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CRITICAL TRANSMISSION SECTORS OF ENERGY-WATER-GHG NEXUS

KRITICKÉ SEKTORY PŘENOSU ENERGIE-VODA-SKLENÍKOVÉ PLYNY NEXUS

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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. Novel 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. Sophisticated 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. Efficient IO and SCN based assessment approach (IO-SCN) for quantifying the sectoral WEGN coefficients.

The proposed methodologies, with the support of a set of comprehensive underlying equations, transform the complicated WEGN network identification and analysis challenges into an easily understandable format, from which arises robust solutions for improving environmental sustainability assessment and mitigating environmental pressures. As an example in one of the case studies, the results run by the novel approach of GIS-IO reveals that 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. 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. This has a dramatic effect on the global environment. Germany, France and Italy benefited most in the CWE network in the EU27. We recommend that the EU27 provide more technical support to upstream countries to improve the efficiency of resource utilisation.

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.

Navrhované metodiky, s podporou sady komplexních základních rovnic, transformují komplikované výzvy identifikace a analýzy sítě WEGN do snadno srozumitelného formátu, z čehož vznikají robustní řešení pro zlepšení posuzování environmentální udržitelnosti a zmírnění environmentálních tlaků. Například v jedné z případových studií ukazují výsledky nového přístupu GIS-IO zjevné rozdíly mezi různými zeměmi v rámci EU27, mezi různými sektory a také pokud srovnáme EU27 jako blok zemí, s ostatními státy světa. Analýza ukázala, že země EU27 přispěly o 1.4 Gt nižšími emisemi CO_2, o 64.5 Gm^3 menší spotřebou vody a 4.9 × 10^4 PJ nižší spotřebou energie ve srovnání se zbytkem světa, přičemž generovaly ekvivalentní ekonomickou produkci. To má dramatický dopad na globální prostředí. Největší úspěch v CWE mezi zeměmi EU27 měly Německo, Francie a Itálie. Práce doporučuje, aby EU27 poskytovala více technické podpory zemím, které těchto výsledků nedosahují, aby se zvýšila účinnost využívání zdrojů.

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Undertaking the PhD has been a truly life-changing experience for me, and it would not have been possible to do without the inspiration, guidance and great support that I received from a number of wonderful individuals. It is most appropriate to reflect and recognise those individuals who have got me to where I am and express my gratitude. My thanks and appreciation to all of them for being part of this journey and light up my life.

I owe my deepest gratitude to my supervisor, Prof Jiří Jaromír Klemeš. This thesis would hardly have been completed without his enthusiasm, encouragement, support and continuous optimism. His dedication and commitment in academics and research made him an excellent role model for the students. More than guiding my research, his earnest attitude to life have been guiding me to live a better and richer life. I would also like to express my warmest gratitude to my co-supervisors, Dr Petar Sabev Varbanov and Prof Yutao Wang. They have been making available their support in a number of ways, especially towards the research, including the completion of this thesis. I have learned a lot from Dr Varbanov, more than doing research; he is a very nice and good person. I am very grateful for the effort of Prof Wang in contributing to the inspiration and improvement of my study. He has always been concern about my future development. Perhaps without him, I might not have the chance to meet Prof Klemeš and Dr Varbanoc.

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I would also like to give sincere thanks to my colleagues and friends from SPIL, co-authors for my several publications and the other places who were sparing time to listen to my stories, for their frequent help and support during the journey, including both research and life. Here I wish to thank my SPIL colleague, Dr Šárka Zemanová, for all the help with communication, supporting administrative work and the translation.

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support. Above all, to my wife, Yanan Hu, as she has been my most powerful spiritual light, which is more than words can tell. Of course, I give all my sweet love to our son, Jiamu Wang, he is an awesome, amazing and brilliant boy, lighting up our life. He is the most precious "publication" during the PhD journey.

Contributing Research Work Presented in Peer-Reviewed Publications

This thesis has been based on my publications 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, CiteScore=10.9) [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, CiteScore=16.4) [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, CiteScore=25.5), Ecosystem services (IF=6.330, CiteScore=10.8), Journal of Environmental Management (IF= 5.647, CiteScore=7.6), Journal of Cleaner Production (IF=7.246, CiteScore=10.9), Ecological Indicators (IF=4.229, CiteScore=7.6), Energies (IF=2.702, CiteScore=3.8), Sustainability (IF=2.576, CiteScore=3.1) and Chemical Engineering Transactions (CiteScore: 1.3). The complete list of the author's publications is presented in Appendix S1. I have presented the research underpinning this thesis at 15 international conferences in Cracow (Poland), Prague (Czech Republic), Palermo (Italy), Johor Bahru (Malaysia), Tomsk (Russia Federation), Dubrovnik (Croatia), Istanbul (Turkey), Irkutsk (Russian Federation), Crete (Greece), Hong Kong (China), San Francisco (USA), Sarajevo (Bosnia and Herzegovina), Xi'an and Shanghai (China). A complete list of the conferences and presentation is provided in Appendix S2.

<u>Publications with Impact Factors</u>

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] [CiteScore = 10.9] (1 citations)**

2 **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]**.

3 **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] [CiteScore = 16.4] (8 citations)**

4 **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. DOI: 10.1016/j.rser.2019.01.049. **[IF = 12.110] [CiteScore = 25.5] (33 citations)**

5 Varbanov, P.S., Klemeš, J.J., **Wang, X.**, 2018. Methods optimisation, Process Integration and modelling for energy saving and pollution reduction. Energy, 146, 1-3. **[IF = 4.968] [CiteScore = 8.5] (9 citations)**

6 Xu, Z., Fan, W., Dong, X., **Wang, X.C.**, Liu, Y., Xue, H., Klemeš, J.J., 2020. Analysis of the functional orientation of agricultural systems from the perspective of resource circulation. Journal of Cleaner Production, 258, p.120642. **[IF = 6.395] [CiteScore = 10.8] (1 citation)**

7 Long, X., Yu, H., Sun, M., **Wang, X.C.,** Klemeš, J.J., Xie, W., Wang, C., Li, W., Wang, Y., 2020. Sustainability evaluation based on the Three-dimensional Ecological Footprint and Human Development Index: A case study on the four island regions in China. Journal of Environmental Management, 265, p.110509. **[IF = 4.865] [CiteScore = 7.6]**

8 Fan, W., Gao, Z., Chen, N., Wei, H., Xu, Z., Lu, N., **Wang, X.**, Zhang, P., Ren, J., Ulgiati, S., Dong, X., 2018. It is worth pondering whether a carbon tax is suitable for china's agricultural-related sectors. Energies, 11(9), 2296. **[IF = 2.707] [CiteScore = 3.3] (3 citations)**

9 Fan, W., Zhang, P., Xu, Z., Wei, H., Lu, N., **Wang, X.**, Weng, B., Dong, X., 2018. Life Cycle Environmental Impact Assessment of Circular Agriculture: A Case Study in Fuqing, China. Sustainability, 10(6), p.1810. **[IF = 2.592] [CiteScore = 2.8] (5 citations)**

10 Fan, W., Dong, X., Wei, H., Weng, B., Liang, L., Xu, Z., **Wang, X.**, Wu, F., Chen, Z., Jin, Y., Song, C., 2018. Is it true that the longer the extended industrial chain, the better the circular agriculture? A case study of circular agriculture industry company in Fuqing, Fujian. Journal of Cleaner Production, 189, 718-728. **[IF = 6.395] [CiteScore = 10.9] (9 citations)**

11 Lu, N., Wei, H., Fan, W., Xu, Z., **Wang, X.**, Xing, K., Dong, X., Viglia, S., Ulgiati, S., 2018. Multiple influences of land transfer in the integration of Beijing-Tianjin-Hebei region in China. Ecological Indicators, 90, 101-111. **[IF = 4.490] [CiteScore = 7.6] (8 citations)**

12 Xu, Z., Wei, H., Fan, W., **Wang, X.**, Zhang, P., Ren, J., Lu, N., Gao, Z., Dong, X., Kong, W., 2019. Relationships between ecosystem services and human well-being changes based on carbon flow - A case study of the Manas River Basin, Xinjiang, China. Ecosystem Services, 37, p.100934. **[IF = 5.572] [CiteScore = 9.2] (4 citations)**

13 Wei, H., Fan, W., Lu, N., Xu, Z., Liu, H., Chen, W., Ulgiati, S., **Wang, X.**, Dong, X., 2019. Integrating Biophysical and Sociocultural Methods for Identifying the Relationships between Ecosystem Services and Land Use Change: Insights from an Oasis Area. Sustainability, 11(9), p.2598. **[IF = 2.576] [CiteScore = 3.2] (2 citations)**

14 Xu, Z., Fan, W., Dong, X., **Wang, X.C.**, Liu, Y., Xue, H., Klemeš, J.J., 2020. Analysis of the functional orientation of agricultural systems from the perspective of resource circulation. Journal of Cleaner Production, 258, p.120642. **[IF = 6.395] [CiteScore = 10.8] (1 citation)**

15 Fan, W., Chen, N., Li, X., Wei, H., **Wang, X.**, 2020. Empirical Research on the Process of Land Resource-Asset-Capitalization - A Case Study of Yanba, Jiangjin District, Chongqing. Sustainability, 12(3), p.1236. **[IF = 2.576] [CiteScore = 3.2]**

Publication with CiteScore

16 **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. **[CiteScore = 1.3] (2 citations)**

17 **Wang, X.C.**, Klemeš, J.J., Fan, W., Dong, X., 2019. An Overview of Air-Pollution Terrain Nexus. Chemical Engineering Transactions, 72, 31-36. **[CiteScore = 1.3] (1 citation)**

18 **Wang, X.C.,** Klemeš, 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. **[CiteScore = 1.3]**

19 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., 2020. Water-Energy-Carbon Nexus Analysis of the EU27 and China. Chemical Engineering Transactions, 81, 469-174. **[CiteScore = 1.3]**

Invited Lectures

1 **Wang, X.C.**, Fan, Y.V., Varbanov, P.S., Klemeš, J.J., Developments of Treatment for Municipal Solid Waste Management. The 6th International Conference on Computational Heat, Mass and Momentum Transfer, Cracow, Poland. 23.05.2018.

2 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Recent Developments of Water Footprints Methodology. The 21st Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Prague, Czech Republic. 28.08.2018

3 **Wang, X.C.**, Varbanov, P.S., Klemeš, J.J., Wang, Y., Multi-Criteria Optimisation of Municipal Solid Waste Management: GIS and P-Graph Approach. The 13th Conference on Sustainable Development of Energy, Water and Environment Systems, Palermo, Italy. 02.10.2018.

4 **Wang, X.C.**, Klemeš, J.J., Dong, X., Fan, W., An Overview of Air-Pollution Terrain Nexus. The 4th International Conference on Low Carbon Asia & Beyond, Johor Bahru, Malaysia. 25.10.2018.

5 **Wang, X.C.**, Klemeš, J.J., Dong, X., Wang, Y., Recent Development of Air-Pollution Terrain Nexus. 1st International Conference on Sustainable and Efficient Use of Energy, Water and Natural Resources, Tomsk, Russia. 15.11.2018.

6 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Water-Energy-Carbon Nexus: Take China as the Case. The 14th SDEWES Conference, Dubrovnik, Croatia. 02.10.2019.

7 Klemeš, J.J., **Wang, X.C.**, Water, Energy and Environment Nexus in Circular Economy. The 1st International Conference on Water, Energy and Environment Nexus. Istanbul, Turkey. 05.09.2019. **(Plenary Lecture)**

8 Klemeš, J.J., Jia, X., **Wang X.C.**, Varbanov, P.S., Wan Alwi, S.R, Overview and Perspectives on Water Footprint (Availability, Scarcity, Virtual and combined with Energy and GHG), 2nd International Scientific Conference on «Sustainable and Efficient Use of Energy, Water and Natural Resources», SEWAN, Irkutsk, Siberia, Russian Federation. 12.09.2019. **(Plenary Lecture)**

9 **Wang, X.C.**, Klemeš, J.J., Sadenova, M., Varbanov, P.S., Zhakupova, G., Energy-Related GHG Emissions, Taking Kazakhstan as A Case. The 22nd PRES Converence, Crete, Greece. 22.10.2019.

10 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Identifying the Water-Energy-Carbon Emissions Nexus, an Input-Output Model-Based Approach. The 1st CPS conference, Hong Kong, China. 31.10.2019. **(Best Presentation Award)**

11 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., Water-Energy-GHG Nexus, Considering the Impact of Terrain. The AGU'19 Conference, San Francisco, USA. 12.12.2019.

12 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., Mapping Water-Energy-Carbon Nexus of the EU27. The 4th SEE SDEWES conference (virtual), Bosnia and Herzegovina, 30.06.2020.

13 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Varbanov, P.S., Water-Energy-Carbon Nexus Analysis of the EU27 and China. The 23rd PRES conference (virtual), Xi'an, China. 17.08.2020.

14 **Wang, X.C.**, Klemeš, J.J., Varbanova, P.S., Critical transmissions of Water-Energy-Carbon Nexus in China. The 6th ICLCA conference (virtual), Shanghai, China. 02.09.2020.

15 Klemeš, J.J., **Wang, X.C.**, Fan, Y.V., Integrated Footprints Accounting for Sustainability Underlining Emissions. Plenary Lecture, the 6th ICLCA conference (virtual), Shanghai, China. 02.09.2020. **(Plenary lecture)**.

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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 (Fan et al., 2018).

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 (Wang et al, 2019a). 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).

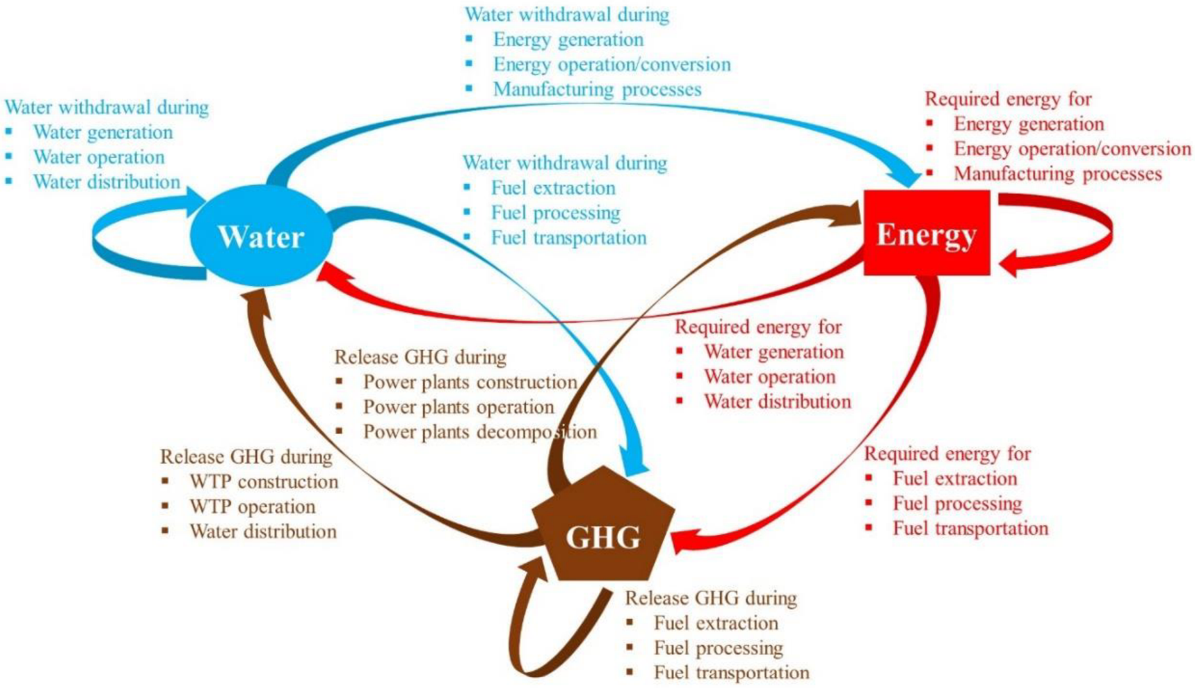


Figure 1 *Water-Energy-GHG Nexus* (Wang et al., 2020b)

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 healthy environment, 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.

1.1.1 Case of the EU

As one of the most significant water and energy consumers as well GHG emitter, EU contributed to 1,561 Mtoe (Mt of oil equivalent) of primary energy consumption in 2017, which accounted for 11.05% of worldwide (Simon, 2019). The primary energy consumption in the EU was still 5.3% higher in 2017 than the 2020 target. The final energy consumption in the EU reached 1,222 Mtoe, which was also 3.3% above the 2020 target (European Commission, 2019). 80% of GHG emissions in the EU comes from energy generation and consumption, making energy production and utilisation related human activities are pivotal elements in the fight against climate change (Simon, 2019). If from the worldwide perspective, around 75% of GHG emissions are from those energy generation and consumption related sources (Wang et al., 2019). EU is still with improvement potential.

As shown in Figure 2, the total energy consumption in the EU has been showing a decreasing trend from 2006 to 2016. The renewable energies have been showing a continuous increase. However, the total primary energy consumption showed conversed trend, slightly continuous rising from 2014 to 2017 (European Commission, 2019). The fossil fuel is still in a dominant position, which contributed 83.46% of total primary energy consumption in the EU in 2016. The total petroleum products accounted for 37.01% of the total primary energy consumption, followed by gas 28.02% and solid fuels 18.25% (e.g. coal). These types of energy are the main source of GHG emissions, which determines that the EU is still facing serious challenges of GHG alleviation.

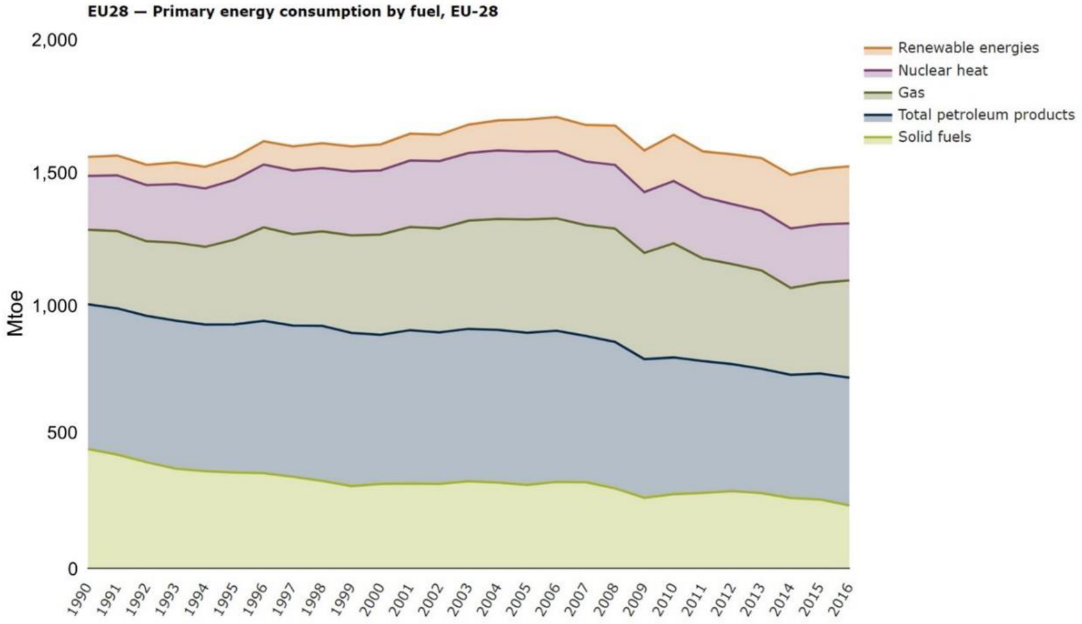


Figure 2 EU28 – Primary energy consumption by fuel (EEA, 2018)

Regarding water utilisation, with thousands of rivers, freshwater lakes, and underground water sources available, the supply of water in Europe may seem limitless. However, with the population growth, urbanisation, environmental degradation, and the influence of climate change (e.g. persistent droughts) have been putting immense pressure on water supplies and its quality of EU. Water stress has been a serious problem that affects a massive number of people worldwide, including over 100 M in Europe (EEA, 2018). It has resulted in an overall decrease in renewable water resources per capita by 24% across Europe. As shown in Figure 3, energy production is one of the most significant contributors of water utilisation in Europe, accounting for around 28% of annual water use. Power plants cooling (e.g. in nuclear and fossil fuel-based power plants) and hydroelectricity purposes are the predominant water use. Especially in western and Eastern Europe, cooling water for power generation has been putting the most pressure on water resources. Followed by mining and manufacturing purposes accounts for 18%, household use accounts for around 12%. All this water utilisation is good for the economy and subsequently for our quality of life. However, local water resources in an area may face competing demands from different water users, which may result in nature's water needs being neglected. Over-exploitation of water resources can harm animals and plants dependent on them. There are also other consequences for the environment. In most cases, after water is used by industry, the resulting wastewater may cause pollution through sewage, chemical discharges, etc. In the case of energy production, the water used for producing hydroelectricity would harm the natural water cycle in rivers and lakes. The water used for cooling in power plants tends to be warmer than that in the river or lakes when it is released back to the environment. The heat can have adverse effects on local species depending on the temperature difference.

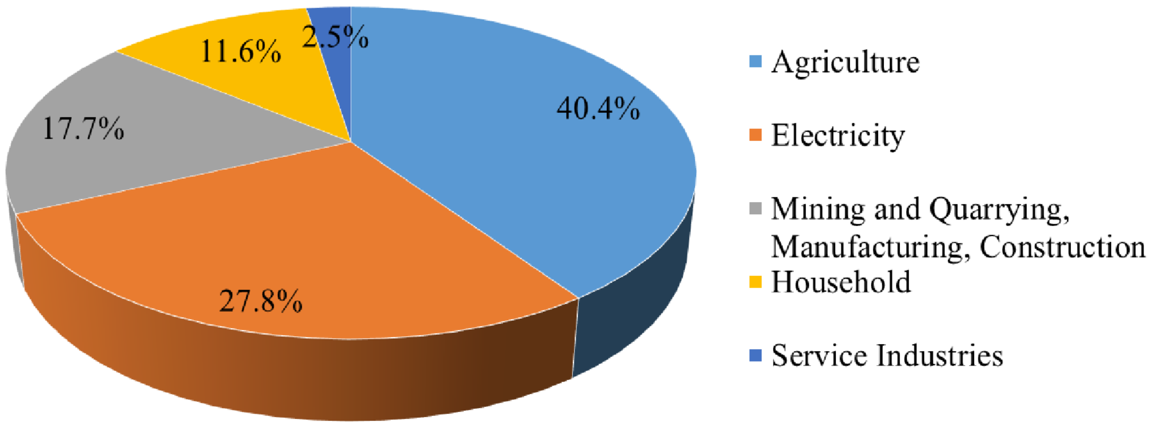


Figure 3 Water use of EU-28 by economic sectors, 2015, data extracted from (European Environment Agency, 2020)

1.1.2 Case of China

China has been one of the fastest-growing economies worldwide, living standards have been rising significantly, and resources have been becoming more abundant. China is the largest energy consumer and the greatest contributor of CO_2 emissions as well (Wang et al., 2016). A huge number of resources consumption and increasing environmental issues have been drawing more and more attention, like excessive consumption of energy and water as well as a large number of pollution emissions. As shown in Figure 4, only the building sector can save lots of energy and water as well as reduce a large amount of CO_2 emissions.

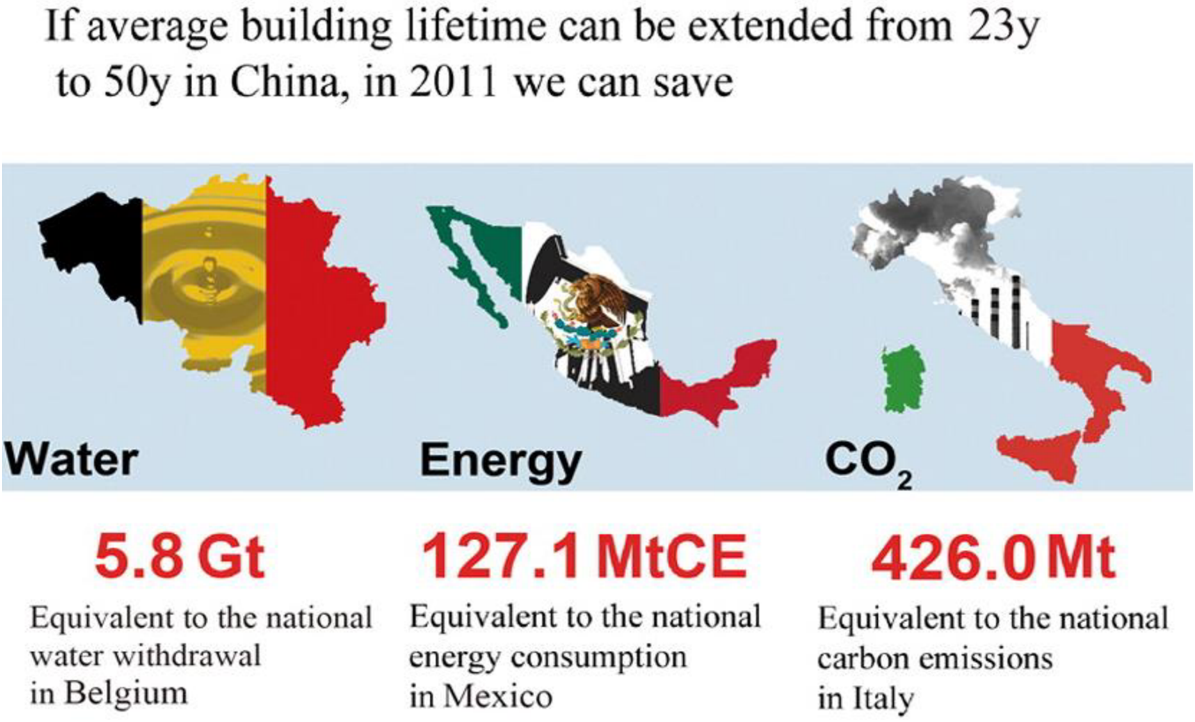


Figure 4 *Potential of resources saving and CO_2 emissions reducing in China's building sector (Cai et al., 2015). MtCE: metric tons carbon equivalent, $MtCO_2$-eq.*

China has been facing severe water pressure. Water scarcity and uneven water distribution are the key water challenges for human beings, and China is facing both two serious problems. From the 1900s to 2000s, the population facing water scarcity increased significantly from 0.24×10^9 (14% of worldwide population) to 3.8×10^9 (58%) (Kummu et al., 2016). Focus on China, about 34% - 38% of the whole population resides in the places which are experiencing high water scarcity for at least one month per year (Wang et al., 2019). The uneven distribution of water in China results in unique difficulties to China, especially under the rapidly increasing demand for water resource (Latham et al., 2019). The key question is how to properly distribute water. 80% of the water in China exist in southern China, however, cannot be used by 12 provinces (35% of total 34), which account for 41% of China's population, 50% of power generation, 46% of the industry and 38% of agriculture (Latham et al., 2019). It is getting worse, the need for water resource has been increasing rapidly, with a forecast to rise to 670×10^9 m^3 consumption per year by the early 2020s. However, the grim truth is that 28,000 rivers in China have dried up during the past 25 y (Latham et al., 2019).

China has been the largest energy consumer worldwide. The total primary energy consumption of China in 2017 was 3,105 Mtoe, which is almost twice the amount consumed in the European Union (EU). This figure accounted for 53.95% of that in Asia and 21.98% of that worldwide (Enerdata, 2019). The primary energy consumption growth rate of China in 2017 was 2.9%, twice the rate in 2016, and was much higher than that of the world, which was 2.3%. 64% of the primary energy consumption of China in 2017 was from coal; 19% was from oil, 7% was from electricity, 6% was from gas, 4% was from biomass, and 1% was heat (Enerdata, 2019). A large amount of fossil fuel consumption results in high pollutant emissions, thereby increasing environmental pressure. As shown in Figure 5, the water stress and energy production in China, both concentrated in the east and most northwest of China.

