag{28}$$

where C^w means the direct water consumption coefficients matrix (1 × n) with elements c_j^w; I represents the identity matrix (n × n); C is the direct consumption coefficients matrix (n × n), and F^{diag} is the diagonal matrix transformed from the total output column vector F_i.

The embodied energy consumption was assessed based on the following equation:

$$E^{em} = C^e (I - C)^{-1} F^{diag} \, , \tag{29}$$

where E^{em} represents the sectoral embodied energy consumption matrix (m × n) with elements E_{kj}^{em}; C^e is the direct energy consumption coefficients matrix (m × n) with elements c_{kj}^e defined as follows:

$$c_{kj}^{e} = E_{kj}/X_j, (k = 1, 2, 3, \dots, m;\ j = 1, 2, 3, \dots, n). \tag{30}$$

4.2.2 Sectoral Embodied Carbon Emissions

The direct carbon emissions coefficients c_j^c can be defined as:

$$c_j^c = C_j/X_j \text{ (j = 1, 2, 3, …, n)} . \tag{31}$$

The embodied carbon emissions are assessed based on the following equation:

$$C^{em} = C^c(I - C)^{-1} F^{diag} , \tag{32}$$

where C^c is the row vector of direct carbon emissions, illustrating the direct carbon emission coefficients with elements c_j^c.

The CO_2 estimation from energy consumption was calculated following the equation:

$$C_j = \sum_{k=1}^{m} A_{kj} \times J_k \times EF_k \times \frac{44}{12}, (j = 1, 2, 3, \dots, n) , \tag{33}$$

where A_{kj} is the consumption amount of energy type *k* by sector *j* expressed in mass or volume units; J_k is the net calorific value of energy type *k*, which comes from the IPCC (IPCC, 2019); EF_k is the emission factor of CO_2 from energy type *k*, which includes the carbon oxidation factor; $\frac{44}{12}$ is the conversion factor between carbon and CO_2 (Ouyang and Lin, 2015).

4.2.3 Sectoral Water and Energy Consumption and Carbon Emission Coefficients

For allocating the embodied consumption coefficients of water and energy as well as the embodied CO_2 emission coefficients, the following equations are defined:

$$H^w = C^w(I - C)^{-1} \tag{34}$$

$$H^e = C^e(I - C)^{-1} \tag{35}$$

$$H^c = C^c(I - C)^{-1} , \tag{36}$$

where H^w and H^e are the matrices of sectoral embodied water and sectoral embodied energy consumption coefficients and H^c is the matrix of sectoral embodied CO_2 emission coefficients. Based on the above equations, the indirect water and indirect energy consumption coefficients as well as indirect CO_2 emission coefficients T^w, T^e, and T^c can be obtained as follows:

$$T^w = H^w - C^w \tag{37}$$

$$T^e = H^e - C^e \tag{38}$$

$$T^c = H^c - C^c \ . \tag{39}$$

4.2.4 Sectoral Water and Energy Consumption and Carbon Emission Indexes

The sectoral embodied water consumption indexes are the results of dividing the embodied water consumption coefficients of each sector by the average embodied water consumption coefficients of all sectors. The following indexes are allocated in the same way: sectoral embodied energy consumption indexes, sectoral CO_2 emissions indexes, direct and indirect water consumption indexes, direct and indirect energy consumption indexes, and direct and indirect CO_2 emission indexes.

4.3 Results

4.3.1 Sectoral Water Consumption

Figure 17 shows the sectoral embodied water consumption and sectoral total water consumption in China. Agriculture led the list of total water consumption at 3,883×10^8 m^3 and contributed to 64.38% of the national total water consumption of China, followed by LI (583×10^8 m^3), SI (513×10^8 m^3) and HI (389×10^8 m^3). LI contributed the most embodied water consumption, which was 1,763×10^8 m^3, Ag was 1,571×10^8 m^3, HI was 1,333×10^8 m^3, Co was 12×10^8 m^3, and SI was 1,196×10^8 m^3. These five sectors were the main consumers, accounting for the overwhelming bulk of embodied water consumption, which was 96.83% in total.