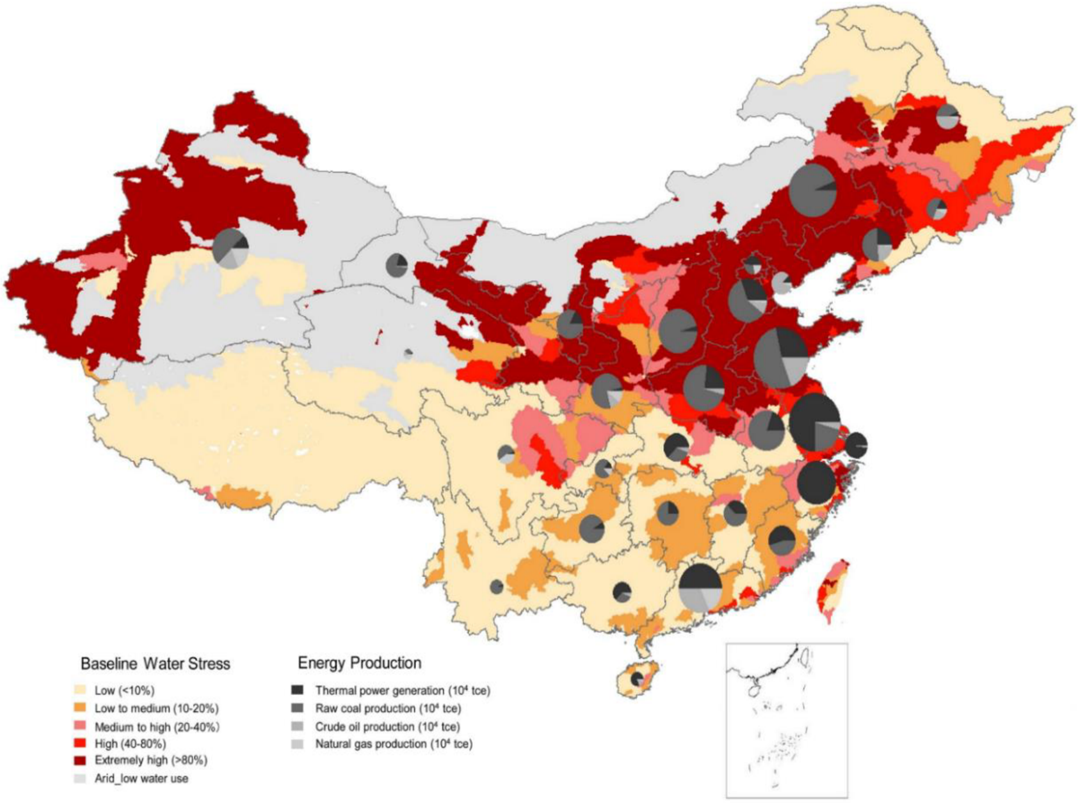


Figure 5 Water stress and energy production in China.

China has been the most significant carbon emitter worldwide. CO_2 emissions of China grew by 2.3% in 2018, faster than in 2017 (1.7%) (National Bureau of Statistics of China, 2019). China contributed 10.15×10^9 t CO_2 emissions, accounting for 28.05% of the worldwide total. CO_2 emissions increased twofold in China from 2000 to 2016 (Ritchie and Roser, 2017). The main contributors were energy generation and consumption-related human activities (Wang et al., 2019a).

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. The research in this thesis fills the following research gaps:

i. Most present studies focused on the driving forces of water and energy consumption and carbon emissions; however, did not investigate in detail the consumption and emissions coefficients and sectoral environmental performance. The comprehensive studies on WEGN of multi-sectors are still very limited.

ii. The water used for energy, energy used for water, and energy-related GHG emissions has been primarily focused on in the present works, which cannot identify the relationships among different sectors and regions. Very limited studies focused on the sets of linked sectors and regions from the supply chain perspective. The WEGN and critical transmission sectors are also very less studied. Broader systems are necessary to be taken into consideration for a better understanding of the WEGN nexus.

iii. The embodied water, energy and GHG emissions of sets of linked sectors and regions still need in-depth exploration, especially for different countries of EU27 as well as different regions in China. The associated benefits need more study to explore mutuality. The linkage between direct and indirect embodied water consumption, energy consumption and GHG emissions are especially crucial.

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. **Novel 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. **Sophisticated 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. **Efficient 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.

1.3 Thesis Outline

Chapter 2 thoroughly reviews the key literature and advances of the available methodologies that are most relevant to the aim of this thesis. The main research comprising this thesis is divided into three chapters (Chapter 3 - 5), where three novel methodologies are developed and presented. The applicability of the proposed methodologies is demonstrated through three case studies related to WEGN exploration. Each of the case studies provides specific results (see Chapter 3 - 5) of the assessed scope (see Section 1.2), which could significantly contribute to the field of study. Chapter 6 overviews the contribution of this thesis with a recommendation for future work, followed by references and appendix.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The chapter provides the literature review relevant to the thesis scope. The research gaps and their potentials in achieving the thesis aim are highlighted.

2.2 Water-Energy-GHG Nexus

This section presents state of the art on the topic of WEGN. Section 2.2.1 provides the review of Water-Energy Nexus with the research gaps for the topic. Section 2.2.2 shows the linkage between energy and GHG, as well as the state of the art of this field. Section 2.2.3 discusses on the WEGN, with extension to the research gaps and potential research directions.

2.2.1 Water-Energy Nexus

Although previous efforts for environmental protection and resources preserve have rather been concerned with the water and energy supply individually (Thiede et al., 2016), the understanding for the requirements of conjoint studies of both resources has been increasingly drawing attention. Both resources are embedded in the climate system through GHG emissions and water cycling. The reinforcing speed-up of demand for both resources is caused by that one of them can only be generated, supplied and used through the other. Decisions made on one of the two resources always have direct or indirect impact consequences on the other, which may cause unforeseen development. Both cannot be operated separately from an industrial system point of view. The water-energy nexus concept was firstly described by Gleick (1993) as an intrinsically bound relationship between water and energy.

At Bonn 2011 Nexus Conference, various stakeholder groups and scholars with the German government together agreed to study the interconnections among water, energy and food, trying to explore a visionary method of achieving sustainability. Since that time, studies focus on the water-energy nexus has been increasingly developing. For example, a program "Thirsty Energy" was established by the World Bank (Rodriguez et al., 2013), focuses on the water need of power generation. A report of "The Water-Energy Nexus: Challenges and Opportunities" was published by the Department of Energy's Water-Energy Tech Team in 2014, aimed at framing an integrated opportunity and challenge space focuses on the water-energy nexus, laying the foundation for future efforts (Energy.gov, 2019). Several reports have also been published by the International Energy Agency focus on the methodologies for studying on water-energy nexus as well as promoting the status of research of this topic (International Environmental Agency, 2017). The International Renewable Energy Agency (IREA) (2015) has analysed that renewable energy plays a key role in balancing the trade-offs among water utilisation, energy consumption and food production. The Department of Energy of the USA (2014) has established a comprehensive system for analysing the water-energy nexus throughout the whole country.

Water-energy nexus studies usually focus on the energy utilisation for obtaining water and water utilisation for obtaining energy. Hamiche et al. (2016) reviewed that the relationship between water and energy includes three types of links, production link, transportation link and consumption link, depending on the industry functions involved. During the past decade's development, water-energy nexus has been subdivided into two links, water for energy and energy for water, as shown in Figure 6.

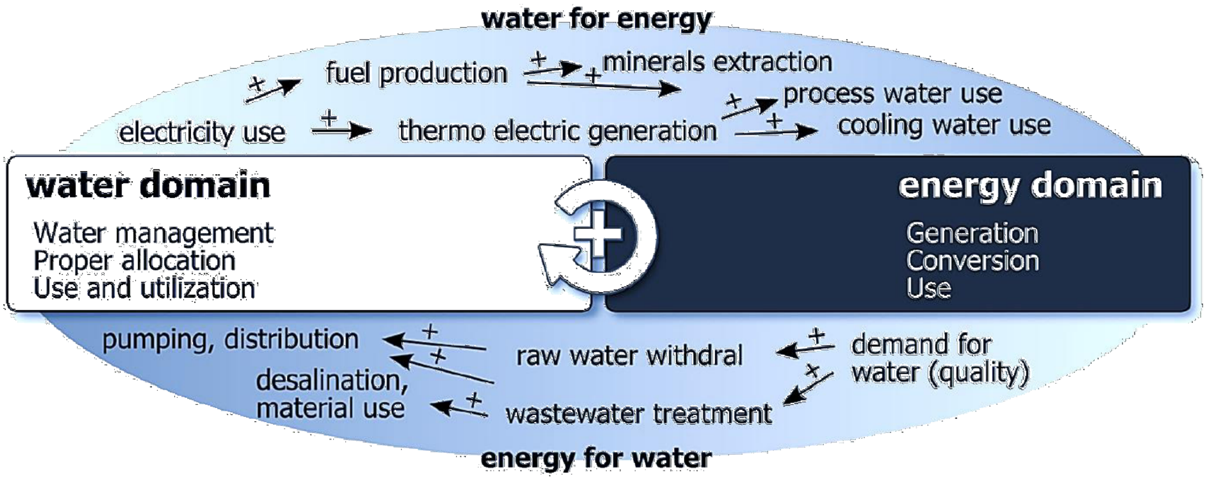


Figure 6 Water-Energy-Nexus (Thiede et al., 2016)

Water for energy is mandatory for energy generation and energy operation/conversion, like mining, mineral extraction, fuel production, energy conversion, etc. It is also one of the key factors for manufacturing processes in multiple ways. For example, it includes process water use, cleaning, heating purposes, various cooling (e.g. heat dissipation through evaporation) as well as steam generation. Conversely, energy requested for water is usually in terms of water generation, water operation, water distribution, etc. For example, water extraction from groundwater through wells, water purification, desalination of brackish water or seawater, regional transport of water resources (Thimmaraju et al., 2018).

Water-energy nexus has been increasingly studied and wildly use, especially during the past decade. The analysis has been conducted to cover a very wide range of categories, include the development of various methods, approaches and tools. Most of them are linked to the context of environmental issues, climate change influences, sustainable intensification, etc. Cases range very widely from macro-level to the micro-level, as shown in Figure 7. Different purposes and categories have been performed for different purposes, which can be concluded into several different aspects: regional water-energy nexus (R-WEN), sectoral water-energy nexus (S-WEN), plants water-energy nexus (P-WEN) and water-energy nexus reviews (WEN-R), as shown in Table 1.

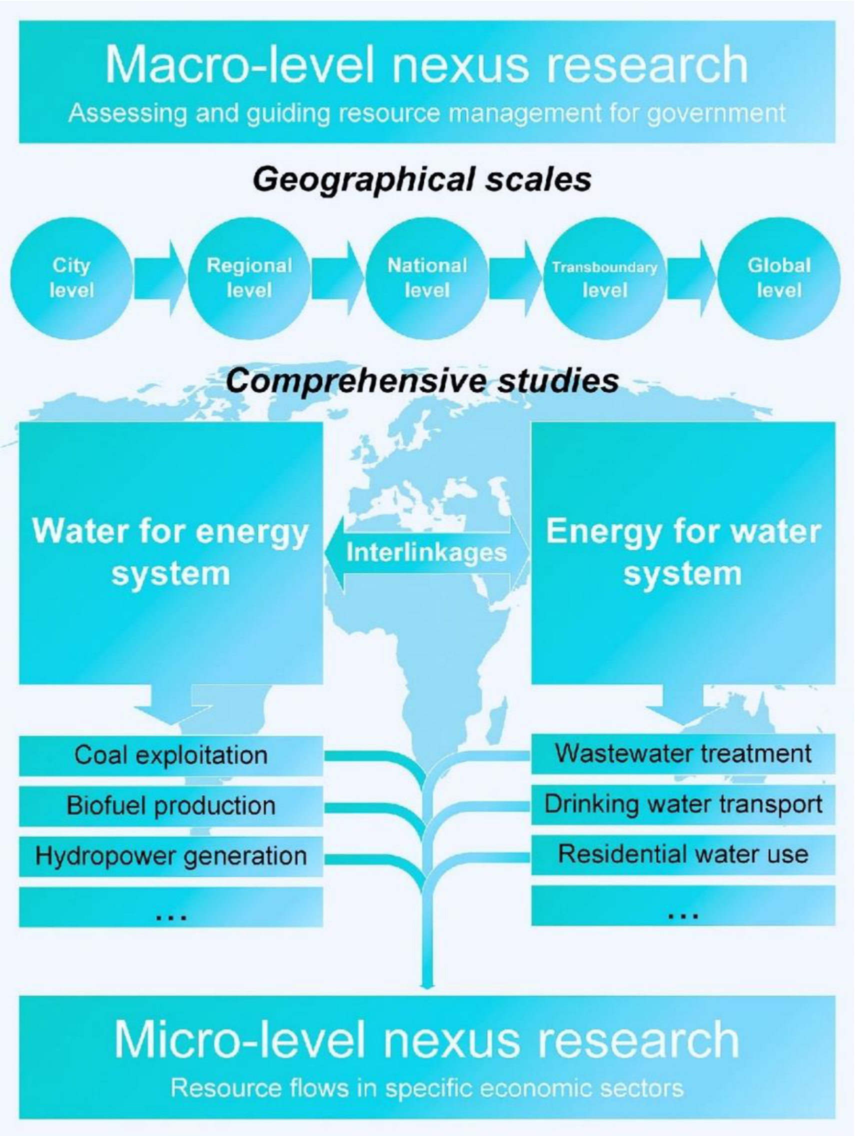


Figure 7 Conceptual framework of water-energy nexus studies from macro-level to micro-level (Dai et al., 2018)

Although the water-energy nexus has been studied widely, most of them focus on the specific target (e.g. a city, one sector, one plant). Most methods are also at the "understanding" stage for the water-energy nexus analysis (Dai et al., 2018). The critical research gap or limitation is that most of the previous studies are limited within water and energy, although some of them included food. There are still very limited studies focused on WEGN. The studies targeted on the critical transmission sectors of WEGN are even less research.

Table 1 Induction and examples of water-energy nexus

Categories	Topic and References	Main Results
R-WEN	Water-energy nexus for Beijing. (Fang and Chen, 2017a)	a. IO and linkages analyses. b. The linkages analysis is used to explore the embodied water and energy flows in the urban economy. c. The key sectors for water-energy nexus in Beijing are identified.
	Evaluation of Spain Water-Energy Nexus. (Hardy et al., 2012)	a. This paper explores the water-energy nexus of Spain and offers calculations for both the energy used in the water sector and the water required to run the energy sector.
	Urban Water-Energy nexus: a network perspective. (Chen and Chen, 2016)	a. A system-based framework for Water-Energy nexus is proposed. b. Direct and embodied energy for water and water for energy are calculated in Beijing. c. Urban nexus alter system properties and dynamics.
S-WEN	Water-Energy nexus analysis in the case of the electricity sector. (Sun et al., 2018)	a. The high-water stress region was estimated. b. Water-Energy nexus analysis of the Electricity Sector in the was explored. c. Potential of power structure adjustment and technological advancement in easing water stress were analysed.
	Pinch Analysis for the planning of the power generation sector: A Climate-Water-Energy nexus study. (Lim et al., 2018)	a. The Climate-Water-Energy nexus of electricity sector was analysed. b. CO_2 emissions reduction targets were examined based on Pinch method. c. The scope of analysis covers CO_2 emissions, EROI and water footprint. d. Clean energy is more economically favourable.
	Coal-fired power industry water-energy-emission nexus. (C. Wang et al., 2018)	a. A multi-objective optimisation method was proposed for identifying the feasible technology sets for the coal-fired power industry. b. The trade-offs and synergies among the water-energy-emission nexus were quantified, and the most feasible technology sets were highlighted. c. The newly introduced ultra-low emission regulation was evaluated regarding water energy consumption and cost.
P-WEN	Water wave energy harvesting (Chen et al., 2015)	a. A network made of triboelectric Nanogenerators was reported for large-scale harvesting of kinetic water wave energy.

Categories	Topic and References	Main Results
	Water-Energy nexus for a hydropower plant (Gaudard et al., 2018)	a. Seasonality pattern is a key factor b. Future revenue is impacted by the changes in streamflow seasonality. c. Price seasonality brings about more uncertainty on revenue than climate change.
WEN-R	A review of the water-energy nexus (Hamiche et al., 2016)	a. Reviewed and compared previous water-energy studies in terms of objectives, scope, methodologies and key findings. b. Discussed major limitations of previous studies. c. Identified important areas that would benefit from more in-depth research. d. Integral Theory is proposed for assessing water-energy nexus.
	A review of methods and tools for macro-assessment (Dai et al., 2018)	a. Most methods are at the understanding stage of water-energy analysis. b. Approaches for implementing or governing the water-energy nexus require more attention and focus.

2.2.2 Energy-GHG Nexus

GHG reduction plays a significant role in supporting sustainable development. GHG emissions, increasingly those from energy generation and consumption, has been the global as well as local-specific issues. About 75% of GHG emissions are from energy generation and consumption related human activities (Wang et al., 2019). It has been an accumulating burden and even a significant threat to global warming, climate change, ecosystem services, human well-being (Wang et al., 2017), plants living, economic development, etc. (Wang et al., 2019). Energy generation and consumption related human activities have been key sources of GHG emissions. The generation or consumption of each energy, such as fossil fuels, biomass, however as well as renewable energies, etc., result in the air pollutant emissions like GHG including NO_x, sulphur oxide (SO_x), dust and PMs, etc. The energy needed for manufacturing, processing and transporting, materials mining, maintenance, cleaning, construction and dealing with it at the end of the life, all these processes are connected with GHG formation and emissions. For example, from the prospect of life cycle GHG emissions, the electricity generation from different kinds of sources related methods result in GHG emissions, as shown in Figure 8. According to the study conducted by Amponsah et al. (2014), the generation of heat and electricity has been the key contributors to GHG emissions worldwide. EPA (US EPA, 2016) report that most GHG and also haze/smog emissions worldwide come from energy production and consumption

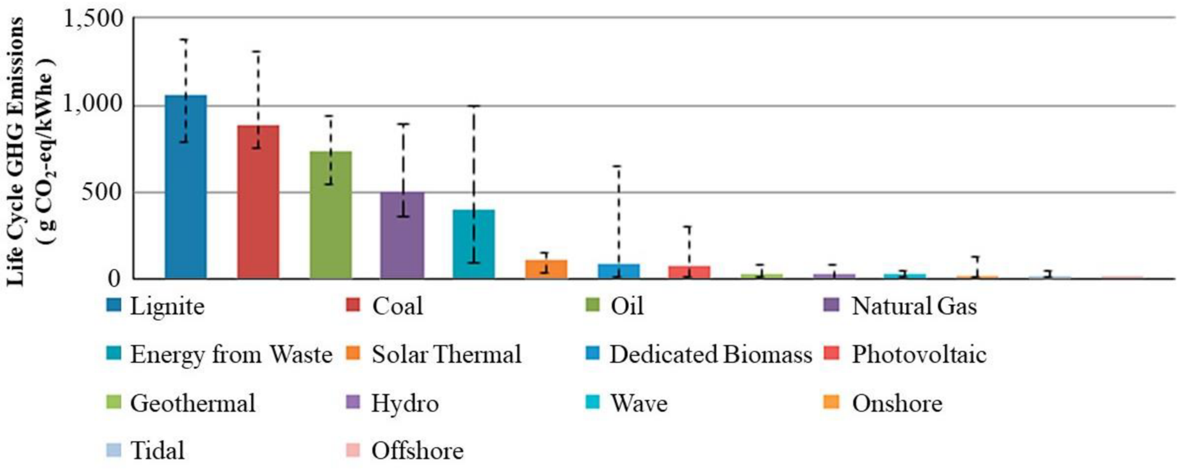


Figure 8 *Life cycle GHG emission estimates of electricity generation methods (Wang et al., 2019)*

As shown in Figure 9, the most significant single contributor (24%) to GHG emissions is the utilisation of coal (which includes lignite), followed by oil and natural gas for the production of heat and electricity, trailed by energy-related sectors industry (21%), transportation (14%), buildings (6%) and other energy-consuming sectors (10%). Energy generation and consumption related human activities contribute about three-quarters of GHG emissions, which is the main driving force of the global climate change.

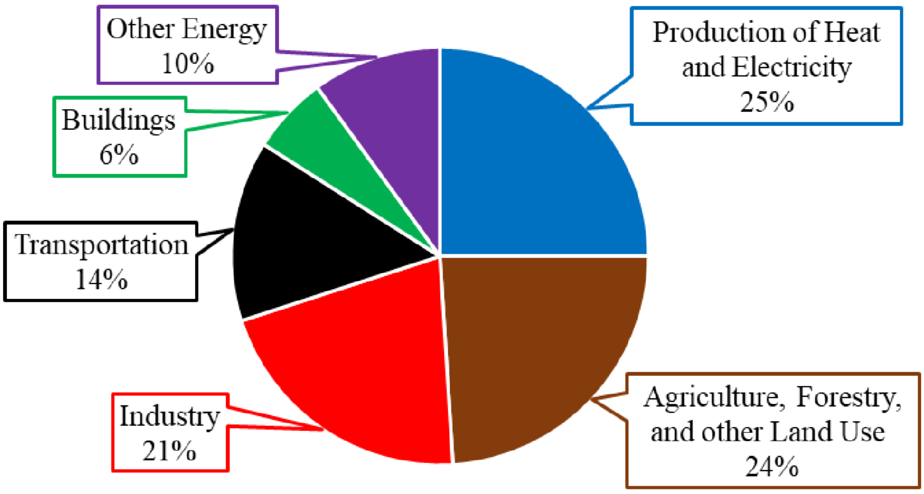


Figure 9 *Global GHG Emissions by Economic Sector, data extracted from EPA (US EPA, 2016). GHG emissions from industry sector mainly include the burning of fossil fuels for energy. It also involves chemical, metallurgical, etc.; GHG emissions from transportation sector include burning of fossil fuels for different kind of transportations; GHG emissions from building sector involves the generation of outside energy and inside burning for heat and cooking.*

Wang et al. (2019) also pointed out there should be direct and indirect causes are responsible for GHG emissions, although they have not yet been distinguished very well. Both direct and indirect causes include energy-related factors. The main contributor of air pollutant emissions is direct energy consumption, which was presented above like energy generation and consumption, manufacturing processes. The indirect factors (like socioeconomic factors) can affect the energies utilisation methods, consequently influent the air pollutant emissions (Yang et al., 2016). For example, NO_x, including NO_2 and NO, mainly come from transportation fuels consumption (15-25%), power plants burned fossil fuels (30-50%), along with industrial facilities (25-35%) (Rohde and Muller, 2015). Energy-related factors contribute to more than two-thirds of NO_x emissions. The NO_x emission factors, as shown in Table 2.

Table 2 NO_x emission factors (kg NO_2/t) (Rohde and Muller, 2015)

Fuel type	**NO_x Emissions**				
	Transportation	**Domestic use**	**Electricity**	**Industry**	**Others**
Coal	7.5	1.19-2.24	4.00–11.80	2.38-7.50	3.75
Gasoline	15.00-58.20	16.7	2.10–16.70	16.7	16.70
Crude Oil	5.09	1.7	2.10–10.60	3.35-7.26	3.05
Coke	9	2.25		9	4.50
Residual oil	27.40-54.10	1.95	2.10–10.06	5.84	3.50
Diesel	13.24-58.20	3.21	2.10–8.54	9.62	5.77
Kerosene	27.4	2.49	21.2	7.46	4.48
Natural gas (10^{-4} kg NO_2/m_3)	20.85	14.62	17.27-55.67	20.85-27.14	14.62

GHG, especially which from energy generation and utilisation, has been corresponding with the local, regional and global environmental issues. The emitted CO_2 is one of the key contributors to GHG, accounting for around two-thirds of all GHG, as shown in Figure 10. Over emitted CO_2 has been drawing increasing attention from human beings worldwide, especially in the context of global warming. N_2O is a typical atmospheric pollutant. It can both destroy ozonosphere and give a contribution to the atmospheric greenhouse effect. Although N_2O is trace gas, its global warming potential is 298 times more than CO_2 for a 100 y timescale (IPCC, 2006).

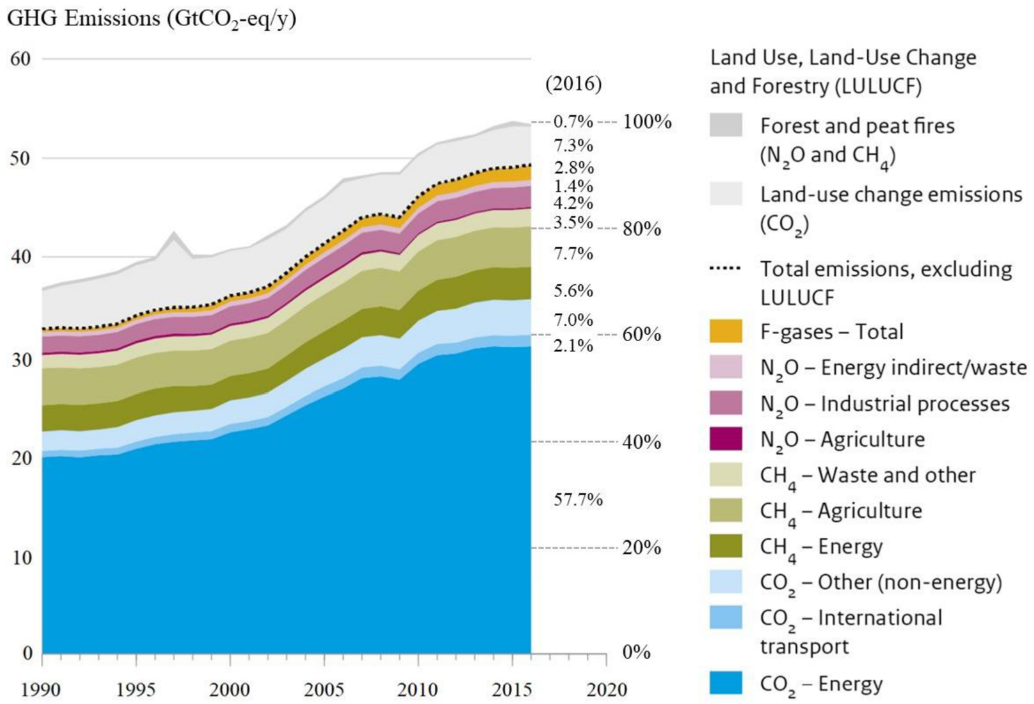


Figure 10 Global GHG emissions, per type of gas and source, including LULUCF (Wang et al., 2019).

Energy-GHG nexus has been studied widely. However, most of them focused on the exploration of GHG emission sources, GHG emissions ratio of different types of energy and the driving forces, etc. Very limited studies focused on the GHG emission among sets of linked energy sectors. The WEGN and critical transmission sectors are also very less studied.

2.2.3 Water-Energy-GHG Nexus

It is crucial to analyse WEGN, which is pivotal for decreasing environmental footprints. Several targets have been set up for ensuring the reduction of energy consumption, water utilisation, as well as GHG emissions (Bianco et al., 2019). A renewed ambition, that for the post-2020 period towards 2030 has been presented by the EU consistent with its environmental strategies, through the Clean Energy for All Europeans policy package proposals. The ambition aims at minimum 30% improvement for the energy efficiency in the horizon, as well as a much stronger governance framework is needed for supporting the delivery of this target (Pereira and da Silva, 2017).

Integrated approaches, for example, input-output (IO) model, LCA method (Fan et al. 2018a), Pinch (Klemeš et al. 2018), should be comprehensively considered for analysing the broader system, in terms of WEGN in the future. It is crucial for decreasing environmental footprints. The WEGN assessment can also be extended from the social and economic system to the agriculture, ecosystem (Fan et al. 2018b). Understanding the mechanism of the interactions between vegetation dynamics and the water cycle is pivotal for determining regional and global water and carbon budgets according to the study of Zeng et al. (2020). They also modelled the WEGN of the ecosystem by integrating the hydrological model and a biogeochemical model, which provided an effective model for the simulation of water-carbon cycles. Water, energy and carbon are profoundly entwined; however, there is still not a holistic, systemic and proper framework to capture the Water-Energy-Carbon Nexus in the urban water system (Wang et al., 2020a). In some cases, the energy use of water end-use is comparatively overlooked.

Energy, water, and GHG have become crucial indicators of social development and environmental sustainability. Energy and water consumptions and GHG emissions are closely related to environmental sustainability achievement via the metabolism of the ecosystem and human society (Yang et al., 2018a). It has been studied that energy and water are among the most significant factors that influence environmental sustainability. In recent studies, the nexus between the three key factors have been increasingly emphasised. Nair et al. (2014) reviewed the WEGN of urban water systems comprehensively surveyed various studies conducted in various regions of the world and focusing on individual or multiple subsystems of an urban water system. Water, energy and GHG are highly entwined; however, there is no holistic, systemic and proper framework to capture the water-energy nexus in the urban water system. In some cases, the energy use of water end-use is comparatively overlooked. Yang et al. (2018a) analysed the environmental sustainability of Beijing and Shanghai, China, from the perspective of WEGN. The WEGN characteristics of different sectors can provide a new perspective for relieving the pressure of environmental challenges. Yang et al. (2019) then explored the key betweenness sectors of WEGN pressures in Shanghai, China. The betweenness sectors that exert a significant amount of environmental pressures were highlighted, the role of transmission sectors should be taken into consideration for decision making. DeNooyer et al. (2016) explored the integration of power generation and water resources. In their study, thermoelectric power plants account for 90% of electricity generation in the US, which requires a lot of water. Consequently, water constraints can translate into energy constraints. The competition for water in different areas would be increasing serious because of the future population growth and climate change. Lee et al. (2017) reviewed the influence of Water-Energy nexus on urban water systems, from the perspective of environmental impacts and energy intensity in relation to global water risks. The water pressure in energy sectors (e.g. hydropower industry, thermoelectric power industry, solar power industry, etc.) has been widely studied, and suggestions for high energy efficiency and water-saving were proposed from the viewpoint of technology improvement, policymaking, and trading patterns, etc. (Wu and Chen, 2017). The Water-Energy nexus is not just about the energy sites or water sites, it is also reflected by the potential, and the real risk of water scarcity exists in the inter-regional energy and water strategies. Based on the study of Wang et al. (2019), the mismatch between the electricity-receiving population reside in water-abundant regions, and the water scarcity exists in the electricity-exporting areas may result in exacerbating the risk of water scarcity. Round 134 M (more than 10%) population of China has been affecting by this kind of inter-regional electricity transmission (Wang et al., 2019). The water scarcity risks are also unequally distributed propagated by inter-basin electricity transmission. A few researchers have taken CO_2 emissions into consideration for the nexus analysis in energy or water systems. Gu et al. (2016) analysed the energy, water and carbon footprints of wastewater treatment plants in China. The extra climate impact associated with wastewater treatment should be taken into account because of the enormous annual discharge of wastewater in China. Some studies analysed the WEGN focused on other industries, like steel industry (Cai et al., 2015), manufacturing industry (Chen and Chen, 2016), the service industry (Meng et al., 2019a), etc.