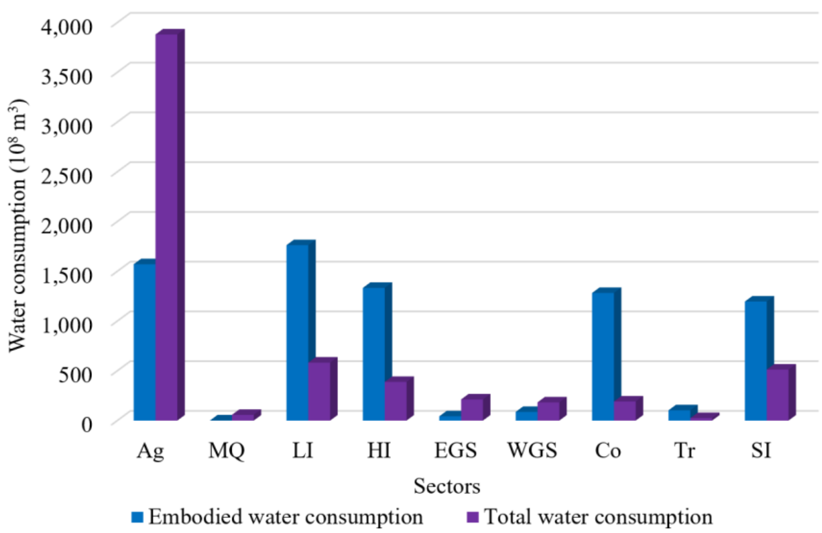

Figure 17 Sectoral water consumption.

4.3.2 Sectoral Energy Consumption

Figure 18 shows the sectoral energy consumption, including sectoral embodied energy consumption, and total energy consumption. EGS, LI, and HI led the list of sectoral total energy consumption at 559×10^{17} J, 405×10^{17} J, and 287×10^{17} J followed by Tr and SI. Sector HI contributed the most embodied energy consumption, 648×10^{17} J, followed by LI, 509×10^{17} J, Co, 380×10^{17} J, and SI, 306×10^{17} J. Those four sectors comprised 91.46% of the total of national embodied energy consumption.

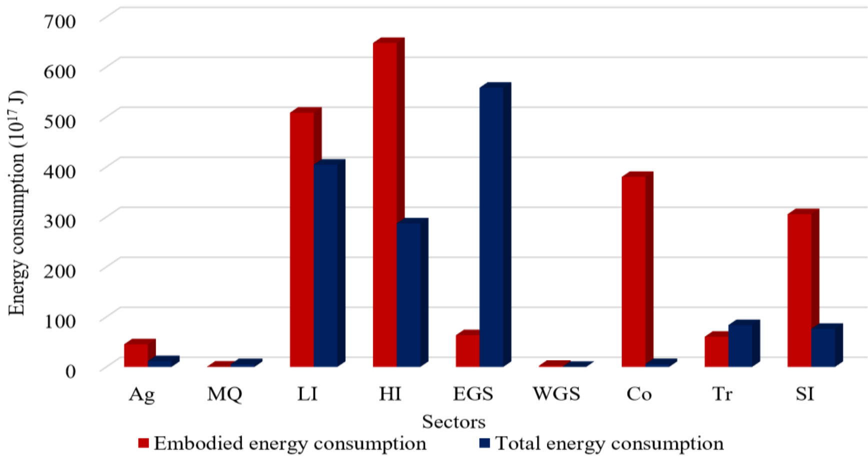

Figure 18 Sectoral energy consumption.

4.3.3 Sectoral CO_2 Emissions

The sectoral total CO_2 emissions and sectoral embodied CO_2 emissions are presented in Figure 19. For sectoral total CO_2 emissions, EGS emitted the most at 38×10^{8} t, followed by LI and HI. These three sectors contributed 87.72% of the total overall CO_2 emissions in China. HI was the largest embodied CO_2 emitter at 47×10^{8} t, followed by LI, Co, and SI with 35×10^{8} t, 26×10^{8} t, and 21×10^{8} t. Sectors Co, HI, SI and LI were with higher embodied CO_2 emissions than total CO_2 emissions. It indicates that a significant part of embodied CO_2 emissions of these sectors came from upstream sectors. Improving the environmental performance of upstream sectors is a considerable and effective way for them to be more environmentally friendly.