Although the nexus between environmental factors have been studied widely within a single sector or specific region, it cannot be ignored that the flow of energy, resources, and emissions depends on trade between sectors. It is also necessary to place the issue of the WEGN in a broader system instead of an individual economic sector. The WEGN needs to be in-depth research. There are trade-offs when considering a comprehensive dynamic system, which includes several sectors. For instance, choosing the power types, wind, solar photovoltaics (PV) are well-known friendly to water resource and environmental health. However, what does good to carbon maybe not good for water, like nuclear power and hydro. Choosing the proper types of energy or making the proper energy strategies is such significant for future energy demands needs, water needs as well as GHG emission requirements, without adding more pressure on water and climate.

The previous studies showed that the research scopes are mainly within the individual sectors or specific regions. The research focuses on the multi-sectors, and the whole EU and China are still relatively limited. The critical transmission sectors of WEGN are also very less studied.

2.3 Environmental Extended Input-Output Approach

The Environmental Extended Input-Output model, including the Multi-Regional Input-Output model, was developed based on economic Input-Output (IO) model. The Environmental Extended Input-Output model is a practical approach to analyse and calculate the supply chain characteristics between different regions and different sectors. This 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). Figure 11 shows how the IO tables are combined in the Environmental Extended Input-Output model.

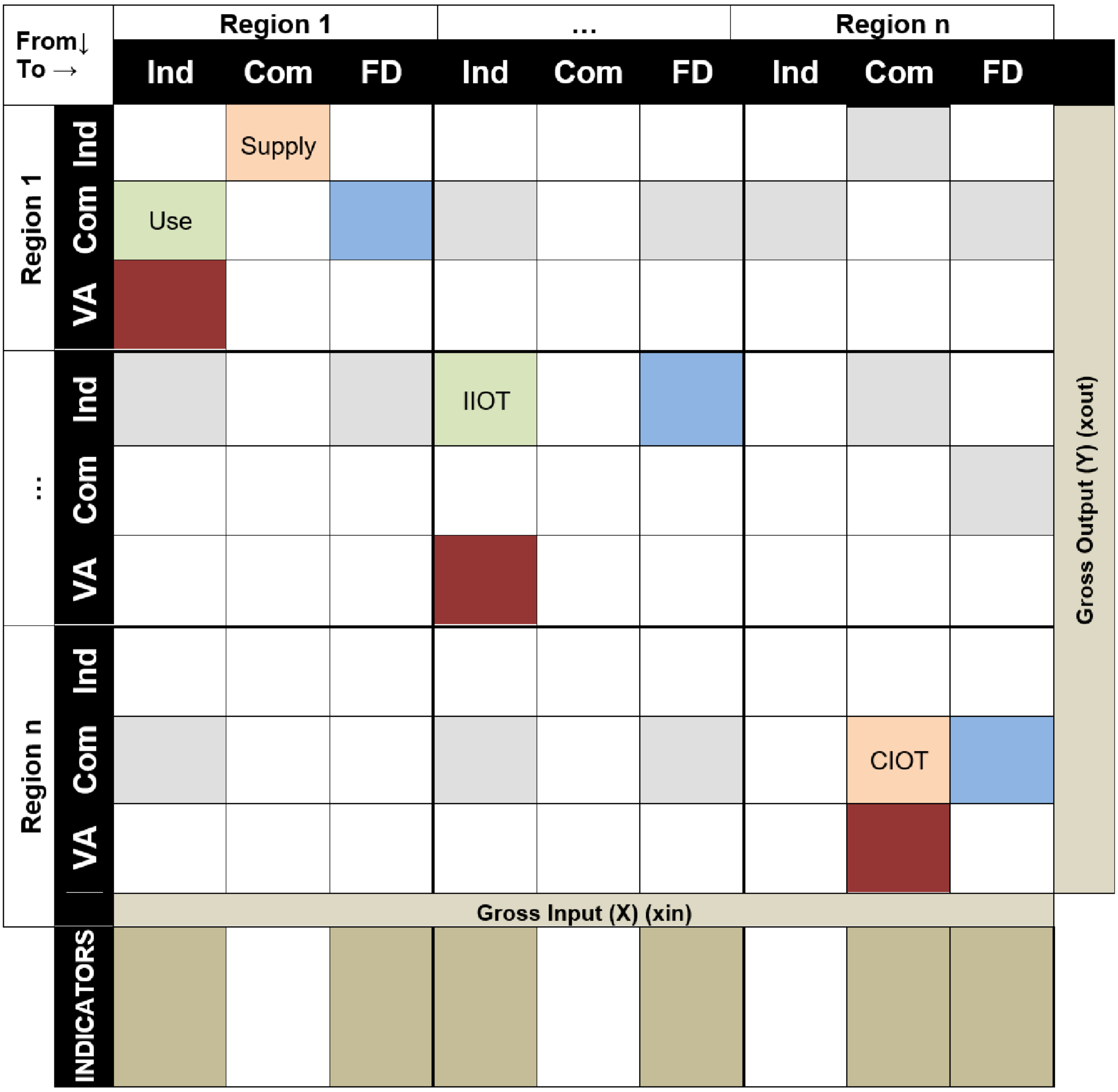


Figure 11 The framework of the Environmental Extended Input-Output model

Entities: Ind - Industries; Com - Commodities; FD - Final demand; VA - Value added (also called primary inputs); Indicators - Satellite indicator accounts, documenting nonmonetary inputs to production.

It includes a mix of different types of IO tables. They are:

- Industry-by-Industry IO tables (IIOT)
- Commodity-by-Commodity IO table (CIOT)
- Supply-Use Table (SUT), with a Commodity to Industry Use table and an Industry to Commodity Supply (also called "Make") table.

Coloured and shaded blocks contain values/transactions; white blocks are empty.

An Environmental Extended Input-Output model should meet the following criteria: 1) Transparent. The underlying data must be transparent to support examination in close detail, and the quality of these data should be clearly described; 2) Reproducible. The generation of the model must be reproducible to allow for efficient modification and customization; 3) Open. The model and data need to be open and freely-shareable to enable widespread adoption and customization for more specific applications; 4) Up-to-date. Models must reflect current conditions to the extent possible for the results to be relevant to decision making (Yang et al., 2017).

The Environmental Extended Input-Output model has been successfully used in broad-scope research in terms of the environmental performance of production and consumption, such as exploring the carbon emissions drivers in China (Liu et al., 2019), identifying the environmental pressures from Swedish consumption (Palm et al., 2019), land-water nexus of biofuel production in Brazil (Munoz Castillo et al., 2019). In this research, the Environmental Extended Input-Output model is used for analysing the environmental efficiency in terms of WEGN of the EU27 and China.

2.4 Geographic Information System (GIS) Approach

The Geographic Information System (GIS) is a computer system for capturing, storing, checking, and displaying data related to positions on Earth’s surface, as shown in Figure 12. GIS can show many different kinds of data on one map, such as streets, buildings, and vegetation. This enables people to more easily see, analyze, and understand patterns and relationships. GIS has been wildly used for supporting Spatio-temporal 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). Expert has long considered conventional mapping, and more recently geographic information systems (GIS), as critical tools in visualising and mapping material flows, including showing the WEGN network.

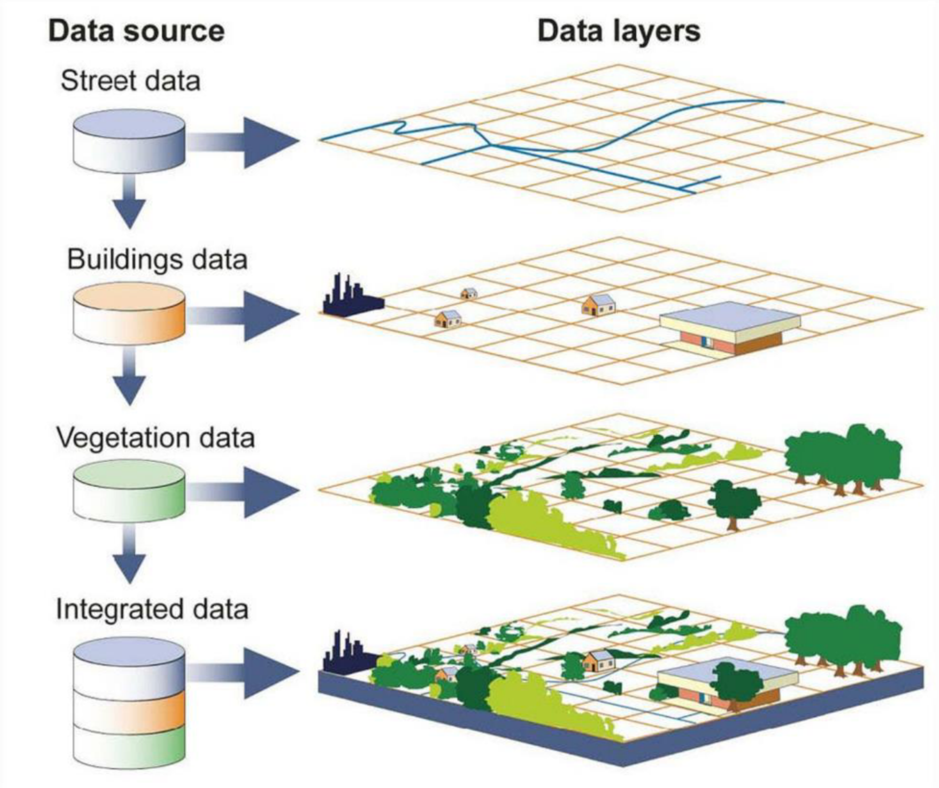


Figure 12 Geographic Information System (Society, 2017)

The GIS has been an important and suitable tool for Spatio-temporal relevant analysis and especially the spatial linkage among different objectives. The GIS-based decision support tools (DSTs), as well as the multiple criteria analysis tools (MCATs), have been used for numerous applications. These GIS-based tools can bring together sustainability-related factors or criteria from an environmental, social and economic point of view to establish a comprehensive and integrated framework for assessing the optimisation. It is a very useful approach for guiding regions to sustainability. The urban ecosystem condition indicators for the large urban zones and city cores in the EU has been analysed based on the GIS approach by Kourdounouli (2018). Aye et al. (2016) proposed a GIS-based framework and explored the risk management of hydro-meteorological hazards in three case studies in Europe, which engages stakeholders toward higher levels of participation and a more extensive evaluation of the platform. It has been successfully used for Geographical tracking and mapping of coronavirus disease COVID-19 and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) epidemic and associated events around the world, showing that how 21st century GIS technologies are supporting the global fight against outbreaks and epidemics (Kamel Boulos and Geraghty, 2020).

In this study, the GIS helps to identify and visualise WEGN data, and the network flows visualisation, supporting decision-making, at the 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). In this study, the GIS method is employed to map the WEGN flows and visualise the WEGN in the EU27.

2.5 Supply Chain Network

A Supply Chain is a complex network of organisations and facilities, which are mostly settled in a vast geographical area or even the globe, synchronises a series of interrelated activities through the network. It usually includes sets of linked sectors (Govindan et al., 2017). The methods for both activities of production and distribution planning in different decision levels are uniformed in the supply chain network, for achieving the chain goals efficiently, which consider the material flows from the life circle perspective.

The industry-specific strategies are usually developed for rescuing the environmental pressures and minimising the environmental footprints. However, previous studies primarily focused on exploring different sectors that directly generate large amounts of environmental stress or indirectly drive large amounts of environmental pressures through supply chains (Liang et al., 2016). In addition to these parts, which are as significant environmental stress drivers or/ and producers, some sectors are also crucial for decreasing environmental pressure, such as transmission centres. The mitigation of regional environmental pressure might be achieved by updating the industries and improving the material consumption efficiency in the critical transmission sectors, which means reducing the embodied environmental footprints. It is crucial to identify the environmental pressure which comes from behind a specific sector, that is, tracking the material flows among various sectors and regions from the supply chain perspective and. The vertex betweenness centrality of sector v in a supply-chain network with seven vertices and six edges is illustrated in Figure 13. In the figure, e_a, e_b, and e_c are the GHG emissions in upstream sectors a, b, and c triggered by the transactions among downstream sectors, d, e, and f. In this case, the vertex betweenness centrality of sector v can be calculated as $b_v = e_a + e_b + e_c$.

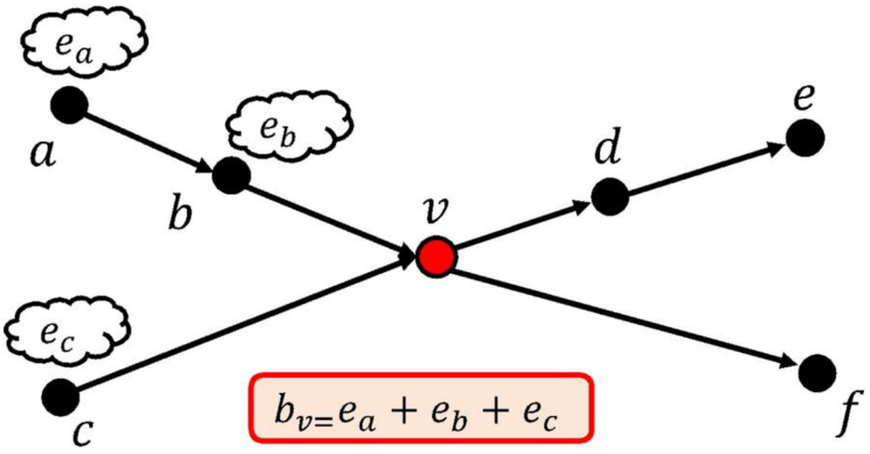
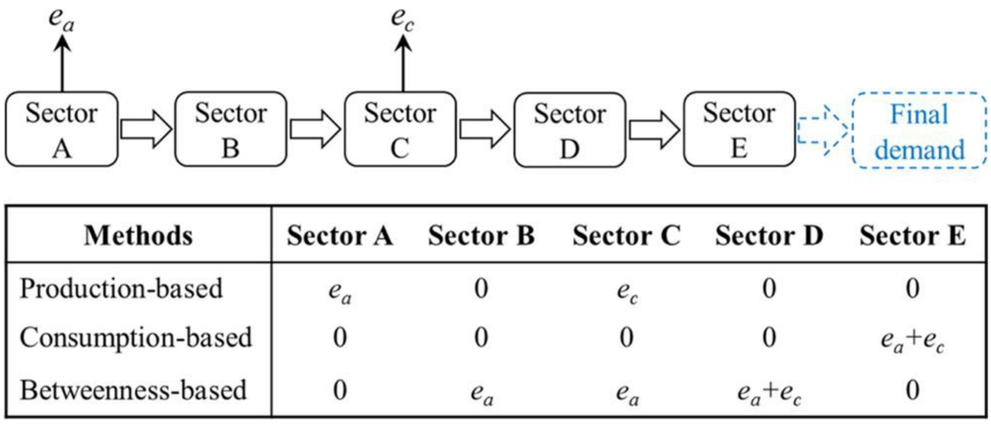


Figure 13 Example of vertex betweenness centrality for a sector v. (Hanaka et al., 2017)

Figure 14 shows an example of a supply chain containing five sectors. Sectors A and C generate emissions in the amounts of e_a and e_c, while sectors B, D, and E don’t generate any emission. It has two supply chain paths: “A→B→C→D→E” (weight: e_a) and “C→D→E” (weight: e_c)”. The weight of a supply chain path is the number of emissions of its starting sector that is caused by the final demand of products from its end sector. Sectors A and C are important according to the production-based method, while sector E is important according to the consumption-based method. Sectors B and D will not be identified as important according to these existing methods. However, improving the production efficiency of sectors B and D (i.e., using fewer inputs of sectors A and C to produce unitary output, respectively) might help reduce economy-wide emissions (i.e., fewer requirements for outputs of sectors A and C leading to fewer emissions from sectors A and C). As a result, to consider all relevant sectors from the supply chain perspective is crucial for identifying environmental performance.



Methods	Sector A	Sector B	Sector C	Sector D	Sector E
Production-based	e_a	0	e_c	0	0
Consumption-based	0	0	0	0	e_a+e_c
Betweenness-based	0	e_a	e_a	e_a+e_c	0

Figure 14 A five-sector example is illustrating production-based, consumption-based, and betweenness-based methods (Liang et al., 2016).

This study took the supply chain idea and quantifying the coefficients of water utilisation and energy consumption and GHG emissions. It contributes to better understanding the sectoral and regional linkage behand the interregional trade.

CHAPTER 3

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

The work presented in this section is based on the author's publication in Journal of Cleaner Production entitled "Measuring the Environmental Performance of the EU27 from the Water-Energy-Carbon Nexus perspective", as clarified on Page IX (Contributing publication). The author of this thesis is the first author of this publication. The other co-authors who contributed to this publication are the supervisor (J.J. Klemeš), co-supervisors (Y. Wang and P.S. Varbanov) and collaborators.

3.1 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.

3.2 Introduction

EU27 have been increasingly inter-linked. A massive amount of production and different kinds of services are shared. However, whether the associated benefits are mutual for all countries still need more study. Water utilisation, energy consumption and carbon emission are three of basic environmental impact factors, and they are profoundly entwined. It is significant for exploring the linkage of water consumption, energy utilisation and carbon emission of EU27, which is crucial for minimising water, energy and carbon footprints. Exploring the Water-Energy-Carbon (WEC) nexus between different regions provides a better understanding of the ways to relieve the regional environmental pressure. Challenges of water-saving, energy high-efficiency utilisation, and low carbon emissions are enormous pressure on the sustainability of the EU (Wang et al., 2019a). Climate change further aggravates water scarcity, energy challenge, and relevant environmental pressures (Jia et al., 2020). The sets of issues have been contributing to global warming along with human well-being degradation, ecosystem services deterioration (Wang et al., 2019a), and slowing down the economic development (Yang et al., 2017), etc. Energy consumption, water utilisation, and CO_2 emission are significant indicators of social development and regional sustainable development. Consumption of water and energy, and CO_2 emission, are essential for environmental sustainability performance via the metabolism of the ecosystem and human society (Jia et al., 2019). These three elements are the most critical factors that influence regional environmental sustainability (Endo et al., 2017). In recent studies, increasing papers have been focusing on the regional or sectoral WEC nexus.

Acquaye et al. (2017) measured the environmental sustainability performance of the global supply chains in terms of carbon and water footprints. Their study provides a good example for analysis of the global supply chain when it comes to environmental sustainability. Zheng et al. (2019) explored the water and carbon networks of north China, showing that the sustainable development of urban agglomeration should be with the trade-off of carbon and water networks. The multi-regional input-output model was used in their study; the water flows and carbon flows between different cities have been identified. Fang and Chen (2018) also analysed the water-carbon nexus in China, suggesting that outsourcing of resources and emission is important for the stringent environmental target. Lee et al. (2017) discuss the impact of energy-water linkage on water systems, in terms of energy intensity in relation to water risks. The water pressure in the energy sectors has been widely studied. High energy efficiency and water-saving suggestions are also proposed from the viewpoint of policymaking, trading patterns, and technology improvement, etc. (Wu and Chen, 2017). Wang et al. (2020) explored the WEC nexus of different sectors in China. Their results indicate the sectors that have more indirect WECC, EECC, and ECEC are more depend on upstream sectors. It can be extended to different countries or regions with high indirect WECC, EECC and ECEC. This kind of countries should be more rely on upstream countries from the supply chain perspective. According to the results of Serrano et al. (2016), it is crucial to reconsider the water policy in the EU, for better balance the embodied water flows through international trade. The WEC nexus of the iron and steel industry was assessed by Wang et al. (2020). They found that the trade-offs of WEC nexus should be considered during the producing process and relevant technology selection.

Although the WEC nexus has been receiving increasing attention, most of the current research works focus on different sectors of city scale. Most studies analyse the impact factor of energy consumption, water efficiency and CO_2 emission. Energy for water, Water for energy, as well as the linkage of energy-carbon, have been explored widely. Fang and Chen (2017) analysed the water-energy nexus for Beijing, identifying the critical flows of water-energy nexus. Feng et al. (2019) explored the impact of energy-water nexus on water conservation of China. However, these studies didn't fully indicate the embodied water, energy and carbon of different countries, especially for the EU27. The associated benefits need more study to explore mutuality. More extensive research is needed for in-depth analysis of the embodied consumptions of energy and water and embodied CO_2 emission in the EU27 in the viewpoint of the supply chain. The nexus between direct and indirect energy consumption, water consumption and CO_2 emission is especially substantial.

For narrowing these research gaps, this study aims at assessing the environmental pressures of the EU27 in terms of WEC Nexus. The objectives of this study are to assess the embodied energy consumption, embodied water consumption, and embodied CO_2 emission of different countries of the EU27. The direct and indirect values of the above indicators are calculated as well. These results demonstrate the intensity of water, energy and carbon emission from the final product perspective.

3.3 Data Sources

This study takes, after BREXIT, the EU27 as cases. The considered countries include Austria (AUT), Belgium (BEL), Bulgaria (BGR), Croatia (HRV), Cyprus (CYP), Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Hungary (HUN), Ireland (IRL), Italy (ITA), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Poland (POL), Portugal (PRT), Romania (ROU), Slovakia (SVK), Slovenia (SVN), Spain (ESP) and Sweden (SWE), as well as a model for the rest of the world (RoW).

The Environmental Input-Output (EIO) model used in this study is based on the world input-output table (WIOD, 2020) and the World Input-Output Database (WIOD) environmental accounts (Amores et al., 2019). The WIOD database has data from 43 countries worldwide, including EU27 and a model for the rest of the world (RoW). It includes world input-output table, national input-output tables and environmental accounts for the period 2000-2014. The unit in world input-output table is \$; however, this study uses € as it deals with the EU countries.

The exchange rate is 1.33 in 2014, taken from the Global No.1 Business Data Platform (Statista, 2020). Data for 56 sectors are classified according to the International Standard Industrial Classification Revision 4 (United Nations, 2008). This study focuses on the latest year (2014) date. The CO_2 emission data and different types of energy consumption data of different countries are collected from WIOD database (Amores et al., 2019). The water consumption data were obtained and proceeded from the water balance table database at Eurostat (Eurostat, 2020), which is the statistical office of the EU. It provides high-quality statistics at European level for the EU. Population data were obtained from the World Bank (World Bank, 2020).

3.4 Environmental Input-Output (EIO) model

Table 3 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., 2018b) 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 3 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.

3.4.1 Embodied Water Consumption

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

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

The direct water use coefficients are given as:

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

where all parameters are introduced in section 3.2.

The embodied water consumption is given as:

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

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 3.4.1.

The direct water consumption of different countries e_j was obtained and proceeded from the water balance table database at Eurostat (Eurostat, 2020), as shown in Table 4.

Table 4 Water consumptions of different countries, 2014, developed from Eurostat (2020).

Countries	Country Total (Mm^3)	Per Capita (m^3)	Countries	Country Total (Mm^3)	Per Capita (m^3)
Estonia	1,724	1,311	Romania	6,269	315
Finland	6,776	1,241	Germany	25,327	313
Greece	9,916	910	Poland	11,309	298
Italy	54,357	894	Sweden	2,375	245
Bulgaria	5,377	744	Cyprus	276	240
Spain	33,787	727	Croatia	813	192
RoW	3,990,000	586	Denmark	989	175
Netherlands	9,408	558	Ireland	751	161
Slovenia	1,000	485	Czech Republic	1,650	157
Portugal	4,837	465	Malta	64	147
Austria	3,585	419	Lithuania	389	133
France	27,075	408	Slovakia	559	103
Belgium	4,557	407	Latvia	168	84
Hungary	3,923	398	Luxembourg	46	83

3.4.2 Embodied Energy Consumption

The direct EECC of different counties are given as:

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

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.

The direct energy consumption of different countries was obtained and proceed from the WIOD (Amores et al., 2019), as shown in Table 5. The WIOD includes gross energy consumption and emission relevant energy consumption of different countries. In this paper, the gross energy consumption data were used.

Table 5 Energy consumptions of different countries in 2014 developed by Amores et al. (2019).

Countries	**Country Total (TJ)**	**Per Capita (GJ)**	**Countries**	**Country Total (TJ)**	**Per Capita (GJ)**
Netherlands	8,520,741	505	Spain	7,621,130	164
Finland	2,245,922	411	Bulgaria	1,115,340	154
Sweden	3,246,763	335	Italy	9,128,070	150
Belgium	3,647,371	325	Portugal	1,534,454	148
Luxembourg	146,954	264	Poland	5,340,160	140
Estonia	318,214	242	Slovenia	276,785	134
Denmark	1,324,731	235	Hungary	1,291,644	131
Czech Republic	2,300,494	219	Ireland	608,098	131
Germany	17,578,727	217	Malta	53,236	123
Greece	2,327,482	214	RoW	694,579,071	102
Lithuania	609,346	208	Romania	1,773,112	89
France	13,009,207	196	Croatia	371,841	88
Austria	1,571,311	184	Latvia	166,672	84
Slovakia	947,858	175	Cyprus	78,661	68

3.4.3 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 CO2 emission matrix with the elements a_j^c, which is the direct CO2 emission coefficients, can be defined as:

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

The CO2 emission data can be obtained and proceed from the WIOD (Amores et al., 2019), as shown in Table 6.

Table 6 The CO2 emission of different countries in 2014, developed from Amores et al. (2019).

Countries	Country Total (kt)	Per Capita (t)	Countries	Country Total (kt)	Per Capita (t)
Estonia	18,609	14.2	Slovakia	28,380	5.2
Luxembourg	6,762	12.2	Lithuania	15,178	5.2
Denmark	63,441	11.2	Austria	43,509	5.1
Netherlands	145,679	8.6	ROW	33,303,055	4.9
Germany	676,143	8.3	Cyprus	5,433	4.7
Finland	44,976	8.2	Spain	207,497	4.5
Malta	3,401	7.8	Sweden	42,054	4.3
Czech Republic	81,923	7.8	Italy	259,346	4.3
Poland	270,070	7.1	Portugal	41,201	4.0
Ireland	32,408	7.0	Hungary	34,674	3.5
Belgium	71,884	6.4	France	230,475	3.5
Bulgaria	43,130	6.0	Latvia	6,767	3.4
Greece	64,271	5.9	Romania	65,800	3.3
Slovenia	11,491	5.6	Croatia	13,171	3.1

3.4.4 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:

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

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

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

3.5 Results and Discussions

This section shows the main contributions and discussions. The environmental pressures in terms of EWCC, EECC and ECEC are illustrated. All coefficients include both direct part and indirect part. Embodied consumptions of energy and water per capita, and embodied CO_2 emission per capita are also provided.

3.5.1 Embodied Water Consumption

Figure 15 shows the EWCC of the EU27. Figure 16 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. Bulgaria leads the list at 112.2 m^3/k€, followed by Estonia (77.2 m^3/k€), Greece (61.9 m^3/k€) and Romania (46.6 m^3/k€). They are the least productive water consumers in the EU27. The values of Bulgaria and Estonia are even higher than the average value worldwide. According to the study by Serrano et al. (2016), these countries have the highest water footprint per unit GDP. They are also the top freshwater abstracters (Eurostat, 2020) and tap water consumers in the EU27. On the contrary, there are 10 countries, including Sweden (14.7 m^3/k€), Denmark (16 m^3/k€), Germany (17.1 m^3/k€), Austria (18.7 m^3/k€), etc., have lower EWCC. They are with the highest water efficiency and the most productive water users in the EU27. The total freshwater use in Sweden has decreased by 10% from 2010 to 2015 because of the water efficiency increase in Agriculture sector (Statistics Sweden, 2017), which is a significant water consumer sector in Sweden and other EU countries (ClimateChangePost, 2020).

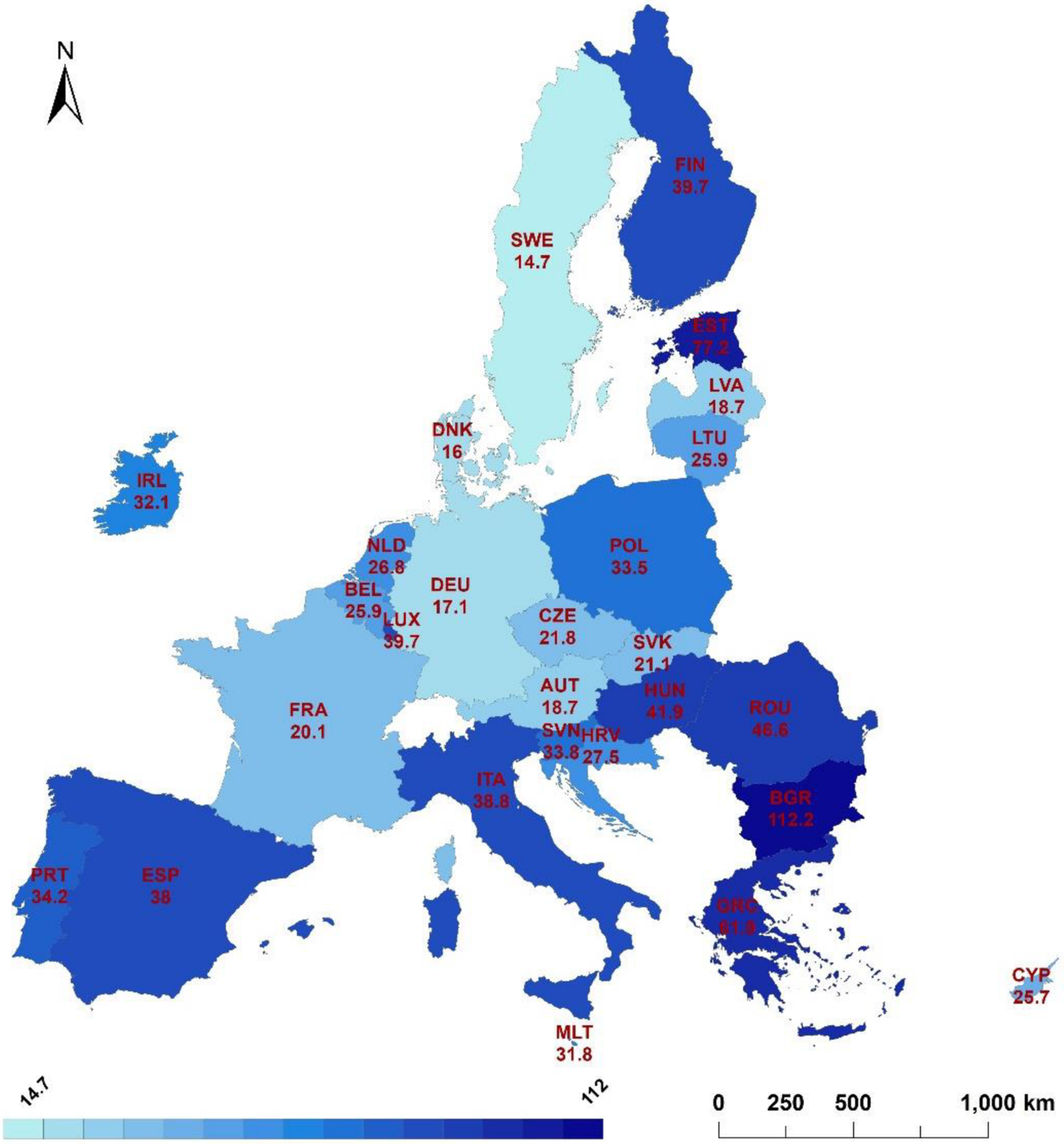


Figure 15 EWCC of the EU27 (m^3/k€)

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. 99% of Luxembourg embodied water consumption is indirect, followed by Ireland (94%), Malta (91%), Denmark (87%), Slovakia (85%), Latvia (82%) and Czech

Republic (80%). The indirect proportions of these countries are all higher than 80%. 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.

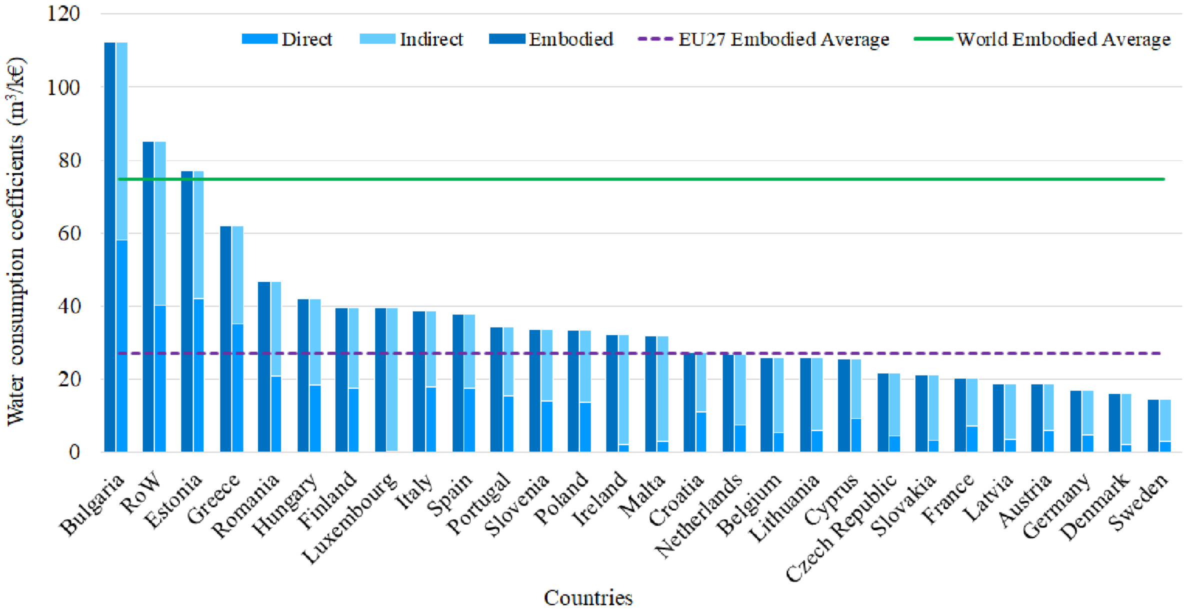


Figure 16 Direct and Indirect EWCC

Figure 17 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). Industrial sectors and agriculture sector are embodied-water-intensive, and Luxembourg has the smallest population except for Malta in the EU27 (World Bank, 2020), which explains why it has high embodied water consumption per capita (11,380 m^3). Finland (2,811 m^3), Ireland (2,644 m^3), Estonia (2,405 m^3), Netherlands (1,996 m^3), Italy (1,953 m^3) and Belgium (1,933 m^3) are the followed top embodied water consumers per capita. Those countries also have their specialised in water-intensive economic activities, for example, they crucially consume water within the sectors of the paper industry, power generation, agricultural activities, etc. (Serrano et al., 2016). Top ten forest and paper industries of EU27 were in Finland, Ireland, Sweden, etc. in 2015, and the top two were in Finland (PwC, 2016). Two-thirds of the forest industry total production value in Finland comes from pulp and paper industries (Finnish Forest industries, 2020).

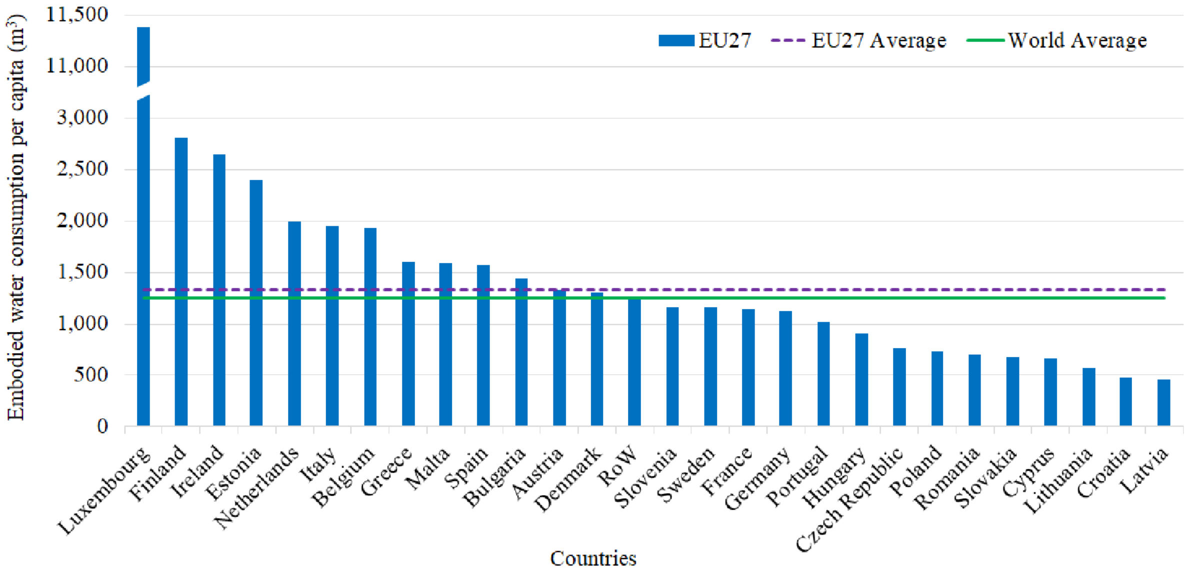


Figure 17 Embodied Water Consumption Per Capita

3.5.2 Embodied Energy Consumption

Figure 18 shows the EECC of the EU27. Figure 19 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 value of Bulgaria (23.3 MJ/€), Lithuania (16.4 MJ/€), Estonia (15.4 MJ/€) and Greece (14.1 MJ/€) are even higher than the world average number. Although they are not the largest energy consumer, they are the least productive energy consumers in the EU27, and have the highest energy footprint per unit GDP. On the contrary, there are 9 countries, including Cyprus (6.4 MJ/€), Austria (6.5 MJ/€), Italy (7 MJ/€), Denmark (7.1 MJ/€), France (7.4 MJ/€), Germany (7.6 MJ/€), Ireland (7.7 MJ/€) and Spain (8.4 MJ/€), have lower EECC. They are with the highest energy efficiency and the most productive energy users in the EU27 and even worldwide. According to the report of Enerdata (2020), these countries as well are top-ranking with the energy efficiency of GDP. 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).

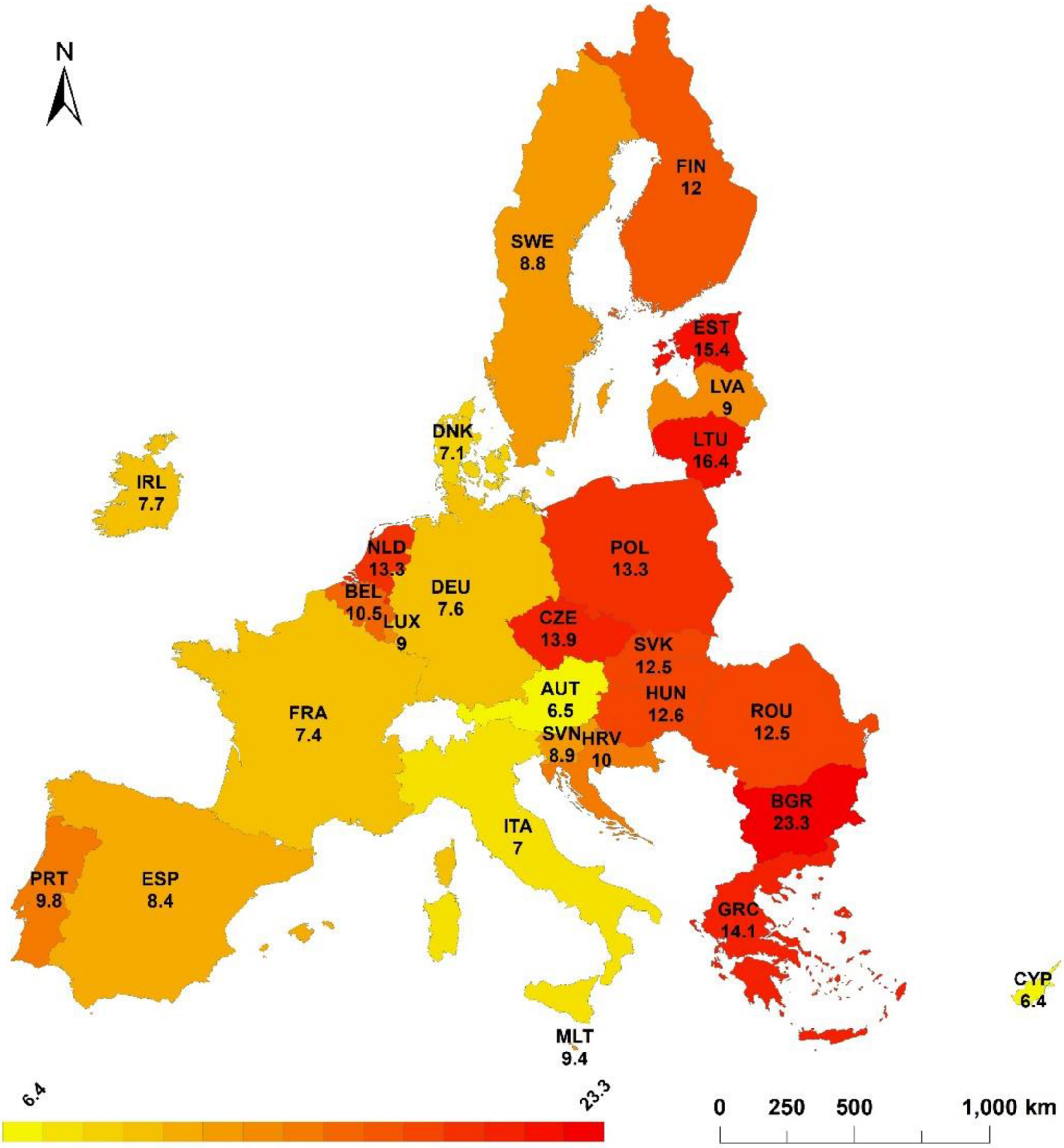


Figure 18 EECC of the EU27(MJ/€)

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. The energy pressure and their environmental performances are also highly related to the upstream countries or regions in the viewpoint of the supply chain. The situation might be even worse for the countries with a higher share of indirect embodied energy consumption. For example, 90% embodied energy consumption of Luxembourg is indirect, followed by Ireland (79%), Malta (74%), Latvia (62%), Austria (60%), Denmark (60%), Belgium (59%), etc. These countries might be more easily affected by the economic fluctuation and industrial restructuring of upstream countries. They also might benefit from importing finished products and leave the environmental impact of manufacturing and producing in the upstream countries.

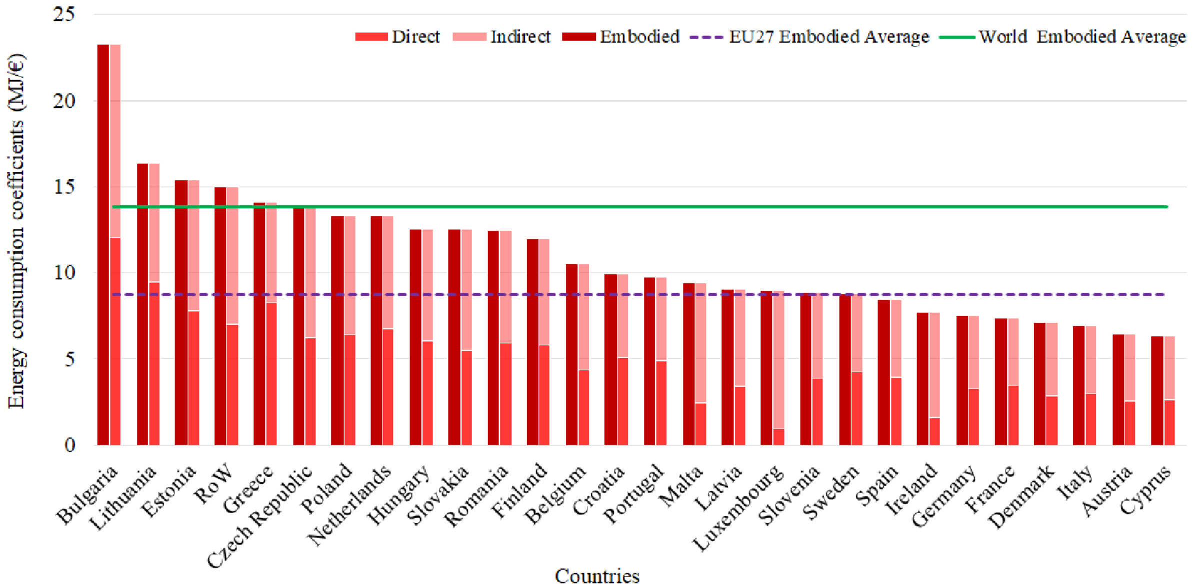


Figure 19 Direct and Indirect EECC

Figure 20 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. EU contributed to 1,561 Mtoe of primary energy consumption in 2017, which accounted for 11.05% of worldwide (Simon, 2019). However, the population of EU27 only accounts for 6% of the whole world. The primary energy consumption in the EU was still 5.3% higher in 2017 than the 2020 target. The final energy consumption in the EU reached 1,222 Mtoe in 2017, which was also 3.3% above the 2020 target (European Commission, 2019). The top energy consumers per capita in EU27 is Luxembourg at 2.58 TJ, followed by Netherland (0.99 TJ), Finland (0.85 TJ), Belgium (0.78 TJ), Sweden (0.70 TJ), Ireland (0.64 TJ), Denmark (0.58 TJ), etc. Those countries have their specialised in energy-intensive economic activities. Some of them also the top energy consumers in EU27, for example, France, Germany, Italy and Spain (Enerdata, 2014).

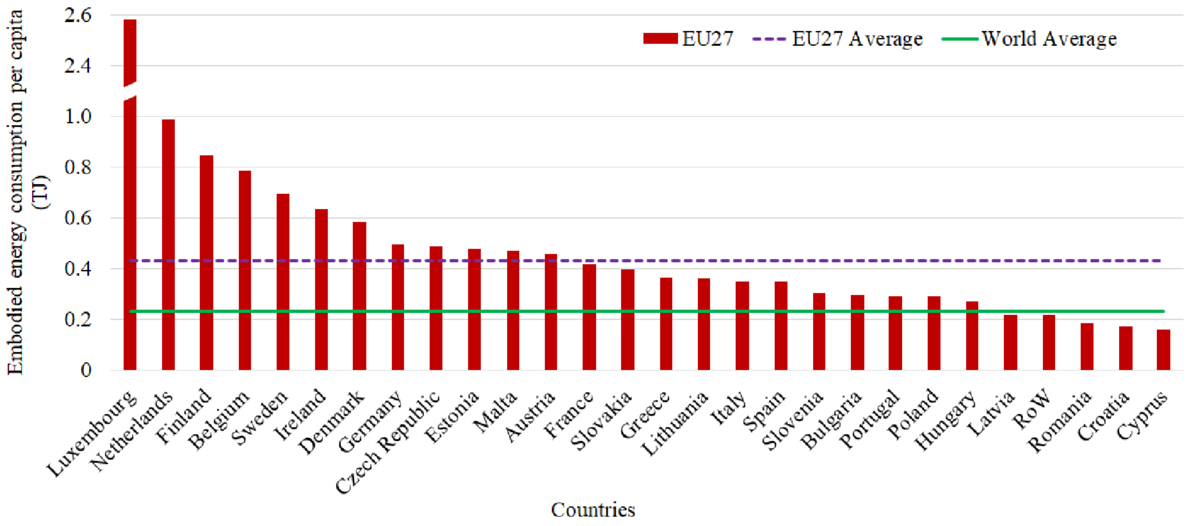


Figure 20 Embodied Energy Consumption Per Capita

3.5.3 Embodied CO_2 Emission

Figure 21 shows the EECC of the EU27. Figure 22 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. The smallest EECC in the EU27 are in France (175 t/M€), Sweden (180 t/M€), Austria (212 t/M€), Italy (221 t/M€) and Spain (258 t/M€). They are also the only five countries perform better than the EU27 average level. The largest indirect EECC in the EU27 are in Bulgaria (447 t/M€), Estonia (371 t/M€), Luxembourg (361 t/M€) and Poland (322 t/M€). 89% ECEC of Luxembourg is indirect, 77% of Ireland, 71% of Belgium, 69% of Sweden and 67% of Malta. It means that these countries transfer a huge amount of embodied CO_2 emission to upstream countries during international trade. Their environmental pressure is also transferred to upstream countries.

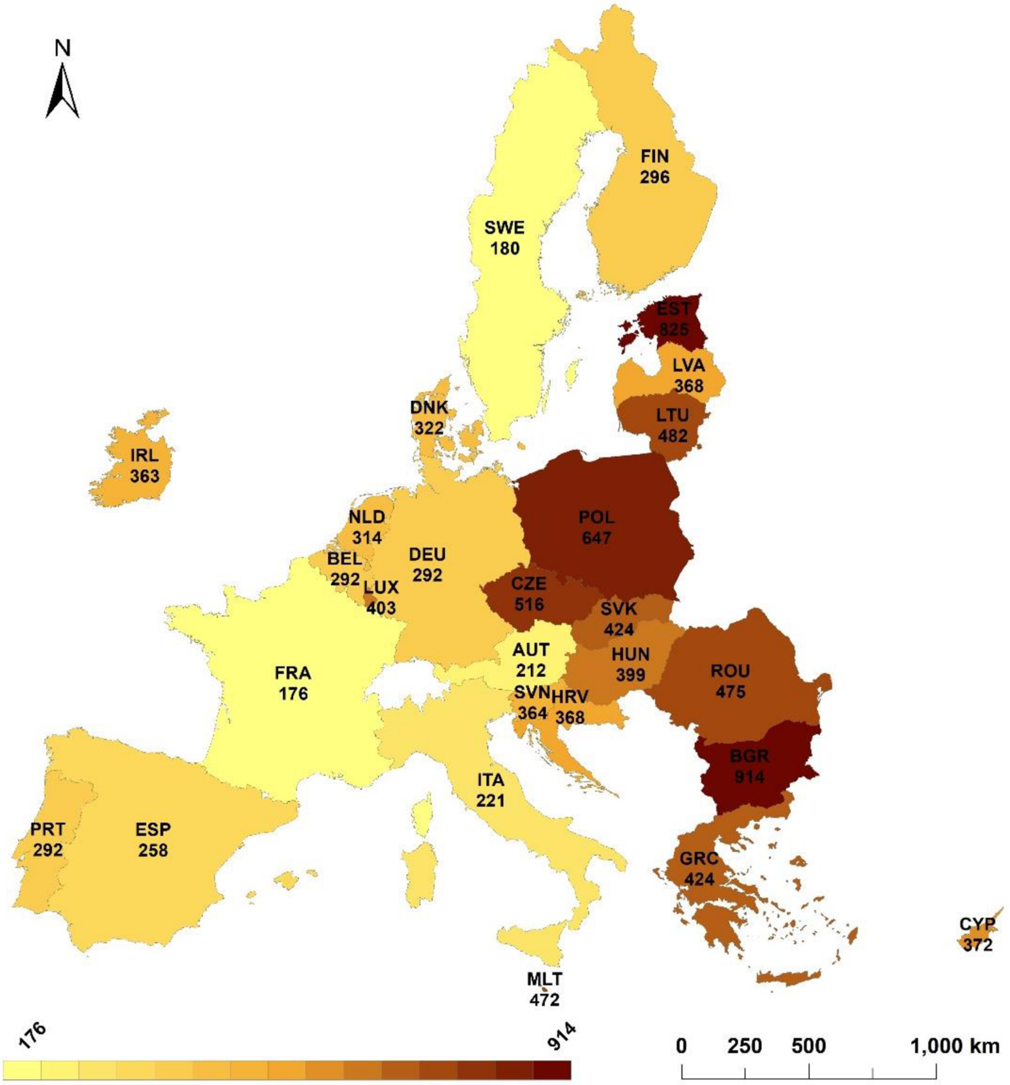


Figure 21 EECC of the EU27(t/M€)

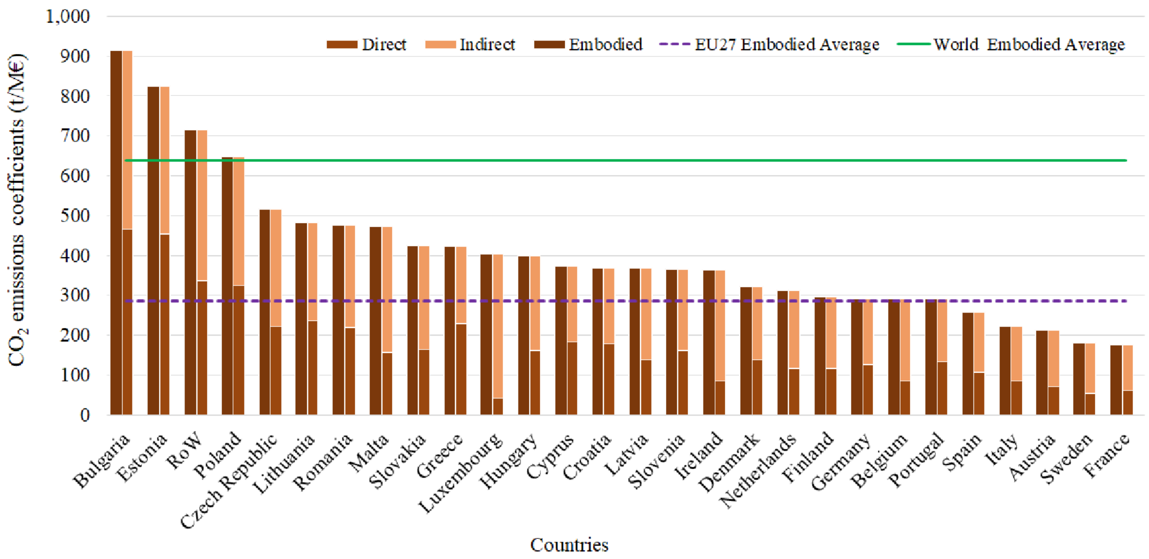


Figure 22 Direct and Indirect EECC

Figure 23 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 20), 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. 19.5% of the electricity in France came from renewable energy in 2014 (RTE France, 2015). The French parliament has decided that renewable energy would account for 40% of national electricity generation by 2030 (Carbon Pulse, 2015). According to the Sweden Energy Report (2015), 50% of the electricity of Sweden came from renewable energy in 2012, and the target by 2040 is 100%. Sweden benefits from its plentiful supply of biomass and moving water, which have been contributing to the high share of renewable energy (Sweden Energy Report, 2015). Similar situations are in Lithuania and Portugal; both of them have high renewable energy share. On the contrary, Poland, Slovenia, Estonia and Cyprus ranking worse in CO_2 emission ranking than embodied energy consumption. Because these countries have low renewable energy share in their national energy structures. For example, the renewable energy share was 10% of total energy supply in Poland (IEA, 2016), and the target by 2020 is 15%, which is lower than the EU average level.

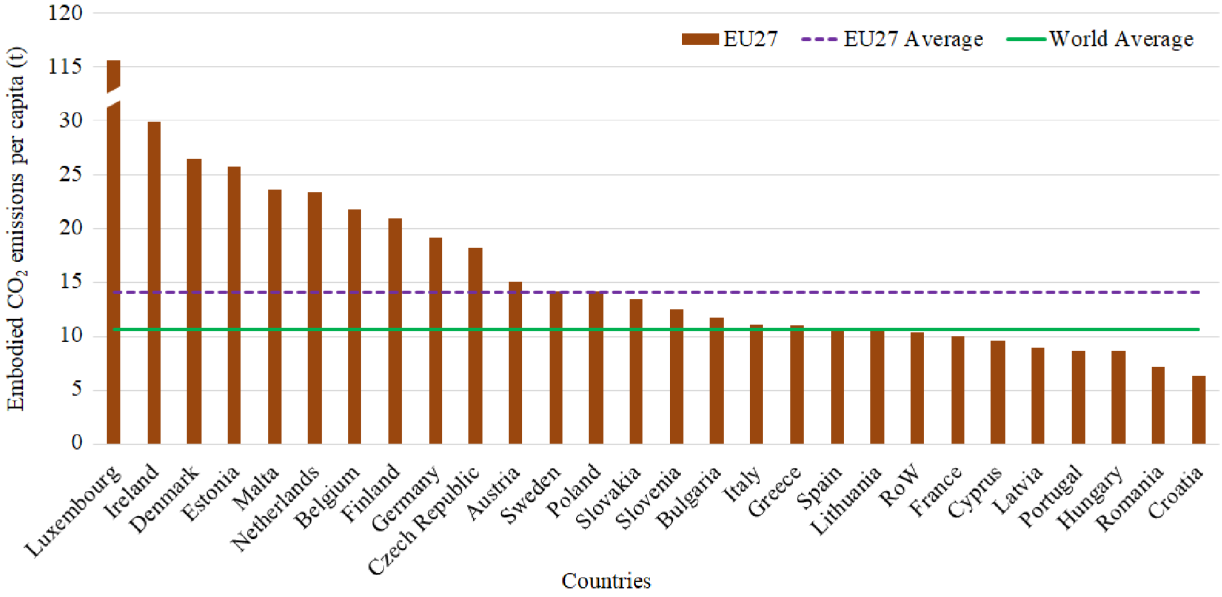


Figure 23 Embodied CO_2 Emission Per Capita

3.6 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.