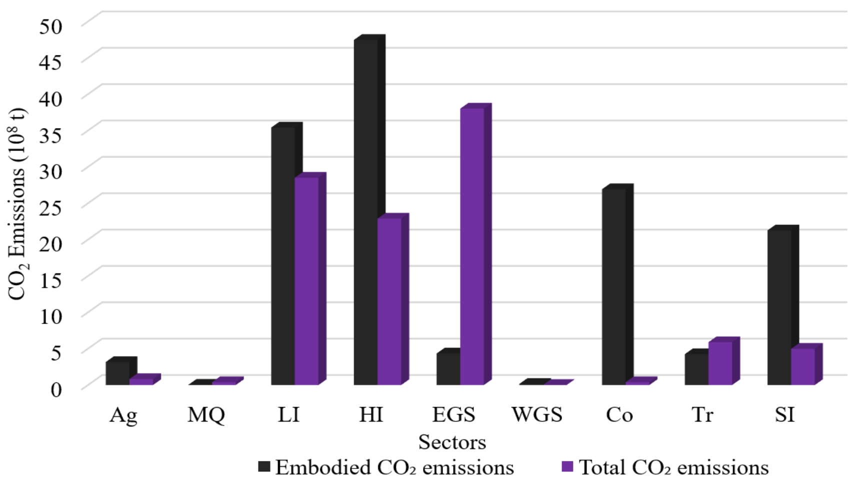

Figure 19 Sectoral CO2 emissions.

4.3.4 Characteristics of the Sectoral WEC Nexus

4.3.4.1 Sectoral Water and Energy Consumption and Carbon Emission Coefficients

Figure 20, Figure 21, and Figure 22 show the respective water consumption coefficients, energy consumption coefficients, and CO_2 emission coefficients. Taking all these three figures into consideration, Sectors MQ, LI, HI, Co, Tr, and SI had an apparent concordance in terms of water and energy consumption coefficients as well as CO_2 emission coefficients. The indirect embodied water and energy consumption coefficients, as well as the indirect embodied CO_2 emission coefficients of these sectors, were much higher than the direct coefficients. This demonstrated that a significant part of the environmental burden of these sectors came from upstream sectoral economic activities. The water protection and saving, energy conservation as well as low carbon emissions of upstream sectors can crucially affect these sectors in terms of resources saving and emissions mitigation.

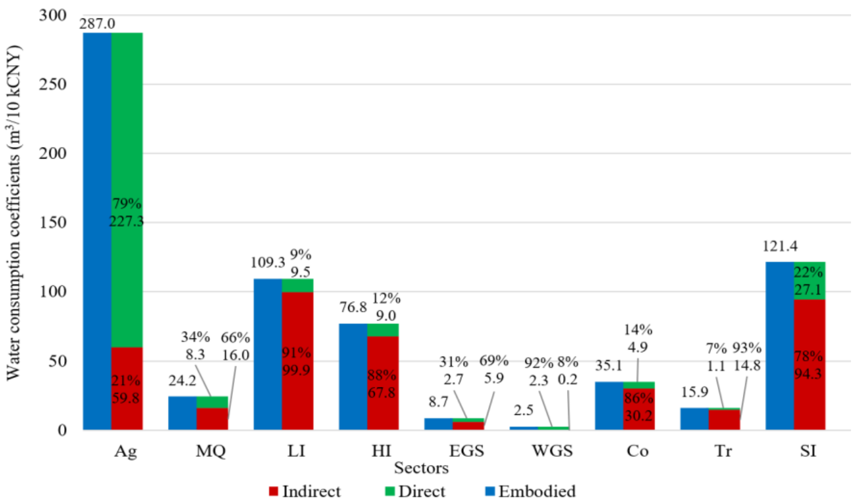

Figure 20 Water consumption coefficients.

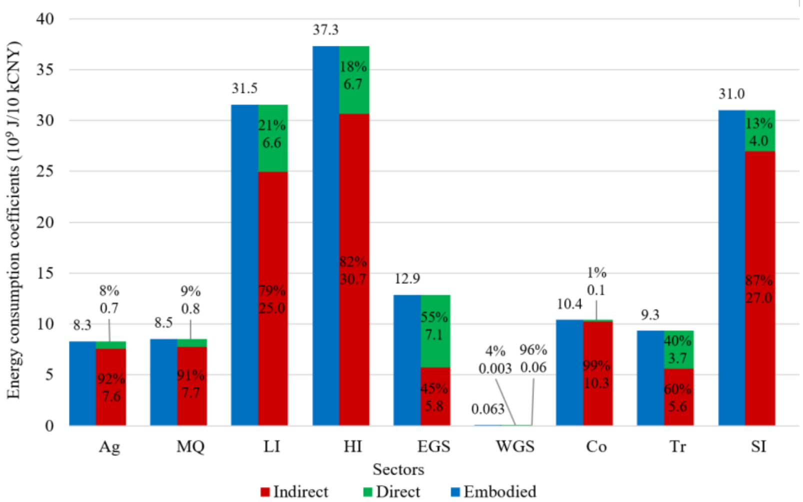

Figure 21 Energy consumption coefficients.