For countries that more rely on import, they should have a higher share of indirect embodied energy consumption, water consumption, as well as CO_2 emission. Their environmental performance also more rely on the upstream countries from the supply chain perspective. They can also benefit from transferring environmental pressure to upstream countries during international trade. For these countries, they should focus on strengthening and deepening cooperation with upstream countries, improving resource efficiency, reducing environmental footprints. On the contrary, for countries that have higher direct embodied resource share and more export should more focus on increasing the resource utilization efficiency within the country. Some countries are water- energy- and carbon-intensive at the same time, including Bulgaria, Greece, Poland and Romania. They should focus on comprehensively readjusting the industrial structure, improving policy and strategy effectiveness, emphasising technology upgrade, etc.

3.7 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. Indirect and direct values of the above indicators have also been assessed. Embodied consumptions of energy and water per capita and embodied CO_2 emission per capita are explored as well. The main conclusions and suggestions are as follow:

(i) The EU27 average EWCC (27 m^3/k€,) is much lower than that of the world average value (75 m^3/k€). Bulgaria (112.2 m^3/k€), Estonia (77.2 m^3/k€) and Greece (61.9 m^3/k€) are embodied-water-intensive countries. On the contrary, Sweden, Denmark, Germany and Austria are with the highest water efficiency in the EU27. For the countries with high indirect EWCC, like Bulgaria, Luxembourg, Estonia and Ireland, they should strengthen and deepen the cooperation with upstream countries, focusing on improving the resource utilisation efficiency, reducing environmental footprints from the supply chain perspective. Because they are the downstream countries in terms of embodied water consumption. Because of specialised in water-intensive economic activities, Finland, Ireland, Estonia, Netherland and Italy, have the top amount of embodied water consumption per capita, such as paper industry, power industry, etc.

(ii) The average EECC of EU27 (8.8 MJ/€) is much lower than the world average value (13.9 MJ/€), because of its better energy efficiency and relevant technologies. Bulgaria (23.3 MJ/€), Lithuania (16.4 MJ/€), Estonia (15.4 MJ/€) and Greece (14.1 MJ/€) are with the highest coefficient values, performing even worse than the world average level. Cyprus, Austria, Italy and Denmark have the highest energy efficiency in € unit. Bulgaria, Luxembourg, Czech Republic, Estonia and Slovakia are the top five countries in the EU27 in terms of indirect EECC, which means they import a massive amount of embodied energy from upstream countries during international trade.

(iii) Regarding ECEC, the EU27 average value (286 t/M€) is much lower than the world average value (637 t/M€) in terms of embodied CO_2 emission. However, there are three countries, Bulgaria (914 t/M€), Estonia (825 t/M€) and Poland (647 t/M€), emit more CO_2 than the average world number. The smallest ECEC are in France (175 t/M€), Sweden (180 t/M€), Austria (212 t/M€), Italy (221 t/M€) and Spain (258 t/M€). Most of Luxembourg ECEC is indirect (89%), followed by Ireland (77%), Belgium (71%), Sweden (69%) and Malta (67%). They transfer a massive amount of embodied CO_2 emission to upstream countries during international trade.

(iv) There are several countries, France, Sweden, Lithuania and Portugal, are with higher embodied energy consumption amount, however with lower CO_2 emission value, because these countries have higher renewable energy consumption share than that of other EU27 members. However, Poland, Slovenia, Estonia and Cyprus are on the opposite, with more CO_2 emissions because of their low renewable energy share in the national energy structures.

The method employed in this study can be an effective approach for analysing sectoral and regional WEC nexus. There are also some limitations to this study. This research only takes

CO_2 into consideration. However, more important are the complete GHG emissions. GHG includes CO_2 and other emissions, like CO, NO_x, SO_x, etc. (Wang et al., 2019a). There are also some overlooked GHG, like ozone-depleting substances (ODSs) (Ortega et al., 2020). Those GHG can directly cause global warming, especially do harm to the Arctic and Antarctic. The CO_2 emission data used in this study is from the WIOD (Amores et al., 2019). The best way is to calculate the GHG emissions based on relevant energy consumption amount and GHG emission factors. The critical transmission flows between different countries, and even different sectors also need more in-depth exploration. These will be explored in future work.

CHAPTER 4

SOPHISTICATED GIS-IO METHODOLOGY TO REVEAL AND MAP WEGN NETWORK

The work presented in this section is based on my paper is going to be published in Renewable and Sustainable Energy Reviews entitled “Unsustainable Imbalances and Inequities in Carbon-Water-Energy Flows across the EU27”, as clarified on Page IX (Contributing publication). The author of this thesis is the first author of this publication. The other co-authors who contributed to this publication are the supervisor (J.J. Klemeš), co-supervisors (Y. Wang and P.S. Varbanov) and collaborators.

4.1 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. We recommend that the EU27 provide more technical support to upstream countries in the EU and elsewhere to improve the efficiency of resource utilisation.

4.2 Introduction

Global greenhouse gas (GHG) emissions have continually risen despite the United Nation (UN) Sustainable Development Goals (UNSDGs) and the Framework Convention on Climate Change (UNFCC) (Roe et al., 2019). Global warming would result in 1.5 °C in 15 to 20 years at the current rate, and if we want to succeed staying below the 1.5 °C targets, the GHG emissions should be reduced to zero within the next 30 to 40 years (IPCC, 2018). This is a daunting and perhaps one of the biggest global challenges humanity will ever face. The likelihood of achieving the 1.5 °C target would considerably decrease if the measures were postponed to 2030 (Smith et al., 2019). The top ten CO_2 emitters in the world in 2017 were

China, the USA, the EU27, India, Russia, Japan, Iran, Sandi Arabia, South Korea, and Canada (Ritchie and Roser, 2017). The EU27 contributes 8.7% (3.12 Gt) to global emissions, which is lower than China at 27% and the USA at 15% (Ritchie and Roser, 2017). If the EU27 were considered as separate countries, then Germany (800 Mt) would be positioned after Japan. Other EU27 emitters in the top twenty list are France and Italy(Ritchie and Roser, 2017). The focus in all global climate action and policy are GHG emissions reduction.

All measures and targets usually revolve around these CO_2 emissions, but this is not the complete picture, and this success of this focus is a moot point. It could be argued that the UN FCCC and the more recent Paris Agreement (REF) have not been effective in achieving any real impact over the last 25 years. The UN and political leaders globally must know this themselves as this is reflected in the more humanity centric holistic approach of the 17 UN SDGs, where food, water, and affordable and clean energy within the context of a sustainable partnership are spelt-out so that we build a sustainable future for us all equitably and in peace. Climate change will bring significant uncertainty in water resource security and management (Kundzewicz et al., 2018), and trigger negative effects on both energy demand and the resilience of energy systems (Perera et al., 2020). This would result in social disharmony and further political imbalance creating problems than humanity cannot afford with the inevitability of the impacts of climate change. Global and regional trade, results in an unprecedented displacement of social and environmental influences, which is accompanied by massive embodied flows of energy, water and CO_2 emissions (Wiedmann and Lenzen, 2018). As a consequence of this growing unprecedented displacement, the wider chasm of disparities among countries or regions in embodied Carbon Dioxide (CO_2) - Water - Energy (CWE) flows is becoming dramatic and more conspicuous to the 'have' and 'have nots'. Where before hydrocarbon energy security was king in the global political landscape, the effects and impacts of the global COVID-19 pandemic with resultant never seen negative crude oil prices, now water, food and green energy for local security are the queen. Water and energy consumption continues to rise in every country, although now the wobble in energy consumption reflects the precariousness of the global COVID-19 pandemic. Irrespective of this, energy consumption will continue to rise, although with more variability. An outlier in the global CWE flows is that the real and virtual footprints for water and energy are very different depending on economic activity (Duan and Chen, 2020). We examine these phenomena considering the UNSDGs and to highlight the disparities and inequities in the current CWE network. In this study embodied CO_2, embodied water and embodied energy are taken to mean the total CO_2 emitted, water used and energy consumed for generating a product or providing the service(Wang et al., 2020b). They cover the entire process from raw material to final product from the supply chain and life cycle perspectives. An appropriate understanding of the CWE nexus is pivotal for mitigating climate changes (Wang et al., 2020b), improving energy and water resource security(Khan et al., 2018), upgrading management resource efficiency (Meng et al., 2019b), reducing environmental footprints (Wang et al., 2020a), and promoting regional sustainability (Yang et al., 2019b). Typically, CO_2 emissions considered pollution and energy considered as a paid-for resource are studied together and assigned to an emitter. However, 'free' water is mostly studied in isolation and has no real borders. It is also analysed very differently by discipline, expert and country depending on user needs (Niva et al., 2020). Work by others have examined total water and virtual water footprints in isolation by looking at green, blue, and greywater flows (Hoekstra, 2019).

No work, to date, has attempted to examine CWE flows in a holistic approach to battle climate change. Here we analyse CWE flows across the EU27 countries using a multiregional input-output (MRIO) approach. We explore the CO_2, water and energy embodied in interregional trade of products across the EU27 and the rest of the world to highlight imbalance. We divide the MRIO flows at a sectoral level to identify trends and strengths, challenges, and weaknesses in the ecosystem. Our findings are discussed in the context of EU27 'Effort Sharing' and binding emissions targets, and energy and water security, considering the UNSDGs, equity and the environment.

4.3 Data

The EU27, after BREXIT, was taken as cases, and a model for the rest of the world. The involved EU27 countries are Austria (AUT), Belgium (BEL), Bulgaria (BGR), Croatia (HRV), Cyprus (CYP), the Czech Republic (CZE), Denmark (DNK), Estonia (EST), Finland (FIN), France (FRA), Germany (DEU), Greece (GRC), Hungary (HUN), Ireland (IRL), Italy (ITA), Latvia (LVA), Lithuania (LTU), Luxembourg (LUX), Malta (MLT), Netherlands (NLD), Poland (POL), Portugal (PRT), Romania (ROU), Slovakia (SVK), Slovenia (SVN), Spain (ESP) and Sweden (SWE).

The Environmental Input-Output (EIO) model used in this study was based on the world input-output table (Timmer et al., 2016) and the World Input-Output Database (WIOD) environmental accounts (Amores et al., 2019). The WIOD database has data from 43 countries worldwide, including EU27 and a model for the rest of the world. It includes world input-output table, national input-output tables and environmental accounts for the period 2000-2014. The unit in world input-output table is $. However, this study uses € as it deals with the EU countries. The exchange rate is 1.33 in 2014, taken from the Global No.1 Business Data Platform (Euro to U.S. dollar exchange rate 1999-2018, 2020). Data for 56 sectors were classified according to the International Standard Industrial Classification Revision 4 (United Nations, 2008). The authors focus upon the latest year (2014) data. The CO_2 emission data and different types of energy consumption data of different countries are collected from WIOD database (Amores et al., 2019). The energy considered in this study includes Coal, Coke, Crude, Jet Fuel, Diesel, Gasoline, Heavy Fuel Oil, Light Fuel Oil, Naphtha, other Petrol, Waste, Geothermal, Hydro, Nuclear, Wind, Solar, Nature Gas, Electricity, Biodiesel and Biogas. The water consumption data were obtained and calculated from the water balance table database at Eurostat (Eurostat, 2020), which is the statistical office of the EU. It provides high-quality statistics at European level for the EU. Population data were obtained from the World Bank (The World Bank, 2020).

4.4 Method

4.4.1 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 a 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). In this study, the GIS method is employed to map the WEGN flows and visualise the WEGN in the EU27.

4.4.2 MOIO

An MRIO database for 28 economies (Format as shown by Table 7), including the EU27 countries and the rest of the world, was complied. The MOIO model is developed based on the World Input-Output Tables (WIOT), which is for 27 EU countries and 16 other major countries/economies (Timmer et al., 2015). 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*. Each sector of each economy was designated as an individual producer node in the global economy to connect all economic activities of water utilisation, energy consumption and CO_2 emissions. There are 1,568 nodes in total for 28 economies involved in this study.

Table 7 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								

There are 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.

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

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

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*.

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

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:

$$E + LZ = LY \tag{18}$$

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

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

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:

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

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

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 (Table 8), 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:

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

Table 8 Coefficients of embodied CO_2 emissions, water utilisation and energy consumption (Wang et al., 2020a)

	EU27 Average (A_{EU})	Worldwide Average (A_{WO})
Embodied CO_2 Emissions Coefficients	286 t/M€	637 t/M€
Embodied Water consumption Coefficients	8.8 MJ/€	13.9 MJ/€
Embodied Energy consumption Coefficients	27 m^3/k€	75 m^3/k€

4.5 Sectors Classification Adjustment

The original economic input-output table has 56 sectors, which is not suitable for the assessment of water and energy consumption or CO_2 emissions. These 56 sectors were merged into 10 aggregated sectors to eliminate this limitation, as shown in Table 9Table 7.

Table 9 Congruent relationship between aggregated and original sectors

Abbreviations	Aggregated Sectors	Original Sectors
AGR	Agriculture	Crop and animal production, hunting and related service activities
		Forestry and logging
		Fishing and aquaculture
M&Q	Mining and quarrying	Mining and quarrying
MAN	Manufacturing	Manufacture of food products, beverages and tobacco products
		Manufacture of textiles, wearing apparel and leather products
		Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
		Manufacture of paper and paper products
		Manufacture of coke and refined petroleum products
		Manufacture of chemicals and chemical products
		Manufacture of basic pharmaceutical products and pharmaceutical preparations
		Manufacture of rubber and plastic products
		Manufacture of other non-metallic mineral products
		Manufacture of basic metals
		Manufacture of fabricated metal products, except machinery and equipment
		Manufacture of computer, electronic and optical products
		Manufacture of electrical equipment
		Manufacture of machinery and equipment n.e.c.
		Manufacture of motor vehicles, trailers and semi-trailers
		Manufacture of other transport equipment
		Manufacture of furniture; other manufacturing
		Repair and installation of machinery and equipment

ENE	Energy supply	Electricity, gas, steam and air conditioning supply
WAT	Water supply	Water collection, treatment and supply
WAS	Waste management	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services
CON	Construction	Construction
W&R	Wholesale and retail trade	Wholesale and retail trade and repair of motor vehicles and motorcycles
		Wholesale trade, except motor vehicles and motorcycles
		Retail trade, except motor vehicles and motorcycles
T&W	Transport and warehousing	Land transport and transport via pipelines
		Water transport
		Air transport
		Warehousing and support activities for transportation
SOC	Social services	Printing and reproduction of recorded media
		Publishing activities
		Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
		Telecommunications
		Insurance, reinsurance and pension funding, except compulsory social security
		Activities auxiliary to financial services and insurance activities
		Scientific research and development
		Advertising and market research
		Other professional, scientific and technical activities; veterinary activities
		Administrative and support service activities
		Public administration and defence; compulsory social security
		Postal and courier activities
		Accommodation and food service activities
		Computer programming, consultancy and related activities; information service activities
		Financial service activities, except insurance and pension funding
		Real estate activities
		Legal and accounting activities; activities of head offices; management consultancy activities
		Architectural and engineering activities; technical testing and analysis
		Education
		Human health and social work activities
		Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
		Activities of extraterritorial organisations and bodies
		Other service activities

4.6 Regional Patterns of EU27 CWE Network

This study quantified the embodied CO_2 emissions chain (Figure 24), water chain (Figure 25) and energy chain (Figure 26) 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 24), for example, Spain, Ireland, Poland, Romania, Bulgaria, Slovenia, the Czech Republic, Estonia and Lithuania. Whereas countries with positive embodied CO_2 values were beneficiaries, namely Germany, France, Germany, Italy, Greece, Denmark, Portugal, Sweden, Croatia and Finland. 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.

Europe emits about 5.06 Gt of embodied CO_2 emissions annually. Specifically, the Netherlands had -43.5 Mt, Poland -27.7 Mt, the Czech Republic -10.8 Mt and Belgium -8.6 Mt net outflow values, accounting for 38.9%, 24.9%, 9.7% and 7.7% separately of the total net embodied CO_2 outflows amount in the EU27 countries. The analysis indicates that these countries are the most upstream economies in the embodied CO_2 emissions chain of EU27, bearing most in terms of embodied CO_2 emissions and suffer the highest environmental pressures transferred from the downstream countries. In contrast, France, Germany and Italy have the highest net inflows values, which were 38.0 Mt, 31.6 Mt and 13.9 Mt, accounting for 34.1%, 28.3% and 12.4% respectively, of the total net import amount in the EU27. These beneficiaries transferred most embodied CO_2 emissions to the upstream countries and benefited most from the EU27 interregional trade from an embodied CO_2 emissions chain perspective. The CO_2 emissions chain is mainly driven by the demand of downstream countries, where France, Germany and Italy are the dominant consumers. The top embodied CO_2 emissions flows in the EU27 are from Germany, France and Italy. As the largest trading partner of Germany in the EU27, the Netherlands exported most to Germany in 2014, 1.2×10^{11} € or 1.6×10^{11} kg in products quantity (European Commission, 2015). This was the biggest embodied

CO_2 emissions flow, 39.4 Mt, from the Netherlands to Germany, followed by 24.3 Mt from Germany to France, 22.9 Mt from Poland to Germany, 19.3 Mt from Belgium to Germany and 17.7 Mt from Germany to Italy. Germany, France and Italy are the top three countries in the EU27 in terms of economy size (GDP European countries, 2020). Since Germany, France and Italy have lower CO_2 emissions per gross domestic product (GDP) (Wang et al., 2020a), they have a good potential to decrease their emissions from a global perspective.

Europe uses about 243 Gm^3 of water annually in economic activity (European Environment Agency, 2018a). 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 25), 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, which is much more than the total amount of all other EU27 countries combined. These two countries that have net outflow amounts of more than 700 Mm^3, placing them at the most upstream position and act as water suppliers in the water chain of EU27. More specific, Spain is the key embodied water supplier in terms of Agriculture section among 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. They are downstream in the water chain of EU27 and benefit most in terms of embodied water from interregional trade. The key driver of the water chain is the demand of the downstream countries, where Germany, France and Italy are the dominant consumers. The top embodied water flows within EU27 are within Germany, France and Italy. The biggest embodied water flow is from the Netherlands to Germany, 3,045 Mm^3, which is because of the large amount of trade from the Netherlands to Germany (European Commission, 2015), followed by 2,036 Mm^3 from Italy to Germany, 1,752 Mm^3 from Italy to France. Although Italy exports a large among of embodied water to Germany and France, it imports massive amounts from other EU27 countries, such as from Germany (1,086 Mm^3), France (632 Mm^3), the Netherlands (564 Mm^3) and Spain (458 Mm^3), which contributes to Italy being one of the top countries in terms of trade-related, embodied water share. Since Germany and France have lower water coefficients (t/k€) (Wang et al., 2020a), the more net embodied water they import, the more opportunity to improve water efficiency from a global perspective. Italy is the antithesis of this trend, with higher water coefficient and lower water utilisation efficiency (Wang et al., 2020a).

The Netherlands leads the list of net embodied energy outflows (Figure 26), -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 superport 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. Germany is the most downstream country in the energy chain of EU27. It is one of two EU27 countries that imports embodied energy from all other E27 countries. Ironically, the other is Sweden, however, with a much lower import value of (8.6×10^3 PJ) and net import value (80 PJ). The biggest embodied energy flow is from the Netherlands to Germany, 2.5×10^3 PJ, followed by 8×10^2 PJ from Germany to France and 7.2×10^2 PJ from Belgium to Germany. Based on our previous study, Germany, France and Italy have higher energy efficiencies (Wang et al., 2020a), indicating that the current energy chain structure of EU27 is beneficial from a global perspective.

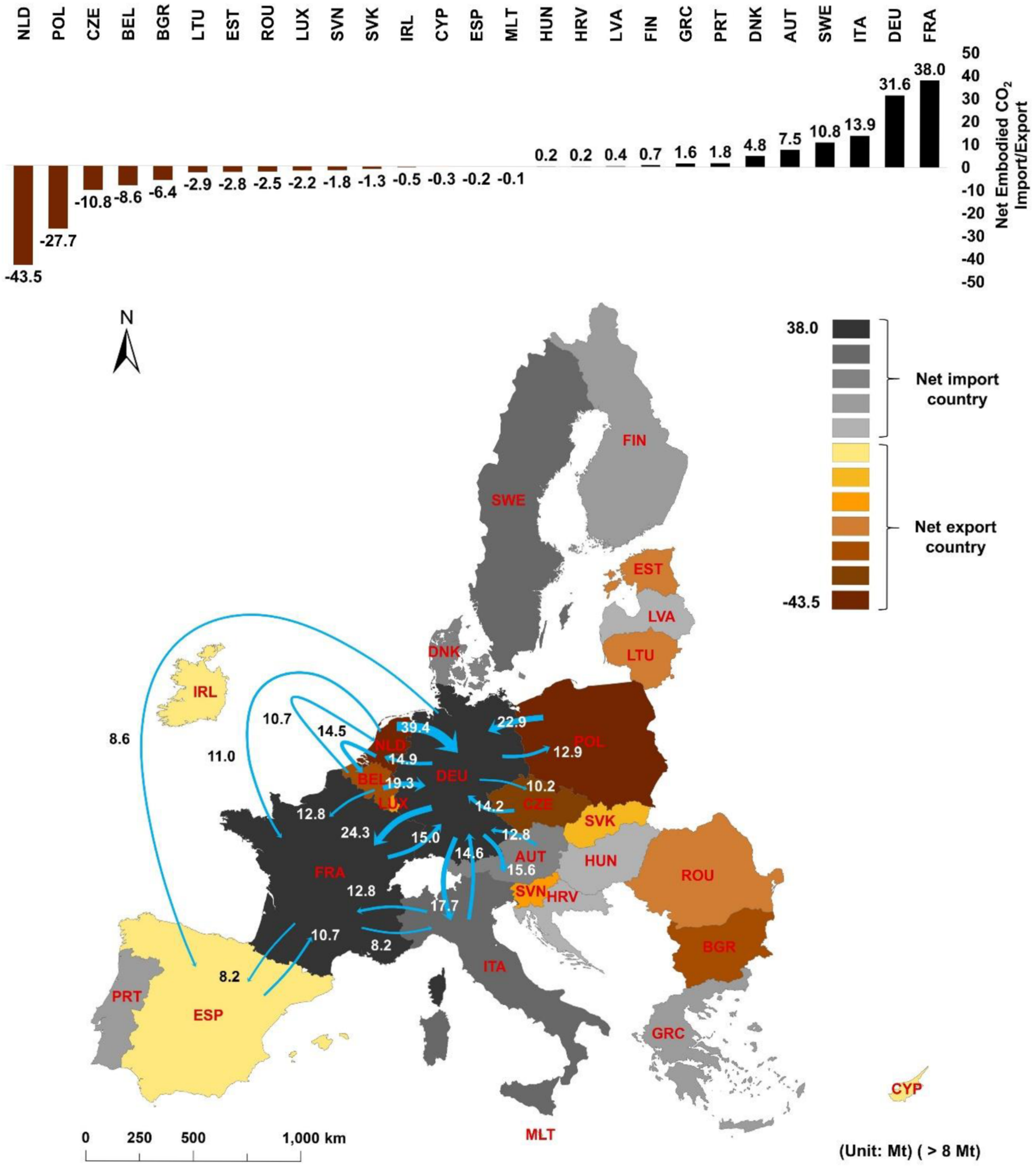


Figure 24   Embodied CO_2 Emissions Chain (> 8 Mt) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (brown) or importers (black). The chains are listed in terms of flows to other countries for amounts greater than 8 Mt.

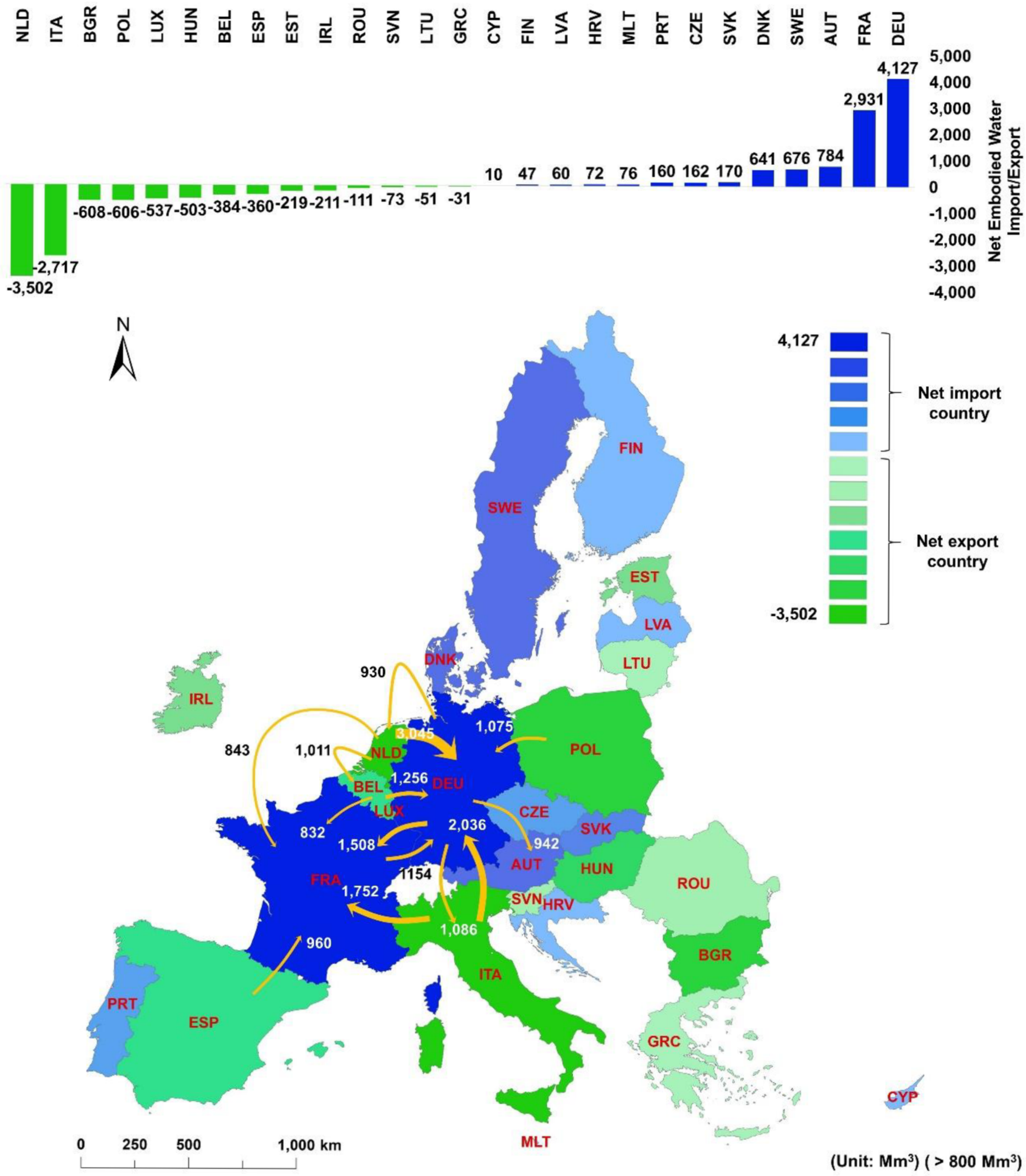


Figure 25 *Embodied Water Chain (> 800 Mm^3) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (green) or importers (blue). The chains are listed in terms of flows to other countries with the amount greater than 800 Mm^3.*

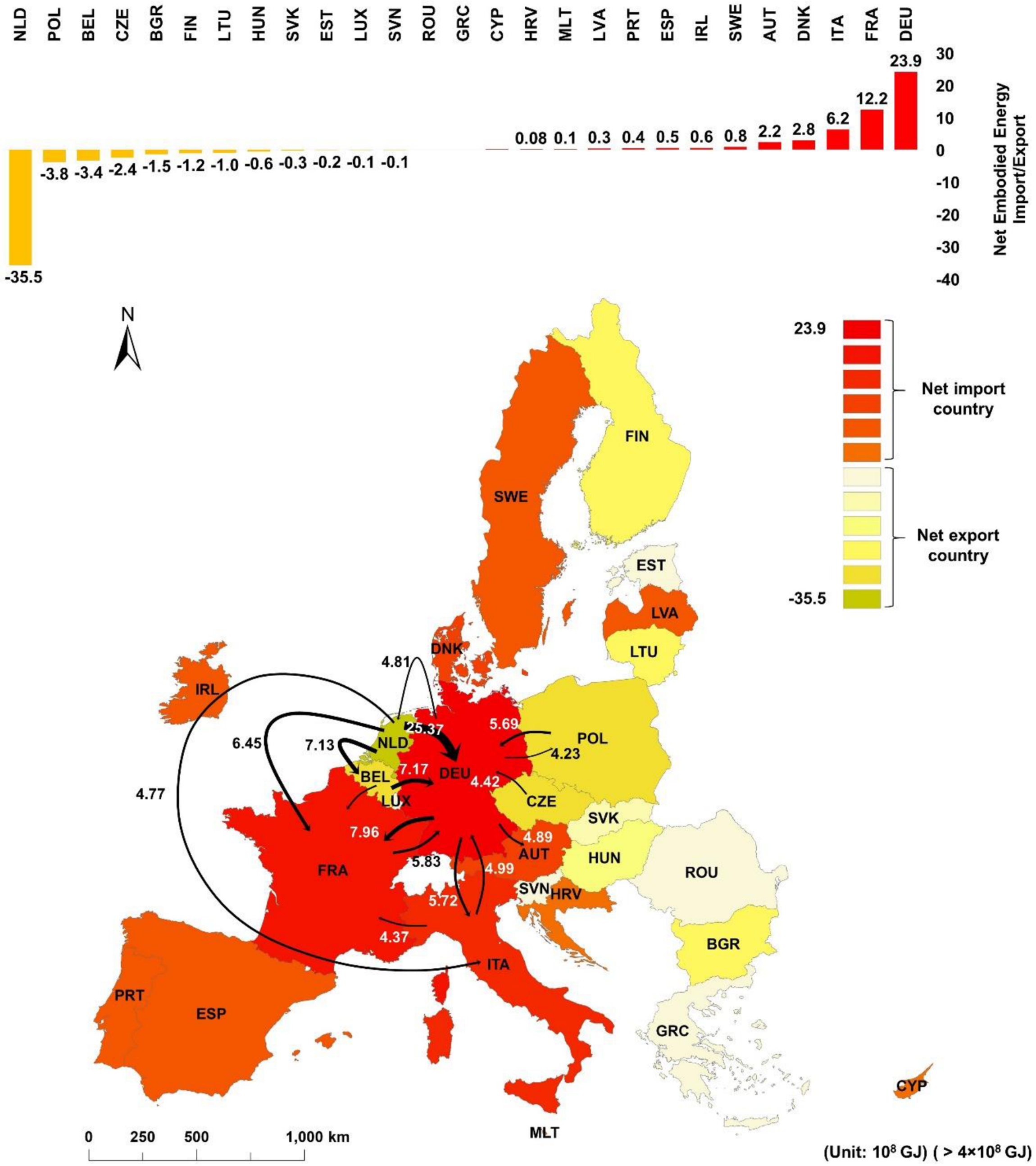


Figure 26 Embodied Energy Chain (> 4×10^{8} GJ) of EU27. The width of the arrows means the magnitude of the net flow. The colours indicate cities as net exporters (yellow) or importers (red). The chains are listed in terms of flows to other countries, with the amount greater than 4×10^{8} GJ.

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 27) 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 27a). 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 24). 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. The upstream countries will be affected even further with stricter emissions and energy obligations in the 2030 climate and energy framework as the EU27 move to a climate-neutral economy(Anonymous, 2016). This will be distributed by the burden sharing, emissions trading scheme (ETS) and fines. The European Commission (EC) and EU27 all Member States need to very mindful of this in any new targets, sharing and fine schemes, especially in light of current COVID-19 challenges and also bailouts or loans from the European Investment Bank.

Trade relevant embodied water demand within EU27 was 52,461 Mm^3 in total (Figure 27b), 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. In any new water, policy plans the EC must consider this for the EU27 so that the food baskets of Europe should not be penalised by the more industrial intensive countries. In the future, this ‘breadbasket’ characterisation of certain EU27 Member States such as Spain, Italy and Irelands needs to be reflected in the Common Agricultural Policy (CAP) agreements and CO_2 emissions burden sharing, reduction targets and fines.

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. This will also enable deep decarbonisation if done correctly using smart technology and electric transport systems in tandem with renewable energy creating further manufacturing jobs across the EU27 (Scott, 2020).

The EC just announced a drive for offshore wind power to supply its electricity needs, for example, Ireland alone could supply up to 5% of the EU27 electricity needs (Environment and Editor, 2020). Similarly, countries along southern latitudes of the EU such as Spain, Portugal, Italy and Greece could supply solar photovoltaic energy. These future green battery countries in the EU27 need very clear support from the EU27 with the bigger economies paying, not just financing for the infrastructure to build these mega offshore wind and solar PV farms. With the European Green Deal roadmap to make the EU27 the first climate-neutral continent by 2050, such opportunities should be embraced, especially with lending never lower and the economic impacts of the COVID-19 pandemic. Key challenges for the EC and the EU27 member states are balancing the conflicting stakeholder interests, the low price of fossil fuel and the significant infrastructure and regulatory gaps at the distribution level, particularly. However, there has perhaps never been a better time to break the fossil fuel addiction across the EU27, which will have significant positive and negative impacts on the global economy and environment.

Another point to note is that electrification of transport will mean increased imports across the globe of precious metals (e.g. lithium, graphite, cobalt etc.) from less developed regions and countries. In addition, China and the USA are also following similar plans so the price of precious metals, reflected in the introduction of the EV metal index by the mining industry (MINING.COM, 2020). The historical fossil fuel energy dynamic across the globe is set to change irresistible. The question is, does carbon emission capture and storage have an honest role to play in the hydrogenation of fossil fuels? It sounds great top decision-makers now, but critically is ‘burying’ carbon an appropriate long-term environmental solution or just a future ticking time bomb on the global low carbon transition.

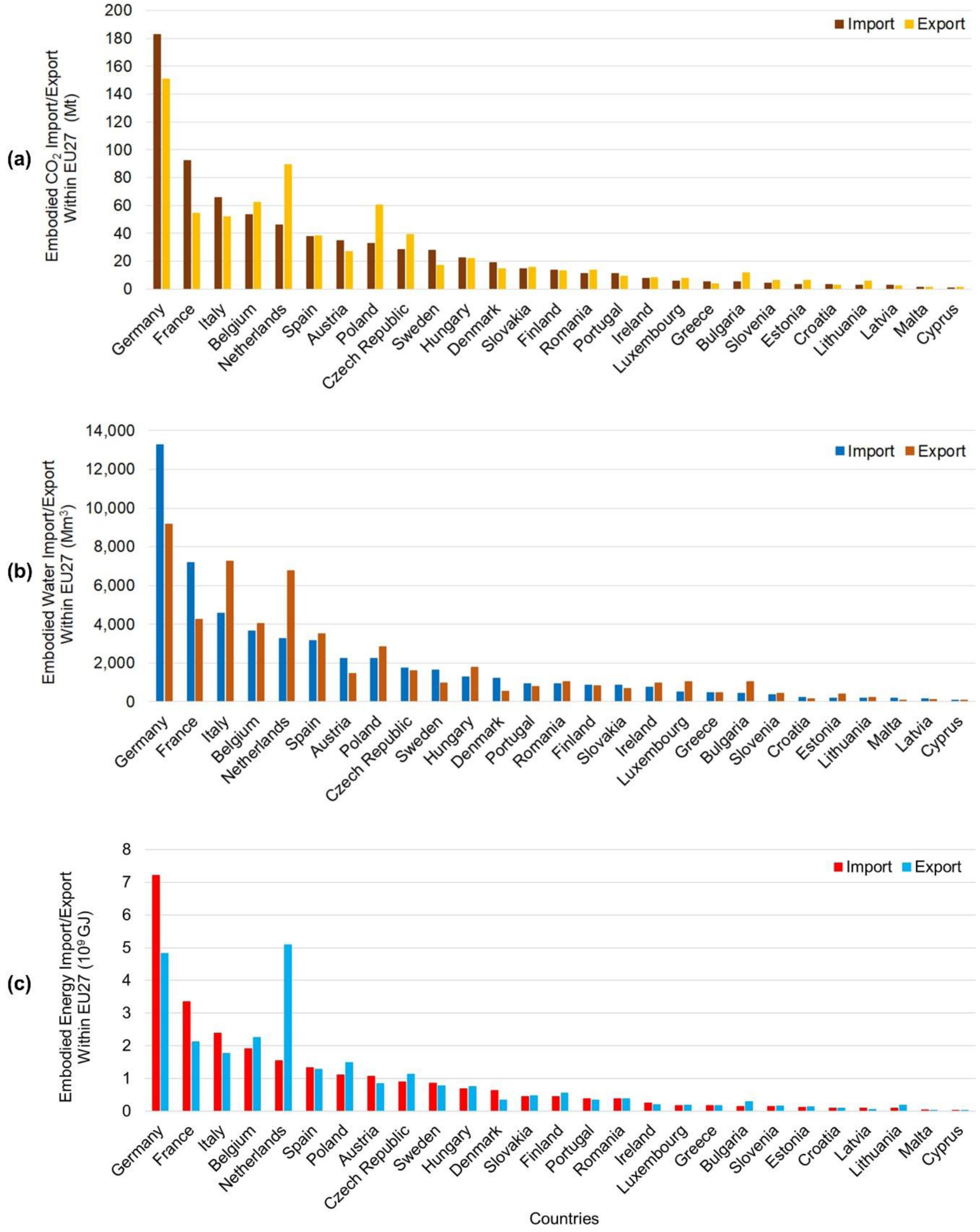


Figure 27 Embodied CWE Import/Export within EU27.

4.7 Sectoral Patterns of EU27 CWE Network

Identifying the critical sector transmissions behind the CWE nexus is crucial for obtaining a clearer understanding of the interactive mechanism among EU27 countries. This study explored ten integrated sectors in 2014, including 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).

The CO_2 chain within EU27 is mainly shaped by MAN, SOC and CON sectors (Figure 28a), 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. The results of other sectors also show the same phenomenon where the SOC sector account 98.5 Mt trade relevant embodied CO_2 flow, with 38% from net upstream countries and 62% from net downstream countries. The CON sector's net upstream countries have 35%, and the new downstream countries have 65%, which is a similar structure. All ten sectors showed a similar structure, with lower share by net upstream countries than by the net downstream countries. The fourth sector, T&W, accounted for 5.7% of the total trade-related embodied CO_2, followed by W&R at 5.3%, ENE at 3.2%, and in last place WAT at only 0.2%. Germany was both the biggest supplier and consumer of embodied CO_2 from the MAN sector, which accounts for 20.5% and 24.8% separately, as it is the most industrialised country in the EU27, followed by France and Italy. France contributes 12.5% of imported CO_2 and 7.4% of export CO_2 of the EU27. In contrast, the Netherlands contributes 12.2% of the total supply; however, they import only 6.3% of the total. Poland provides 4.4% of the import and 8.2% of the export, while the Czech Republic provides 3.9% of the imports and 5.3% of the exports of CO_2. Comparing global exporter importer CO_2 emissions can be examined on a production basis also referred to as territorial emissions or on a 'consumption-based' approach adjusted for emissions. Consumption-based emissions can reflect the consumption and lifestyle choices of a country's citizens (Our World in Data, 2019). Typically, consumption-based emissions increase when a country becomes richer (e.g. Ireland and the Czech Republic in the 2000s) and production-based emissions remain stationary. Some EU27 with growing economies (e.g. Latvia, Lithuania, etc.) need to be monitored carefully for this phenomenon, especially when making future CO_2 burden-sharing plans. The reverse of this can also be seen with positive investment in decarbonisation projects and infrastructure in some of the wealthier industrialised nations, e.g. the UK, France and Germany. Although one could also argue that living standards and opportunities for many have fallen in the UK, France and Germany; as a result, jobs in certain MAN sectors have been replaced with SOC sector jobs. Thus seeing declines in production and also consumption-based CO_2 emissions.

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 28b), 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 28c), 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.

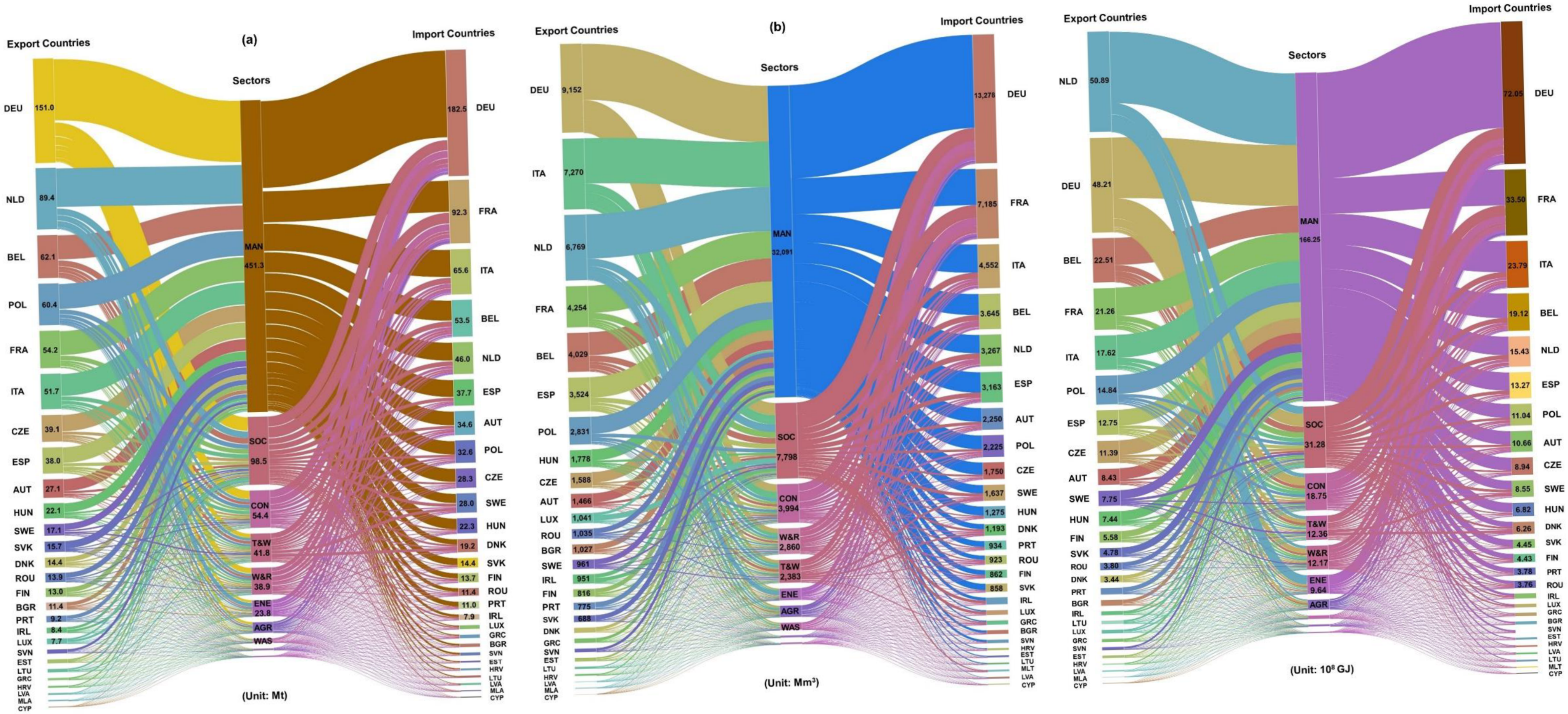


Figure 28 CWE Chain in Sector Level of EU27.

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).

4.8 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 29) 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 29a) 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 has the highest proportion of embodied CO_2 imported from EU27, which is 35 Mt and accounts for 58.5% of its total imported amount, followed by Hungary at 54.7% (22 Mt), the Czech Republic at 53.9% (28 Mt), Estonia at 53% (3Mt) and Slovakia at 51.3% (14 Mt). They 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. Ireland imported 85.3% embodied CO_2 from non-EU27 countries, namely the UK, the USA, Switzerland and China (OEC, 2020), Greece imports 78.2% of trade-related embodied CO_2 from non-EU27 such as Iraq, China, and Turkey (OEC, 2020). Countries with large economies, like Germany, France, Italy and Spain, also import more from non-EU27 countries than from EU27. Germany imports most embodied CO_2 from the rest of the world, which is 227 Mt, followed by France at 152 Mt, Italy at 118 Mt, the Netherlands at 110 Mt and Belgium at 109 Mt. These five countries account for 61.5% of that EU27 import from the rest of the world. The EU27 accounted 15% of global trade in goods in 2019 (European Parliament, 2018), and the top 5 imported products were crude petroleum and natural gas (13% of the total import of EU27), computer, electronic and optical products (13%), chemicals & chemical products (7%), machinery, equipment and motor vehicles, trailers and semi-trailers (both 6%) (Eurostat, 2020).

Approximately 32% of the imported embodied water of EU27 countries is from the EU27 (Figure 29b). 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. In contrast, the other 26 EU27 countries imported more from the rest of the world than from EU27. More than 91% of

Ireland's trade-related water import is from non-EU27 countries, which is because of the nature of the products it imports (e.g. pharmaceuticals, medical devices, integrated circuits and planes). A significant amount of product is virtually imported from the rest of the world—followed by Luxembourg (88.2%), Lithuania (78.4%) and the Netherlands (77.9%). Countries with big economies, like Germany, France, Italy, the Netherlands, Spain, and Belgium, import more embodied water from the rest of the than from the EU27. Germany, import most embodied water from the rest of the world, which is 22,257 Mm^3, followed by France at 14,647 Mm^3, the Netherlands at 11,513 Mm^3 and Italy at 10,320 Mm^3, account for 52.8% of that EU27 import from the rest of the world.

For EU27 countries, 48.5% imported embodied energy is from the EU27 (Figure 29c). 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. 65.7% (1.1×10^3 PJ) of imported embodied energy of Austria is from the EU27 countries, the rest 34.4% is from the rest of world, followed by the Czech Republic at 60.5% (8.9×10^2 PJ) and Hungary at 60.3% (1.1×10^2 PJ). In contrast, Ireland only imported 19.1% of embodied energy from the EU27 countries but imported 80.9% from the rest of the world because of its trade with the UK, USA and China (OEC, 2020). Greece is in second place, with 71.4% import from the rest of the world, most refined petroleum (OEC, 2020). Although Germany imports more from the EU27, it also imports most from the rest of the world, which is 5.6×10^3 PJ, followed by France at 3.7×10^3 PJ and Italy at 2.3×10^3 PJ. These three countries dominate to shape the structure of the EU27 energy chain.

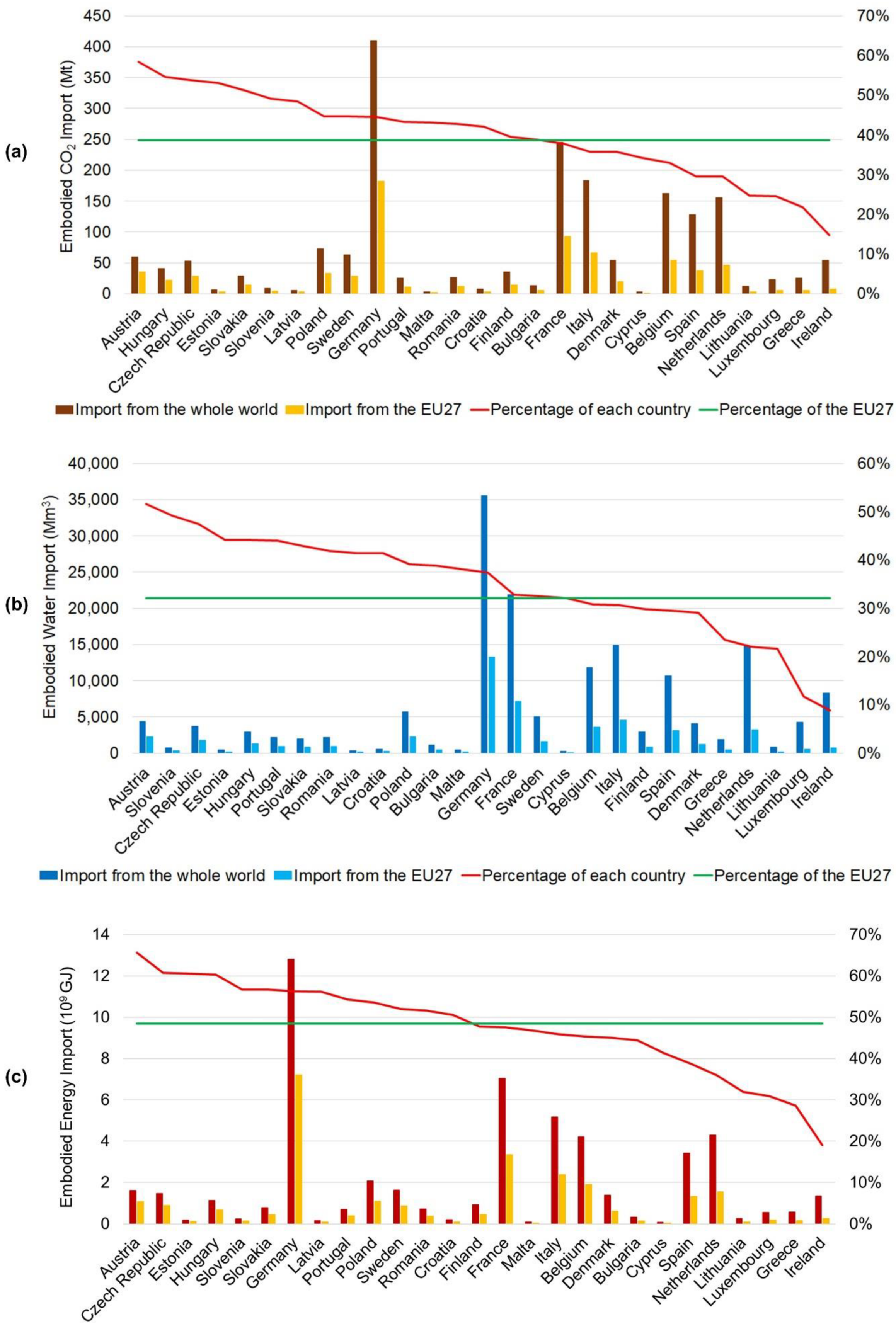


Figure 29 Importation Sources Distribution of Embodied-CO_2 (a), -Water (b), -Energy (c) of EU27.

Notes: 1) Import from the world: the total amount of embodied resource imports of a specific country; 2) Import from the EU27: the total amount of embodied resource that imported from the EU27 countries; 3) Percentage of each country: the ratio of “import from the EU27” to “import from the world”; 4) 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.

4.9 Discussions and Implications

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 (Wang et al., 2019b) related to products and goods. Germany and France have lower embodied CO_2 emissions, embodied water utilisation and embodied energy consumption per unit GDP (Wang et al., 2020a). Although both of them are the top net import countries and also the top import countries in terms of embodied CWE, their higher efficiencies are beneficial when making plans to reduce emissions, water and energy utilisations from the global perspective.

Italy has lower embodied CO_2 and energy consumption; however, they have higher water consumption per unit of GDP. Fortunately, Italy is the second-largest net embodied water supplier, instead of the importer, and one of the top net demanders of embodied CO_2 and embodied energy. The Netherlands has lower efficiency of embodied water and energy and serves as the largest supplier of embodied water and energy, which is good because it transfers embodied resources to downstream countries with higher efficiency. For net upstream countries like the Netherlands, they should focus on improving the domestic efficiency of resources for reducing CO_2 emissions, water utilisation and energy consumption. The effect of lower coefficients and higher efficiencies in the EU27 than the rest of the world based on our previous study (Wang et al., 2020a) show that the more the EU27 import from the rest of the world, the better for reducing CO_2, water and energy consumption in the EU27 while generating the same amount of economic output.

A quandary for the resource supplier countries and the EU27 is how to mitigate climate change, water scarcity and the energy scarcity, in essence, the only way to achieve this is by improving efficiency. However, this can only be done by increased resources and regulations like those in the EU27. The issue is that this will need money, and may result in an increase in over costs from the supplier country. Traditionally, then pushing manufacturing to a poorer, less developed economy. Then the CWE virtual merry go round would begin again. How can this cycle be broken?

Although the EU showed global leadership in brokering the Paris Agreement and is at the forefront of worldwide contributions to fight climate change, the Paris Agreement diluted the UNFCCC targets agreed in the Kyoto Protocol meaning that each country and or region is responsible for their own house. Although the EU did adopt crucial legislation in 2018 to achieve the Paris Agreement target of reducing GHG emissions by at least 40% by 2030 compared to 1990 (Anonymous, 2020), and the annual targets until 2016, which are the latest data, have been achieved(European Environment Agency, 2018b). For energy utilisation targets of EU from 2021 to 2030, renewable energy shares would achieve at least 32%, and energy efficiency would be improved at least by 32.5%. Those targets will help to mitigate global warming and energy crises. The big question though for the EU27 strongest economies of Germany, France and Italy is, will we import from outside the EU27 block and reduce or will we strick a balance with the other Member States to achieve harmony in the CWE network?

Another challenge, unlike climate and energy targets, is that there are only vague goals for water utilisation. The main objective of EU water policies is to ensure water quality standards across the EU27 (European Commission, 2020). There are relevant actions and policies to mitigate water scarcity, to ensure the sustainability of the water systems and to improve water savings and efficiencies, such as launching the Blueprint to Safeguard Europe's Water Resources (European Parliament, 2020) and updating the "peer-to-peer process support for the improvement of Water Framework Directive and Floods Directive implementation" (P2P, 2020). However, there are large gaps in water; for example, the water aspect is overlooked for the EU27 in terms of Germany, France and Italy with limited water for their industrial activity (Blue-Cloud, 2020). More polluting activities might be transferred to upstream EU countries or elsewhere, as they need massive embodied water to support the industrial development. This needs urgent attention because water is something that Germany, France and Italy cannot really import from further afield than its own neighbours. Water is something that will prove a more valuable commodity into the future, especially in the more industrialised nations.

With COVID-19 pandemics the situation and the relations become even more complicated, and this demands close observation step by step as CO_2 emissions have been embodied in masse in PPE (Personal Protective Equipment) (Klemeš et al., 2020).

4.10 Conclusions

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.

Germany, France and Italy are the largest beneficiaries of embodied CWE, accounting for 46.3% of imported embodied CO_2, 47.7% of imported embodied water and 49.9% of imported embodied energy in the EU27. In contrast, the Netherlands is the largest supplier of these resources. However, considering the higher efficiency of Germany and France, the current structure is beneficial for reducing emissions and the consumption of water and energy from a global perspective. Upstream countries should focus on improving domestic efficiency and industrial upgrading.

MAN, SOC and CON share 82.1% of the total trade relevant t embodied CO_2, 83.7% of the total trade-related to embodied water and 83.5% of the total trade-related to embodied energy. In contrast, the ENE, WAT and AGR contribute a small part at the sector level, in the EU27 CWE chain, indicating the products of these sectors are not directly involved in interregional trade but are mainly involved in domestic trade.

In the EU27, 51% of imported embodied energy, 68% imported embodied water, and 61.3% imported embodied CO_2 are from the rest of the world. Due to the higher efficiency of the EU27 average than of the rest of the world, it contributes to 1.4 Gt less CO_2 emission, 64.5 Gm^3 less water utilisation and 4.9×10^4 PJ less energy consumption, compared to the same economic value outputs generated by the rest of the world. This indicates that the less industrialised economies in the EU27 should look for more support in terms of the CO_2 burden-sharing scheme, emissions and green energy targets and CAP updates considering the EU27 Green Deal if Germany, France and Italy and the remaining EU27 countries wish to transition seriously to the first climate-neutral continent by 2050.

This systematic analysis of the CWE chains in the EU27 is crucial to understand the roles of every country and each sector in the whole system at the local, regional and global levels. This analysis can provide support and direction for future research, education and policymaking in the CWE trilemma.

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 5

EFFICIENT IO-SCN ASSESSMENT TOOL FOR QUANTIFYING WEGN COEFFICIENTS

The work presented in this section is based on the author’s publication in Applied Energy entitled “Water-Energy-Carbon Emissions Nexus Analysis of China: An Environmental Input-Output Model-Based Approach”, as clarified on Page IX (Contributing publication). The author of this thesis is the first author of this publication. The other co-authors who contributed to this publication are the supervisor (J.J. Klemeš), co-supervisors (Y. Wang and P.S. Varbanov) and collaborators.

5.1 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.