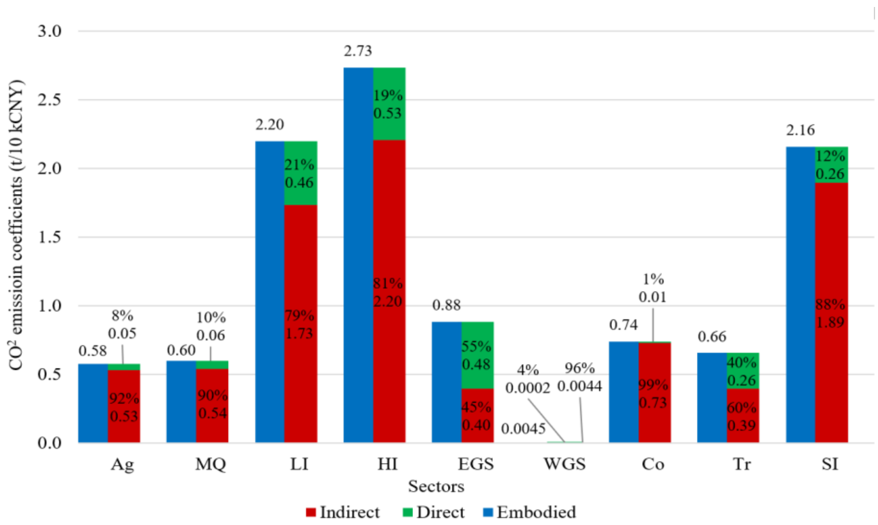

Figure 22 CO_2 emission coefficients.

4.3.4.2 Consumption and Emissions Structure

In this section, the sectoral embodied water consumption indexes, energy consumption indexes and CO_2 emission indexes are presented in Table 4. The WEC nexus characteristics of sectors LI, HI, and SI were similar: water-intensive, energy-intensive, and carbon-emission-intensive, especially the indirect part, meaning that they were environment-stress-intensive sectors. In contrast, sectors MQ, WGS, Co, and Tr had low embodied water and energy consumption as well as low embodied CO_2 emissions per unit output.

Table 4 Consumption and emission indexes

Sectors	Water consumption indexes			Energy consumption indexes			CO_2 emission indexes		
	Embodied	Indirect	Direct	Embodied	Indirect	Direct	Embodied	Indirect	Direct
Ag	3.79	1.38	7.00	0.50	0.57	0.20	0.49	0.57	0.20
MQ	0.32	0.37	0.25	0.51	0.58	0.24	0.51	0.58	0.24
LI	1.44	2.31	0.29	1.90	1.88	1.99	1.88	1.85	1.97
HI	1.02	1.57	0.28	2.25	2.31	2.02	2.33	2.35	2.25
EGS	0.11	0.14	0.08	0.78	0.43	2.16	0.75	0.42	2.06
WGS	0.03	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00
Co	0.46	0.70	0.15	0.63	0.77	0.04	0.63	0.78	0.04
Tr	0.21	0.34	0.03	0.56	0.42	1.13	0.56	0.42	1.11
SI	1.60	2.18	0.83	1.87	2.03	1.22	1.84	2.02	1.12

4.4 Conclusions and Discussions

The WEC nexus is highly dependent on the industry structure (Liu et al., 2018). The industry structure of China presents that proportions of primary industry, secondary industry, and tertiary industry are distinct. Direct and indirect consumption coefficients exhibit the source of sectoral embodied resources. Sectors with high direct consumption coefficients should focus more on improving their own resource utilisation efficiency. In contrast, improving resource utilisation efficiency and reducing emissions of upstream sectors is an effective approach for the sectors with higher indirect consumption coefficients.

CHAPTER 5 OVERALL CONCLUSIONS

Integrating IO, GIS and SCN into the WEGN is crucial for ensuring the strategies are proper for environmental sustainability. The novel methodologies proposed in this thesis have emphasised the accurately and quantitively identify the critical material transmissions and regional and sectoral environmental efficiency, in terms of WEGN system. Their effectiveness in environmental assessment was demonstrated through a number of case studies (See Chapters 3-5). The novel methodologies are easier to adapt and employ for better understanding the mechanism of WEGN system, as well as having the following other advantageous features:

i. they consider embodied water utilisation, energy consumption and GHG emissions from the supply chain perspective;
ii. they make the WEGN network more visualized where the multi-regional or multi-sectoral linkages are intricate;
iii. they emphasize the critical embodied material transmissions among different regions or sectors, and insight the environmental performance;
iv. they provide a robust approach and a possibility for a broader system that not solely limited to WEGN.

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