5.2 Introduction

It is crucial to analyse the Water-Energy-Carbon Emissions (WEC) nexus, as this is pivotal for decreasing the environmental footprints. Water utilisation, energy consumption, and carbon emissions represent three significant environmental strategy elements in China (Sun et al., 2014). China has one of the fastest-growing economies worldwide. The country is also one of the largest water consumers, energy users, and carbon emitters (Wang et al., 2016). The increasing consumption of natural resources and serious environmental issues have been drawing increasing attention (Varbanov et al., 2018). Problems such as excessive consumption of water and energy, as well as a large volume of carbon emissions, are even more worrisome (Qu et al., 2019). Water resource-saving, high energy efficiency, and low carbon emissions have been significant challenges for the sustainable development of China (Wang et al., 2017). Climate change further aggravates water scarcity, consequently interfering with environmental sustainability (Flörke et al., 2018). These issues result in the degradation of human well-being (Wang et al., 2017), along with degradation of ecosystem health (Wei et al., 2017) and economically sustainable development (Yang et al., 2017). Water, energy and carbon are crucial indicators of environmental sustainability and social development (Wang et al., 2018). Water and energy consumption, as well as carbon emissions, are very much related to the achievement of environmental sustainability (Yang et al., 2018a). It has been shown that water, energy and carbon emissions are among the most significant elements for maintaining environment sustainability (Endo et al., 2017).

It is crucial to explore the WEC nexus in China, with the aim of analysing the total water and energy consumption, total CO_2 emissions, embodied water and energy consumption as well as embodied CO_2 emissions of different sectors.

The total water consumption includes both the direct and indirect water input of a specific sector. The total energy consumption includes both the direct and indirect energy input of a specific sector. Sectoral total CO_2 emissions mean the sectoral direct CO_2 emissions. Embodied water consumption, a measure of the amount of water affected by the creation of a material, is the sum of all the water embodied in generating the product or providing the service itself. Embodied energy consumption is the sum of all the energy embodied in generating the product or providing the service itself. Embodied carbon emissions are the total carbon emitted for producing a product or providing the service. All of these indicators include the entire process from raw material production to final product manufacturing (MakeItFrom.com, 2019), 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 (Acquaye et al., 2011). The sectoral environmental performance has also been analysed, as indicated by the consumption and emissions coefficients as well as the indexes. A consumption coefficient is the ratio of sectoral resources consumption to the sectoral output value. Emission coefficients are the ratios of sectoral emissions to the sectoral output values. The consumption coefficient consists of direct consumption coefficient and indirect consumption coefficient, and all of them are based on embodied consumption. For example, the direct water consumption coefficient of a specific sector indicates the part that transferred from the total water consumption of this sector. The indirect water consumption coefficient means the part that transferred from upstream sectors.

5.3 Literature Review

The WEC nexus has been increasingly emphasised in recent studies. Nair et al. (2014) reviewed the WEC nexus of urban water systems, focusing on multiple or individual subsystems in the urban water system. Their study concluded that water, energy and carbon emissions are profoundly entwined; however, a holistic, systemic, and proper framework is still under development for systematically illustrating the WEC nexus. Yang et al. (2018a) analysed the environmental sustainability of Beijing and Shanghai from the perspective of the WEC nexus, indicating that WEC nexus characteristics of different sectors can provide a new perspective for relieving challenges of environmental pressure. Yang et al. (2019b) explored the critical transmission sectors of the WEC nexus of Shanghai, China, suggesting that crucial transmission sectors should be taken into consideration in urban sustainability strategies. However, this study was confined to a developed city and is not suitable for the whole country scale. DeNooyer et al. (2016) explored the integration of power generation and water resources. In their study, thermoelectric power plants accounted for 90% of the overall electricity generation in the US, which requires a lot of water. Energy constraints can be translated from water constraints. The competition for water in different areas can be increasingly severe due to future population growth and climate change. Lee et al. (2017) reviewed the influence of the Water-Energy nexus of urban water systems from the perspective of environmental impacts and energy intensity. The water consumption in the energy sectors was analysed. Based on the study of Wang et al. (2019), the mismatch between “water-abundant regions with electricity-importing” and “water scarcity regions with electricity-exporting” may result in exacerbating the risk of water scarcity. A limited number of studies have taken carbon emissions into consideration for analysing whole WEC nexus systems. Gu et al. (2016) analysed the WEC nexus of wastewater treatment plants. Wastewater treatment-related climate change should be considered because of the enormous annual discharge of wastewater in China. Li et al. (2019) analysed most recently the driving forces of the Water-Energy nexus in Beijing city, using the Logarithmic Mean Division Index model. The key Water-Energy nexus sectors have been highlighted in terms of water and energy consumption. The main driving factors for the changes in water and energy consumption were explored. However, the water and energy consumption coefficients and indexes were not presented in the study of Li et al. (2019), and the carbon emissions were not involved as well. Zhou et al. (2019) explored the intertwined impacts of the WEC nexus in China, integrating the Water-Energy nexus modelling based on energy technology. This analysis provided a systematic, comprehensive and bottom-up method for analysing the water-energy nexus in China. The water for energy and energy for the water of China were studied, resulting in a better understanding of the water-energy nexus in China. However, the water and energy consumption coefficients and indexes were not presented in their study. Li et al. (2018) analysed the water consumption efficiency of different departments of China, exploring the sectoral water consumption driving forces. Saidi and Hammami (2015) explored the relationship between carbon emissions, energy consumption coefficients, and economic growth in 58 countries worldwide. In addition, some studies that analysed the WEC nexus have focused on different industries. For example, Cai et al. (2015) analysed the impacts of short-lived buildings on water and energy consumption and carbon emissions. Extending the product lifetime or reducing sectors replacement rates can considerably reduce environmental footprints. Chen et al. (2016) proposed a system-based framework for analysing the water-energy nexus in Beijing, China. Meng et al. (2019a) analysed the water-carbon nexus of Beijing China, employing the input-output model. The key routes and nodes of the water-carbon nexus of economic system in Bejing have been explored.

In previous work, the research scopes were limited to an individual sector or a city scale. Most studies focused on the driving forces of water and energy consumption and carbon emissions and did not investigate in detail the consumption coefficients or sectoral environmental performance. Most studies primarily focused on the water used for energy, energy used for water, and energy-related GHG emissions; this cannot reflect the relationships among different sectors. Broader systems are necessary to be taken into consideration for a better understanding of the WEC nexus. The relationships between direct and embodied water consumption, energy consumption and carbon emissions are especially important.

For narrowing these gaps, the WEC nexus in 2012 of China is examined herein for the first time. The objective of this study is to calculate the total water and energy consumption, total CO_2 emissions, embodied water and energy consumption as well as embodied CO_2 emissions of different sectors. A comprehensive analysis of sectoral consumption and emission coefficients, as well as WEC nexus characteristics are provided. These characteristics indicate the sectoral water and energy efficiency as well as carbon emissions intensity from the viewpoint of the final product. The analysis reflects the sectoral water and energy consumption as well as carbon emissions driving forces more precisely. It is significant for an in-depth understanding of the environmental performance of different sectors.

The following sections of this paper are organised as follows: Section 3 illustrates the data source and methods employed in this study. The environmental input-output (EIO) model is explained and employed. Section 4 presents the main results. Discussions and implications are given and analysed in section 5; Section 6 is the conclusion section of this paper.

5.4 Data Source

The 2012 China input-output table was used for economic data (National Bureau of Statistics of China, 2019). These are the latest Chinese input-output data. The other data adopted in this work were also consistent with the year 2012. The data of total sectoral consumption of different types of energy were obtained and processed from the Statistical Yearbook of China - Energy Balance of China (Physical Quantity) (National Bureau of Statistics of China, 2019). All types of energy employed in this study were from fossil fuels. The sectoral total water consumption, which includes both direct and indirect water input, was obtained and processed based on the data of the China Statistical Yearbook of the Environment (National Bureau of Statistics of China, 2019). 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. All data used in this study have been provided as supplementary materials.

5.5 Method - EIO Model

The EIO model (McGregor et al., 2008) was initially developed from the economic input-output model. It is a useful framework for modelling the input and output characteristics of environmental factors. It is also a widely used model for analysing human activities-related environmental stresses, including water consumption, energy utilisation, and CO_2 emissions. (Yang et al., 2018a). In this study, the EIO model is used for calculating the embodied water and energy consumption, embodied CO_2 emissions as well as the consumption and emission coefficients in different sectors of China.

The general framework of the EIO model is shown in Table 10. 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 10 The input-output table of the EIO model, adopted and developed from (Yang et al., 2018a).

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

5.5.1 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:

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

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

where the variables W_j, X_j, X_{ij}, and X_j have been explained in Table 10.

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.

In the Statistical Yearbook of China, direct water use sectors have been merged into three integrated sectors: agriculture, industry, and household. Based on the notes from the Statistical Yearbook of China (2019), water consumed by agriculture includes that for irrigation, replenishment of fishing water, and poultry and livestock utilisation; industrial water consumption includes that for mining and industrial enterprises of manufacturing, cleaning, cooling, and washing, excluding the enterprise reused water; household water consumption refers to that used by the both rural and urban areas. Both public water consumption and household water consumption are involved in the urban part, which includes cargo transportation, construction, commerce, posts, services, restaurants, and telecommunication. The agricultural water consumption data used in this study were directly adopted from the statistical data. The direct water consumption of other sectors is allocated based on the distribution value of the water sector to all other sectors in the input-output table of China. The raw data are shown in Table 11.

Table 11 The water consumption of China in 2012 (m^3)

Region	**Agriculture**	**Industry**	**Household**
China	3.890×10^{11}	1.424×10^{11}	0.729×10^{11}

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:

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

5.5.2 Sectoral Embodied Carbon Emissions

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

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

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.

Regarding C_j, the direct carbon emissions from sector *j*, this depends on the carbon emission factors in China. Both the Intergovernmental Panel on Climate Change (IPCC) (2019) and China's National Development and Reform Commission (NDRC) (NDRC, 2019) have provided default carbon emission factors both globally and for China (Shan et al., 2016). However, according to the study of Liu et al. (Liu et al., 2015), the carbon emission factors of both IPCC and NDRC frequently lead to overvaluation of carbon emissions from China, although that of the NDRC is more accurate than that of the IPCC. In this study, the carbon emission factors from Liu et al. (Liu et al., 2015) are adopted, and those from the NDRC and IPCC are employed as supplementary data.

According to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2019), contributors to carbon emissions can be classified into four sectors: 1) Energy consumption; 2) Agriculture, forestry, and other land use; 3) Use by Industrial processes and products; 4) Waste treatment. In this study, the energy consumption related to carbon emissions were analysed. The CO2 estimation from energy consumption was calculated following the equation:

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

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 CO2 from energy type *k*, which includes the carbon oxidation factor; $\frac{44}{12}$ is the conversion factor between carbon and CO2 (Ouyang and Lin, 2015). For avoiding double counting, this study did not take electricity and heat into consideration in the perspective of CO2 emissions, as they do not emit CO2 during the consumption stage. Their carbon emission factors were set as zero by default.

5.5.3 Sectoral Water and Energy Consumption and Carbon Emission Coefficients

For allocating the embodied consumption coefficients of water and energy as well as the embodied CO2 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 CO2 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:

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

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

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

5.5.4 Sectoral Water and Energy Consumption and Carbon Emission Indexes

According to the results of Yang et al. (2018a), water consumption indexes can reveal the characteristics of sectoral water consumption, for example, water-intensity. Energy consumption indexes can indicate the performance of sectoral energy utilisation. CO_2 emissions indexes can reflect the sectoral carbon emissions characteristics. In this study, 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.

5.5.5 Embodied Values, Total Values, Direct Values, and Indirect Values

Total values in this study include total water consumption, total energy consumption, and total carbon emissions. Total value means both the direct and indirect materials input or the direct emissions of a specific sector from the single specific sector perspective.

Embodied values in this study include embodied water consumption, embodied energy consumption, and embodied carbon emissions. The embodied value is from the viewpoint of life cycle water and energy consumption and carbon emissions of the product or the service involving a specific sector and its upstream sectors.

According to Equations (34), (35), and (36), the embodied water consumption coefficients, embodied energy consumption coefficients, and embodied CO_2 emission coefficients can be obtained. As indicated by Equations (37), (38), and (39), the embodied consumption coefficient is the sum of the direct consumption coefficient and indirect consumption coefficient; the embodied carbon emission coefficient is the sum of direct carbon emission coefficient and the indirect carbon emission coefficient.

5.6 Sectors Classification Adjustment

The original economic input-output table for China has 139 sectors; this is not suitable for the assessment of water and energy consumption or CO_2 emissions. To eliminate this limitation, these 139 sectors were merged into nine aggregated sectors: agriculture (Ag), heavy industry (HI), light industry (LI), mining and quarrying (MQ), energy generation and supply (EGS), water generation and supply (WGS), construction (Co), transportation (Tr), and service industry (SI). The congruent relationship between the nine aggregated sectors and the original sectors is shown in Table 12Table 9 In order to avoid taking up too much space, the 139 original sectors have been preliminarily aggregated.

Table 12 Congruent relationship between aggregated sectors and original sectors.

Aggregated sectors	**Original sectors, after preliminarily aggregated**
Ag	Agriculture, forestry, animal husbandry, fishery.
MQ	Mining and processing of non-ferrous metal ores, non-metal ores, ferrous metal ores, other ores, as well as support activities for mining.
LI	Food processing from agricultural products.
	Manufacturing and processing of foods, liquor, beverages, refined tea, tobacco, wearing apparel, accessories, textile, leather, fur, feather, rattan, palm, straw products, wood, bamboo, timber, furniture, paper, paper products, chemical fibres, medicines, rubber products, raw chemical materials, plastics products, chemical products as well as articles for culture, education, arts and crafts, sport and entertainment activities.
	Processing of petroleum, coking and processing of nuclear fuel.
	Printing and reproduction of recording media.
HI	Manufacturing and processing of non-metallic mineral products, smelting and pressing of ferrous metals, metal products, smelting and pressing of non-ferrous metals, special-purpose

	machinery, general-purpose machinery, electrical machinery and apparatus, computers, communication, other electronic equipment, automobiles, railway, ship, aerospace, other transport equipment, measuring instruments, machinery other manufacture. Repair service of metal products, machinery and equipment. Utilization of waste resources.
EGS	Coal mining and washing, petroleum and natural gas extraction, gas production and supply, electric power and heat power production and supply.
WGS	Water production and supply.
Tr	Transport, post and storage.
Co	Construction
SI	Wholesale and retail trade, information transmission, software, information technology services, accommodation, food, beverage services, renting and leasing, finance, business services, real estate, water conservancy management, environment and public facilities management, technical services, scientific research and developments to households, repair and other services, healthcare and social work activities, education, public management, social security, and social organization, culture, sports, and entertainment.

5.7 Results

This section presents the results and discussion of this study. Sectoral consumption of water and energy, as well as sectoral carbon emissions, are presented. The sectoral WEC nexus characteristics are also illustrated, including the structure of water and energy consumption, CO_2 emissions, sectoral water and energy consumption indexes, and CO_2 emission indexes.

5.7.1 Sectoral Water Consumption

Figure 30 shows the sectoral embodied water consumption and sectoral total water consumption in China. Agriculture led the list of total water consumption at $3{,}883\times10^{8}$ 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). The total water consumption includes both the direct and indirect water input of a specific sector. Agriculture has been the largest consumer of the Earth's available freshwater, accounting for 70% of "blue water" withdrawals worldwide (Water-Global Agriculture, 2019). It has been reported that the agriculture water demand is estimated to increase by a further 19% due to irrigational needs by 2050 (Water-Global Agriculture, 2019). China is one of the most significant agricultural countries, with plenty of water consumption in agriculture, especially for irrigation (Fan et al., 2018). This is also consistent with the world trend. LI, SI and HI are the most significant contributors for the secondary and tertiary industries of China (Zhang et al., 2018), resulting in the consumption of plenty of water.

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. Embodied water consumption, as introduced in section 1, is the sum of all the water embodied in generating the product or providing the service itself. These sectors had plenty of embodied water consumption because they seriously relay on the outputs of upstream sectors to be as inputs.

Comparing the sectoral embodied water consumption and total water consumption, all sectors were distinct. Sectors Ag, MQ, EGS and WGS, had higher total water consumption than embodied water consumption. This demonstrates that part of the total water consumption of these sectors was not transferred to embodied water. It can reflect the sectoral total water consumption efficiency, and that of these sectors is low. For example, the total water consumption amount of agriculture was more than twice of embodied water consumption. It means that more than half of total water consumption was lost via infiltration, evaporation etc., instead of transferred into embodied water of sectoral output. It implicates that the sectors with higher total water consumption should more focus on improving water efficiency within the sectors. In contrast, sectors LI, HI, Co, and Tr had lower total water consumption than embodied water consumption. This means the total water consumption cannot fully support the activities of the sector. The bulk of the embodied water of these sectors came from upstream sectors during economic activities. For example, more than 85% of the embodied water of Co came from other sectors, followed by Tr, HI, and LI with 76%, 71%, and 67%.

The sectoral total water consumption reflects the sectoral initial water input during economic activities; however, this figure cannot represent the sectoral water consumption from the perspective of the product. Sectoral embodied water consumption provides the view of water occupation from the perspective of the sectoral product.

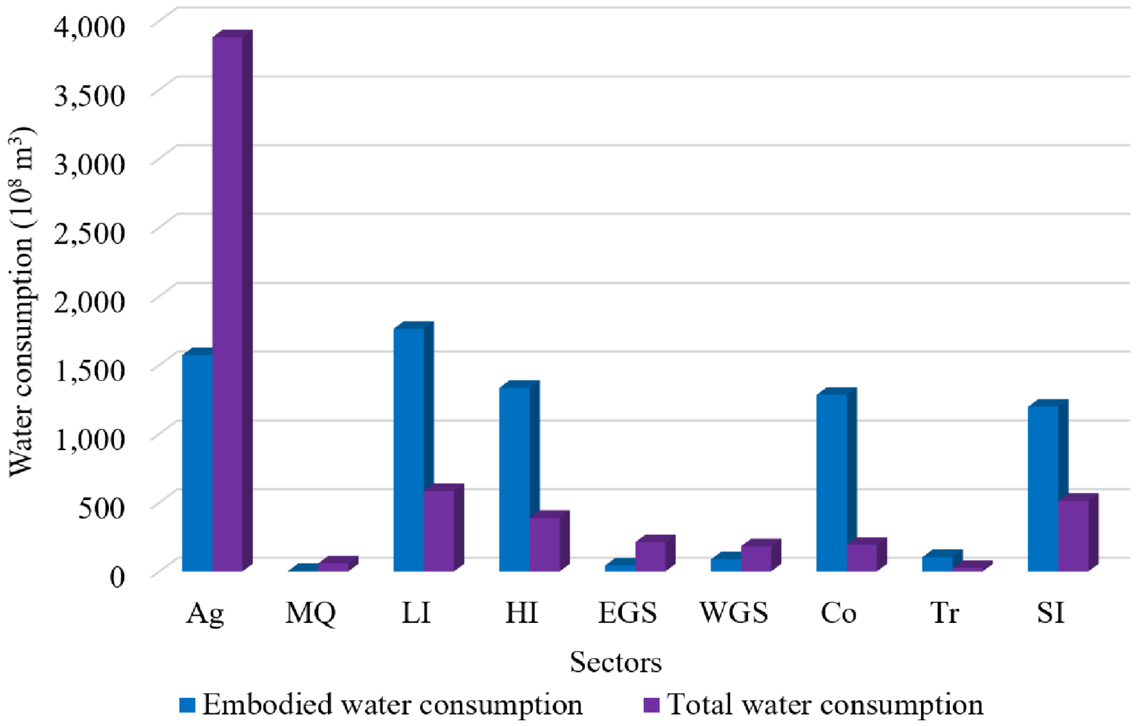


Figure 30 Sectoral water consumption.

5.7.2 Sectoral Energy Consumption

Figure 31 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. According to the China Energy Efficiency Report (2019), sectors HI, LI, SI EGS and Co have been the top energy consumers in China, and also the major contributors to economic activities in China.

Regarding the difference between sectoral embodied energy consumption and total energy consumption, sector EGS was significantly different, with much higher total energy consumption of 495×10^{17} J. This was consistent with the economic activities in China because EGS plays a crucial role in supporting the energy supply for other sectors. In contrast, sectors

Co, HI, SI and LI were the top four sectors in embodied energy consumption, with 374×10^{17} J, 361×10^{17} J, 229×10^{17} J, and 104×10^{17} J. These four sectors also represented the highest embodied energy consumers in China. It means that the inputs of these sectors seriously relay on the outputs of upstream sectors. They should pay attention to improving the efficiency of upstream sectors. The difference between sectoral embodied energy consumption and the total energy consumption is distinctive. It is crucial to take both into consideration when devising energy strategies.

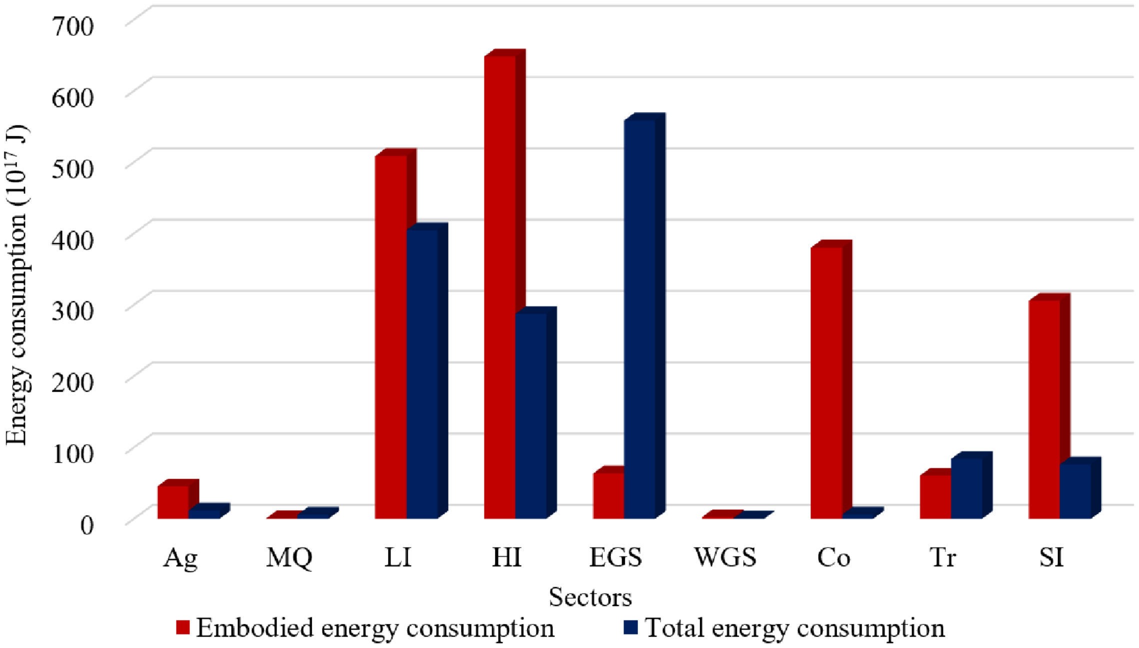


Figure 31 Sectoral energy consumption.

5.7.3 Sectoral CO_2 Emissions

The sectoral total CO_2 emissions and sectoral embodied CO_2 emissions are presented in Figure 32. 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. This is consistent with sectoral energy consumption because fossil fuels still play a major role in the energy supply system 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. This is consistent with the conditions of China because these sectors contribute to most economic activities (China Energy Efficiency Report, 2019). In contrast, sectors Ag, MQ, and WGS contributed less to both sectoral embodied CO_2 emissions and total CO_2 emissions, since they were not major fossil fuel consumers. 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 these sectors to be more environmentally friendly.

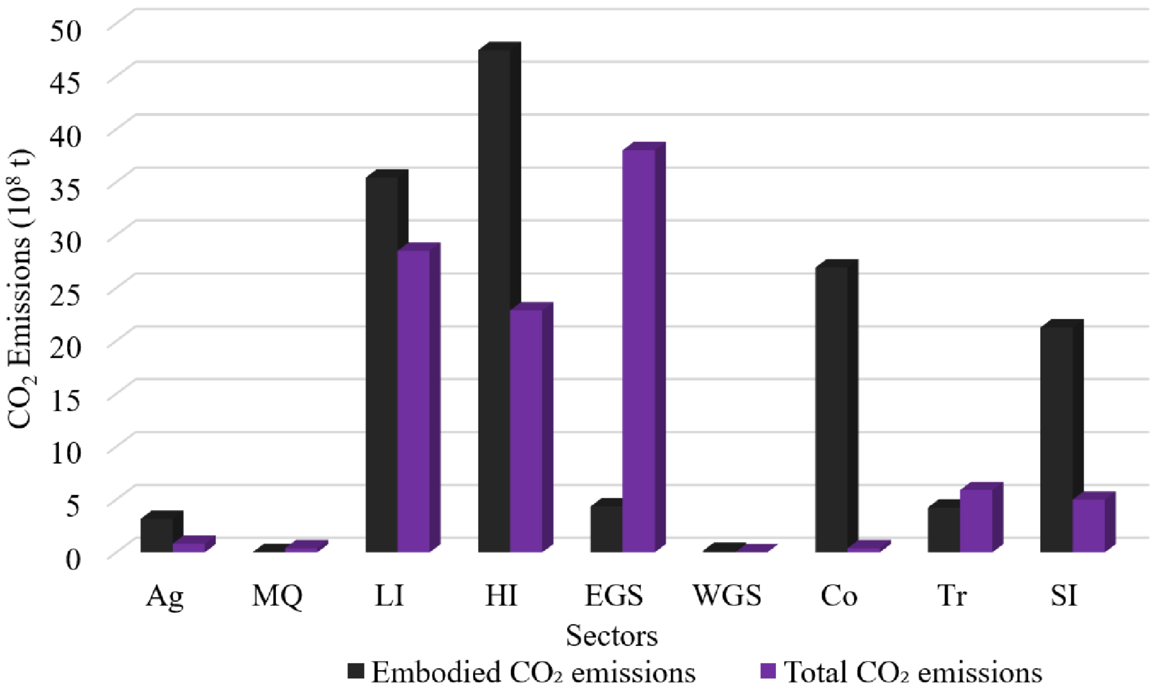


Figure 32 Sectoral CO2 emissions.

5.7.4 Characteristics of the Sectoral WEC Nexus

This section presents the characteristics of the sectoral WEC nexus, including sectoral water and energy consumption coefficients, CO_2 emissions coefficients, sectoral water and energy consumption indexes, as well as CO_2 emission indexes.

4.7.4.1 Sectoral Water and Energy Consumption and Carbon Emission Coefficients

Based on the study of Yang et al. (2018a), the water consumption structure can be defined as the ratio of direct and indirect water consumption coefficients to the corresponding total coefficients. The energy consumption structure and CO_2 emissions structure were allocated in the same way.

Figure 33, Figure 34, and Figure 35 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. Sectors Ag and WGS had different characteristics, with much higher direct water consumption coefficients, indirect energy consumption coefficients, and indirect CO_2 emission coefficients. This indicated that Ag and WGS actually belonged to the downstream sector in terms of energy consumption and CO_2 emissions. This result was consistent with the characteristics of the primary industry. EGS had the opposite characteristic, with lesser direct water consumption coefficient, indirect energy consumption and CO_2 emission coefficients, indicating that EGS belonged to the downstream sector in terms of water consumption.

Focusing on Figure 33, sector Ag led the list of water consumption coefficients at 287 m^3/10 kCNY, followed by SI, LI, and HI. This demonstrated that Ag, SI, LI, and HI were the highest embodied water consumers in terms of water consumption coefficients. Most sectors, including MQ, LI, HI, EGS, Co, Tr, and SI, had higher indirect water consumption coefficients, meaning that these sectors need more water support from upstream sectors. Their environmental performance also significantly relied on other sectors. On the contrary, sectors Ag and WGS had opposite characteristics.

Figure 34 presents the energy consumption coefficients, including those for embodied, direct, and indirect consumption. Sectors HI, LI, and SI were the top three sectors in terms of embodied energy consumption coefficients, followed by EGS, Co, Tr, MQ, and Ag. Sector WSG had the lowest embodied energy consumption coefficients due to the production features of this sector, and playing the role of energy supply for other sectors. Most sectors, including Ag, MQ, LI, HI, WGS, Co, and SI, had much higher indirect energy consumption coefficients, meaning that they were significantly influenced by upstream sectors. EGS and Tr had a better balance between direct and indirect energy consumption coefficients.

Figure 35 shows the CO_2 emission coefficients, including embodied, direct, and indirect consumption. The figures are consistent with the energy consumption coefficients shown in Figure 34. Sectors HI, LI, and SI were the top three sectors of embodied CO_2 emission coefficients, followed by EGS, Co, Tr, MQ, and Ag. The WSG had the lowest embodied CO_2 emission coefficients due to the production features of this sector and playing the role of energy supporter instead of an energy consumer. Most sectors, including Ag, MQ, LI, HI, WGS, Co, and SI, had much higher indirect CO_2 emission coefficients, meaning that their environmental impacts were significantly influenced by the upstream sectors. EGS and Tr had a better balance between direct and indirect CO_2 emission coefficients.

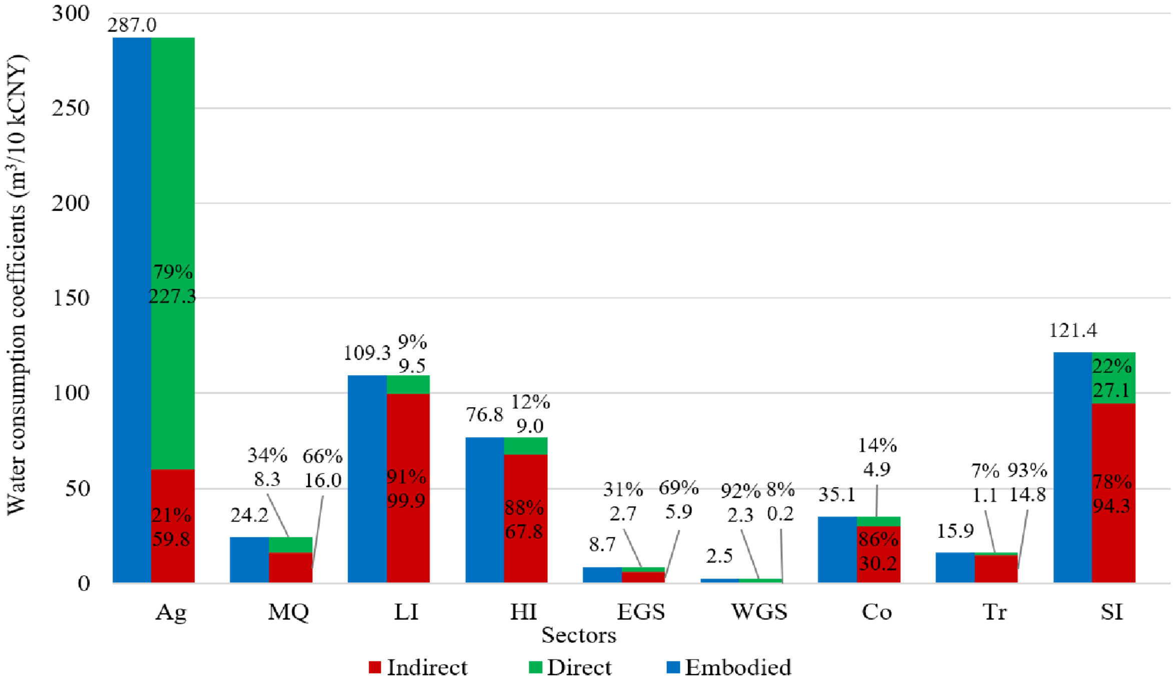


Figure 33 Water consumption coefficients.

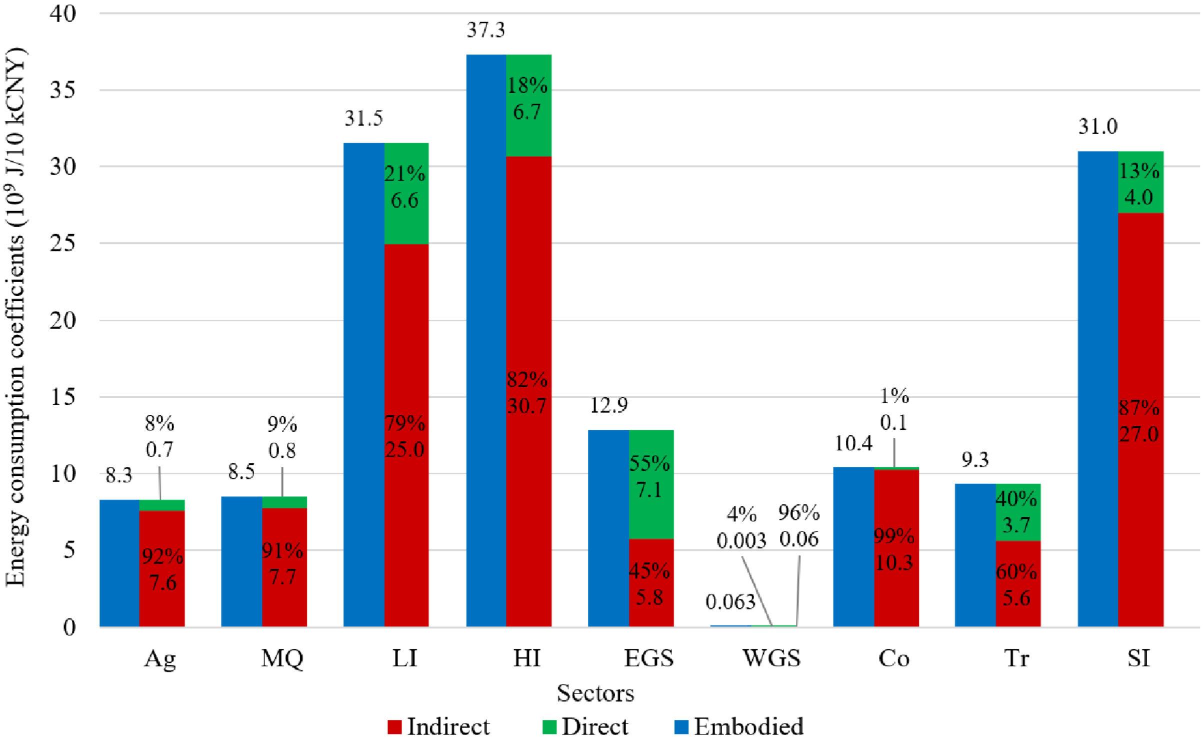


Figure 34 Energy consumption coefficients.

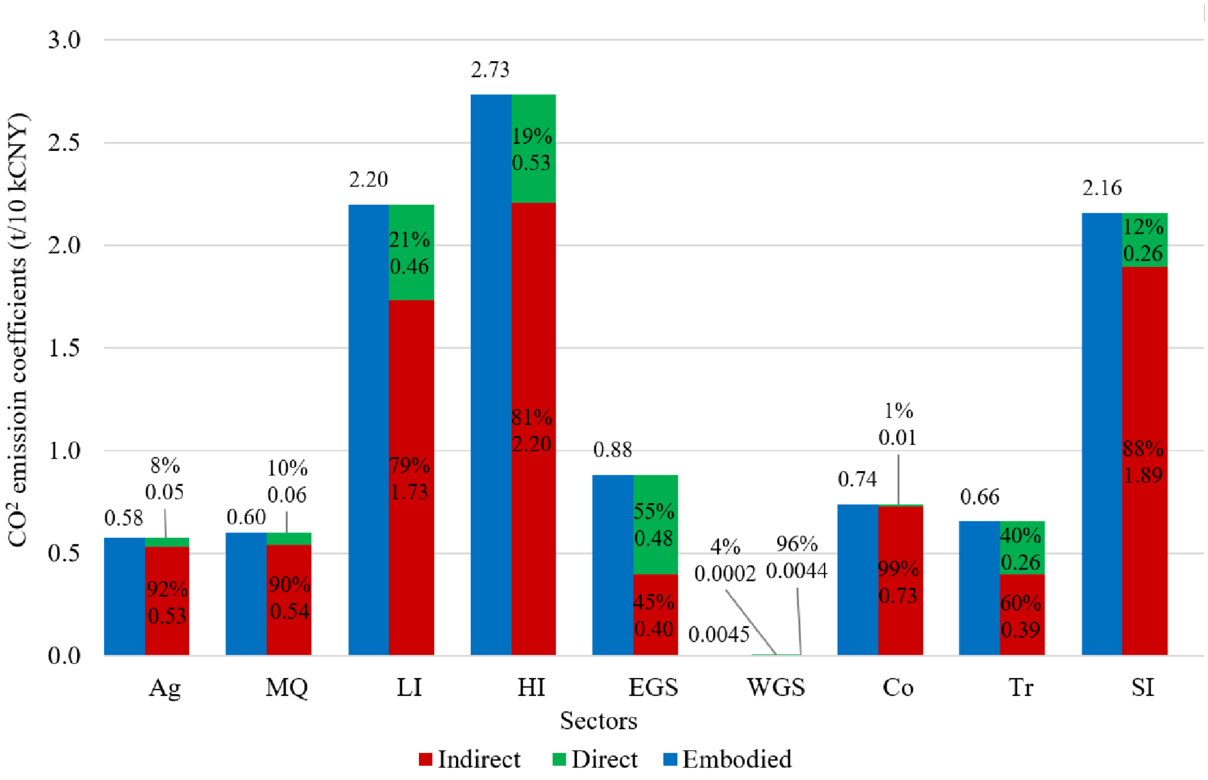


Figure 35 CO_2 emission coefficients.

4.7.4.2 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 13. Table 14 shows the sectoral WEC nexus characteristics in a more direct way.

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. Sector Ag was the most embodied water-intensive sector, especially the direct part. SI, LI, and HI were the three next highest water-intensive sectors. In contrast, other sectors had the opposite characteristics. As the top three embodied energy-tensive sectors, HI, SI, and LI played crucial roles in the economic development of China, accounting for most output of the country's secondary and tertiary industries. The CO_2 emissions of these three sectors were correspondingly high.

Table 13 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

Table 14 Sectoral WEC nexus characteristics.

	Water			Energy			CO_2		
	Embodied	Indirect	Direct	Embodied	Indirect	Direct	Embodied	Indirect	Direct
Ag	●	●	●	○	○	○	○	○	○
MQ	○	○	○	○	○	○	○	○	○
LI	●	●	○	●	●	●	●	●	●
HI	●	●	○	●	●	●	●	●	●
EGS	○	○	○	○	○	●	○	○	●
WGS	○	○	○	○	○	○	○	○	○
Co	○	○	○	○	○	○	○	○	○
Tr	○	○	○	○	○	○	○	○	○
SI	●	●	○	●	●	○	●	●	○

(●: High, the index value is greater than 1, means water-intensive, energy-intensive or carbon-emissions intensive. ○: Low, the index value is smaller than 1)

5.8 Discussion and Implications

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. The primary industry contributed 10.1% of the Gross Domestic Product (GDP) of China, which is much lower than that of the secondary and tertiary industries at 45.3% and 44.6% (Annual GDP Accounting Instructions of China, 2019). Although the overall output of primary industry has been increasing significantly during the past decades, the contribution to the proportion to GDP of the primary industry has been decreasing, from 14.4% to 10.1% from 2001 to 2012 (National Bureau of Statistics of China, 2019). In contrast, the GDP contribution proportion of tertiary industry has been increasing, from 40.5% to 44.6% during the same period. The secondary and tertiary industries have been crucial contributors to the economic development of China, meaning that the overall outputs were similar. According to Table 11, the total water consumption of the primary industry was much higher than those of secondary and tertiary industries. However, the overall output of the primary industry was much lower. This indicates that the water efficiency (in monetary units) of the primary industry was much lower than those of secondary and tertiary industries. Water efficiency (in monetary units) is the ratio of sectoral output to the sectoral water consumption amount. A similar correlation existed between the secondary industry and tertiary industries. There is still room for the primary and secondary industries to improve water utilisation efficiency, especially the primary industry.

The values of total sectoral consumption and embodied consumption suggest that the results of input-based perspective and product-based perspective can be significantly different. Sectoral total consumption defines the sectoral original resources input; however, this cannot reflect the sectoral output embodied resources. Sectoral embodied consumption provides the view of resource occupation from the perspective of the sectoral product, which is better for understanding the sectoral output embodied resources, resources utilisation efficiency, and sectoral resources transfer. Sectoral total consumption and embodied consumption are critical for developing resource strategies.

Direct and indirect consumption coefficients exhibit the source of sectoral embodied resources. Sectors with different situations should apply appropriate strategies for resource conservation, emissions reduction, and environmental protection. 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. In addition, the consumption and emission coefficients provide significant support for creating sustainable development strategies. For decreasing environmental pressure of sectors with higher indirect consumption coefficients such as LI, HI, SI, and Co, the utilisation efficiency of intermediate products should be improved. Sectors such as Ag with high direct consumption coefficients should pay more attention to improving efficiency within sectors. If the sectors are extended to different countries, those with more end items exported than imported should focus on improving the manufacturing efficiency within the country.

There are also some limitations to this study. The consumption coefficients (water and energy) depend on both the physical specific consumption (water and energy) and the output value of each sector. The CO_2 emission coefficients depend on both the physical specific CO_2 emissions and output value of each sector. The consumption and emission coefficients of different year can be different. However, the analysis of specific water consumption, specific energy consumption and specific CO_2 emissions is going to be part of the future extended research. The output value of each sector also depends on the economic market. The analysis of these elements was not involved in this study. The critical transmissions among different sectors need to be explored in more details, driving factors of embodied consumption and emission changes need in-depth analysis. The sensitivity analysis can also be explored. These also are going to be the targets of extended research.

5.9 Conclusions

This study explored the WEC nexus in China by using the EIO model. The embodied water and energy consumption, embodied CO_2 emissions, water and energy consumption coefficients, CO_2 emission coefficients, and the characteristics of the WEC nexus have been analysed. The main conclusions are as follows:

1) Ag dominates the list of sectoral total water consumption, accounting for 64.38% of the total national water consumption. However, only 79% of Ag embodied water directly came from total water consumption, at 1,241 $\times 10^8$ m^3. The water utilisation efficiency of Ag was only 32%. There was a large potential for increased Ag water utilisation efficiency. Improving technologies, especially irrigation methods, is a crucial step. Sectors LI, Ag, HI, Co, and SI, were the top five sectoral embodied water consumers, distinct from the total water consumption. Sectoral embodied water consumption provides a view of water occupation from the perspective of sectoral products.
2) Ag had the highest water consumption coefficient, 287 m^3/10 kCNY, and direct water consumption coefficient, 227 m^3/10 kCNY; these values were much higher than those of all other sectors. LI, SI, and HI were the top three sectors regarding indirect water consumption coefficients.
3) Sectors EGS, LI, and HI were the three most significant contributors to sectoral total energy consumption. However, sectors HI, LI, Co, and SI were the top four sectoral embodied energy consumers. It is crucial to take both into consideration

during energy strategies decision making. CO_2 emissions were in a similar situation due to being closely related to energy consumption.

4) The top three sectors of energy consumption coefficients were HI, LI and SI. Their indirect energy consumption coefficients were also much higher than those of direct consumption. This means that these sectors were more easily influenced by upstream sectors.
5) Ag was the most water-intensive sector. LI, HI, and SI were water-intensive, energy-intensive and CO_2-emissions-intensive sectors, and they also had the top three indirect water consumption coefficients. The water protection and saving, energy conservation, as well as low carbon emissions of upstream sectors can crucially affect these sectors in terms of resource-saving and emissions mitigation.

CHAPTER 6

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.

The specific key insights identified in each of the case studies are summarised as follows.

The IO based assessment tool identifies the EWCC, EECC and ECEC. Indirect and direct values of the above indicators have also been assessed. Embodied consumptions of energy and water per capita and embodied CO_2 emission per capita are explored as well. (i). The EU27 average EWCC (27 m^3/k€,) is much lower than that of the world average value (75 m^3/k€). Bulgaria (112.2 m^3/k€), Estonia (77.2 m^3/k€) and Greece (61.9 m^3/k€) are embodied-water-intensive countries. On the contrary, Sweden, Denmark, Germany and Austria are with the highest water efficiency in the EU27. For the countries with high indirect EWCC, like Bulgaria, Luxembourg, Estonia and Ireland, they should strengthen and deepen the cooperation with upstream countries, focusing on improving the resource utilisation efficiency, reducing environmental footprints from the supply chain perspective. Because they are the downstream countries in terms of embodied water consumption. Because of specialised in water-intensive economic activities, Finland, Ireland, Estonia, Netherland and Italy, have the top amount of embodied water consumption per capita, such as paper industry, power industry; (ii). The average EECC of EU27 (8.8 MJ/€) is much lower than the world average value (13.9 MJ/€), because of its better energy efficiency and relevant technologies. Bulgaria (23.3 MJ/€), Lithuania (16.4 MJ/€), Estonia (15.4 MJ/€) and Greece (14.1 MJ/€) are with the highest coefficient values, performing even worse than the world average level. Cyprus, Austria, Italy and Denmark have the highest energy efficiency in € unit. Bulgaria, Luxembourg, Czech Republic, Estonia and Slovakia are the top five countries in the EU27 in terms of indirect EECC, which means they import a massive amount of embodied energy from upstream countries during international trade; (iii). Regarding ECEC, the EU27 average value (286 t/M€) is much lower than the world average value (637 t/M€) in terms of embodied CO_2 emission. However, there are three countries, Bulgaria (914 t/M€), Estonia (825 t/M€) and Poland (647 t/M€), emit more CO_2 than the average world number. The smallest ECEC are in France (175 t/M€), Sweden (180 t/M€), Austria (212 t/M€), Italy (221 t/M€) and Spain (258 t/M€). Most of Luxembourg ECEC is indirect (89%), followed by Ireland (77%), Belgium (71%), Sweden (69%) and Malta (67%). They transfer a massive amount of embodied CO_2 emission to upstream countries during international trade; (iv). There are several countries, France, Sweden, Lithuania and Portugal, are with higher embodied energy consumption amount, however with lower CO_2 emission value. Because these countries have higher renewable energy consumption share than that of other EU27 members. However, Poland, Slovenia, Estonia and Cyprus are on the opposite, with more CO_2 emissions because of their low renewable energy share in the national energy structures.

The GIS-IO methodology reveals and map WEGN network of EU27. It 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. (i). Germany, France and Italy are the largest beneficiaries of embodied CWE, accounting for 46.3% of imported embodied CO_2, 47.7% of imported embodied water and 49.9% of imported embodied energy in the EU27. In contrast, the Netherlands is the largest supplier of these resources. However, considering the higher efficiency of Germany and France, the current structure is beneficial for reducing emissions and the consumption of water and energy from a global perspective. Upstream countries should focus on improving domestic efficiency and industrial upgrading; (ii). MAN, SOC and CON share 82.1% of the total trade relevant t embodied CO_2, 83.7% of the total trade-related to embodied water and 83.5% of the total trade-related to embodied energy. In contrast, the ENE, WAT and AGR contribute a small part at the sector level, in the EU27 CWE chain, indicating the products of these sectors are not directly involved in interregional trade but are mainly involved in domestic trade; (iii). In the EU27, 51% of imported embodied energy, 68% imported embodied water, and 61.3% imported embodied CO_2 are from the rest of the world. Due to the higher efficiency of the EU27 average than of the rest of the world, it contributes to 1.4 Gt less CO_2 emission, 64.5 Gm^3 less water utilisation and 4.9×10^4 PJ less energy consumption, compared to the same economic value outputs generated by the rest of the world. This indicates that the less industrialised economies in the EU27 should look for more support in terms of the CO_2 burden-sharing scheme, emissions and green energy targets and CAP updates considering the EU27 Green Deal if Germany, France, Italy, and the remaining EU27 countries wish to transition seriously to the first climate-neutral continent by 2050. The systematic analysis of the CWE chains in the EU27 is crucial to understand the roles of every country and each sector in the whole system at the local, regional and global levels. This analysis can provide support and direction for future research, education and policymaking in the CWE trilemma.

IO-SCN assessment tool explored the WEGN nexus in China. The embodied water and energy consumption, embodied CO_2 emissions, water and energy consumption coefficients, CO_2 emission coefficients, and the characteristics of the WEEN have been analysed. (i). Ag dominates the list of sectoral total water consumption, accounting for 64.38% of the total national water consumption. However, only 79% of Ag embodied water directly came from total water consumption, at 1,241 $\times10^8$ m^3. The water utilisation efficiency of Ag was only 32%. There was a large potential for increased Ag water utilisation efficiency. Improving technologies, especially irrigation methods, is a crucial step. Sectors LI, Ag, HI, Co, and SI, were the top five sectoral embodied water consumers, distinct from the total water consumption. Sectoral embodied water consumption provides a view of water occupation from the perspective of sectoral products; (ii). Ag had the highest water consumption coefficient, 287 m^3/10 kCNY, and direct water consumption coefficient, 227 m^3/10 kCNY; these values were much higher than those of all other sectors. LI, SI, and HI were the top three sectors regarding indirect water consumption coefficients; (iii). Sectors EGS, LI, and HI were the three most significant contributors to sectoral total energy consumption. However, sectors HI, LI, Co, and SI were the top four sectoral embodied energy consumers. It is crucial to consider both during energy strategies decision making. CO_2 emissions were in a similar situation due to being closely related to energy consumption; (iv). The top three sectors of energy consumption coefficients were HI, LI and SI. Their indirect energy consumption coefficients were also much higher than those of direct consumption. This means that these sectors were more easily influenced by upstream sectors; (v). Ag was the most water-intensive sector. LI, HI, and SI were water-intensive, energy-intensive and CO_2-emissions-intensive sectors, and they also had the top three indirect water consumption coefficients. The water protection and saving, energy conservation, as well as low carbon emissions of upstream sectors can crucially affect these sectors in terms of resource-saving and emissions mitigation.

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APPENDIX S1 Publications List

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., 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. DOI: 10.1016/j.rser.2019.01.049. **[IF = 12.110] [CiteScore = 25.5]**

3 **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] [CiteScore = 16.4]**

4 **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] [CiteScore = 10.9]**

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7 **Wang, X.C.**, Klemeš, J.J., Fan, W., Dong, X., 2019. An Overview of Air-Pollution Terrain Nexus. Chemical Engineering Transactions, 72, 31-36. **[CiteScore = 1.3]**

8 **Wang, X.C.**, Klemeš, 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, pp.1057-1062. **[CiteScore = 1.3]**

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10 **Wang, X.C.**, Wei, H., Lu, N., Xu, Z., Fan, W., Dong, X., Liu, Y., Zhao, Y., 2017. Study on the Balance between Ecosystem Services Supply/Consumption and Surplus, a Case Study of Miyun County, Beijing. Journal of Beijing Normal University (Natural Science), 53(3), 366-371. (In Chinese)

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circulation. Journal of Cleaner Production, 258, p.120642. **[IF = 6.395] [CiteScore = 10.8]**

12 Long, X., Yu, H., Sun, M., **Wang, X.C.,** Klemeš, J.J., Xie, W., Wang, C., Li, W., Wang, Y., 2020. Sustainability evaluation based on the Three-dimensional Ecological Footprint and Human Development Index: A case study on the four island regions in China. Journal of Environmental Management, 265, p.110509. **[IF = 4.865] [CiteScore = 7.6]**

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14 Fan, W., Chen, N., Li, X., Wei, H., **Wang, X.**, 2020. Empirical Research on the Process of Land Resource-Asset-Capitalization - A Case Study of Yanba, Jiangjin District, Chongqing. Sustainability, 12(3), p.1236. **[IF = 2.576] [CiteScore = 3.2]**

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19 Xu, Z., Wei, H., Fan, W., **Wang, X.**, Huang, B., Lu, N., Ren, J., Dong, X., 2018. Energy modeling simulation of changes in ecosystem services before and after the implementation of a Grain-for-Green program on the Loess Plateau—A case study of the Zhifanggou valley in Ansai County, Shaanxi Province, China. Ecosystem Services, 31, 32-43. **[IF = 5.572] [CiteScore = 9.2]**

20 Fan, W., Gao, Z., Chen, N., Wei, H., Xu, Z., Lu, N., **Wang, X.**, Zhang, P., Ren, J., Ulgiati, S., Dong, X., 2018. It is worth pondering whether a carbon tax is suitable for china's agricultural-related sectors. Energies, 11(9), 2296. **[IF = 2.707] [CiteScore = 3.3]**

21 Fan, W., Zhang, P., Xu, Z., Wei, H., Lu, N., **Wang, X.**, Weng, B., Dong, X., 2018. Life Cycle Environmental Impact Assessment of Circular Agriculture: A Case Study in Fuqing, China. Sustainability, 10(6), p.1810. **[IF = 2.592] [CiteScore = 2.8]**

22 Fan, W., Dong, X., Wei, H., Weng, B., Liang, L., Xu, Z., **Wang**, **X.**, Wu, F., Chen, Z., Jin, Y., Song, C., 2018. Is it true that the longer the extended industrial chain, the better the circular agriculture? A case study of circular agriculture industry company in Fuqing, Fujian. Journal of Cleaner Production, 189, 718-728. **[IF = 6.395] [CiteScore = 10.9]**

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25 Wei, H., Fan, W., Ding, Z., Weng, B., Xing, K., **Wang, X.**, Lu, N., Ulgiati, S., Dong, X., 2017. Ecosystem services and ecological restoration in the Northern Shaanxi Loess Plateau, China, in relation to climate fluctuation and investments in natural capital. Sustainability, 9(2), 199. **[IF = 2.592] [CiteScore = 2.8]**

26 Dong, X., Dai, G., Ulgiati, S., Na, R., Zhang, X., Kang, M., **Wang, X.**, 2015. On the relationship between economic development, environmental integrity and well-being: the point of view of herdsmen in northern China grassland. PloS One, 10(9), p.e0134786. **[IF = 2.776] [CiteScore = 5.6]**

APPENDIX S2 Invited Lectures

1 **Wang, X.C.**, Wei, H., Lu, N., Dong, X., Study on the Balance between Ecosystem Services Supply/Consumption and Surplus, a Case Study of Miyun County, Beijing. The 9th Biennial Emergy Research Conference, Florida University, Florida, USA. 08.01.2016. **(Best Poster Award)**

2 **Wang, X.C.**, Fan, Y.V., Varbanov, P.S., Klemeš, J.J., Developments of Treatment for Municipal Solid Waste Management. The 6th International Conference on Computational Heat, Mass and Momentum Transfer, Cracow, Poland. 23.05.2018.

3 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Recent Developments of Water Footprints Methodology. The 21st Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction, Prague, Czech Republic. 28.08.2018

4 **Wang, X.C.**, Varbanov, P.S., Klemeš, J.J., Wang, Y., Multi-Criteria Optimisation of Municipal Solid Waste Management: GIS and P-Graph Approach. The 13th Conference on Sustainable Development of Energy, Water and Environment Systems, Palermo, Italy. 02.10.2018.

5 **Wang, X.C.**, Klemeš, J.J., Dong, X., Fan, W., An Overview of Air-Pollution Terrain Nexus. The 4th International Conference on Low Carbon Asia & Beyond, Johor Bahru, Malaysia. 25.10.2018.

6 **Wang, X.C.**, Klemeš, J.J., Dong, X., Wang, Y., Recent Development of Air-Pollution Terrain Nexus. 1st International Conference on Sustainable and Efficient Use of Energy, Water and Natural Resources, Tomsk, Russia. 15.11.2018.

7 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Water-Energy-Carbon Nexus: Take China as the Case. The 14th SDEWES Conference, Dubrovnik, Croatia. 02.10.2019.

8 Klemeš, J.J., **Wang, X.C.**, Water, Energy and Environment Nexus in Circular Economy. The 1st International Conference on Water, Energy and Environment Nexus. Istanbul, Turkey. 05.09.2019. **(Plenary Lecture)**

9 Klemeš, J.J., Jia, X., **Wang X.C.**, Varbanov, P.S., Wan Alwi, S.R, Overview and Perspectives on Water Footprint (Availability, Scarcity, Virtual and combined with Energy and GHG), 2nd International Scientific Conference on «Sustainable and Efficient Use of Energy, Water and Natural Resources», SEWAN, Irkutsk, Siberia, Russian Federation. 12.09.2019. **(Plenary Lecture)**

10 **Wang, X.C.**, Klemeš, J.J., Sadenova, M., Varbanov, P.S., Zhakupova, G., Energy-Related GHG Emissions, Taking Kazakhstan as A Case. The 22nd PRES Conference, Crete, Greece. 22.10.2019.

11 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Identifying the Water-Energy-Carbon Emissions Nexus, an Input-Output Model-Based Approach. The 1st CPS conference, Hong Kong, China. 31.10.2019. **(Best Presentation Award)**

12 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., Water-Energy-GHG Nexus, Considering the Impact of Terrain. The AGU'19 Conference, San Francisco, USA. 12.12.2019.

13 **Wang, X.C.**, Klemeš, J.J., Varbanov, P.S., Mapping Water-Energy-Carbon Nexus of the EU27. The 4th SEE SDEWES conference (virtual), Bosnia and Herzegovina, 30.06.2020.

14 **Wang, X.C.**, Klemeš, J.J., Wang, Y., Varbanov, P.S., Water-Energy-Carbon Nexus Analysis of the EU27 and China. The 23rd PRES conference (virtual), Xi'an, China. 17.08.2020.

15 **Wang, X.C.**, Klemeš, J.J., Varbanova, P.S., Critical transmissions of Water-Energy-Carbon Nexus in China. The 6th ICLCA conference (virtual), Shanghai, China. 02.09.2020.

16 Klemeš, J.J., **Wang, X.C.**, Fan, Y.V., Integrated Footprints Accounting for Sustainability Underlining Emissions. Plenary Lecture, the 6th ICLCA conference (virtual), Shanghai, China. 02.09.2020. **(Plenary lecture)**