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Water-Energy-Carbon Nexus Analysis of the EU27 and China

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EU27 and China have been two of the largest economies as well as water consumers, energy utilisers and carbon emitters. However, the linkages and key flows of Water-Energy-Carbon Nexus (WECN) in the EU27 and China remain not entirely clear. It is still under exploration, whether the associated benefits are mutual or not. This study aims at assessing the WECN of different countries in the EU27 and different sectors in China. The Environmental Extended Input-Output (EEIO) model is used to analyse the embodied water consumption, energy consumption and CO_2 emissions. The total water consumption, energy consumption and CO_2 emissions of the specific country in the EU27 and specific sector in China are analysed as well. The results identify the characteristics of water and energy consumption, and carbon emission of the EU27 and China. This study provided an approach to identify the synergies in terms of Water-Energy-Carbon Nexus. It provides decision-making support to apply to other regions for better cope with the possible consequences of climate change.

1. Introduction

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 carbon emissions. An in-depth understanding of the Water-Energy-Carbon Nexus (WECN) 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 WECN, including the concepts, research focuses, mechanisms, and methodologies. Because of its extremely significant for regional sustainability and the environment healthy, the WECN has been arousing increasing attention worldwide. The WECN 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).

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 WECN in the future. It is crucial for decreasing environmental footprints. The WECN 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 WECN of the ecosystem by integrating the hydrological model and a biogeochemical model, which provided an effective model for the simulation of water-carbon cycles. Nair et al. (2014) reviewed the WECN 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 carbon are profoundly entwined; however, there is still not a holistic, systemic and proper framework to capture the WECN in the urban water system (Wang et al., 2020a). In some cases, the energy use of water end-use is comparatively overlooked. Yang et al. (2018) analysed the environmental sustainability of Beijing and Shanghai from the perspective of WECN. The WECN characteristics of different sectors can provide a new perspective for relieving challenges of environmental pressure.

EU and China have been two of the largest economies as well as water consumers, energy consumers and carbon emitters (Varbanov et al., 2018). However, the linkages and key flows of WECN in the EU27 and China

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remain not entirely clear. It is still under exploration, whether the associated benefits are mutual or not. Most previous studies were consumption-based assessment, focusing on the individual sectors and fully following the vital intersectoral or interregional supply-chain connections. The optimised strategies for balancing the WECN in the EU27 and China should more intensively be considered. This study aims at analysing the WECN of different countries in the EU27 and different sectors in China.

2. Data and Method

2.1 Method

Environmental Extended Input-Output (EEIO) model is an approach for analysing the structure of input and output between different sectors or regions from the supply chain perspective, exploring the environmental factors. It can be widely used for assessing the human activities-related environmental stress, including water consumption, energy utilisation, CO_2 emissions (Wang et al., 2020b). The EEIO model has been used in this study, for analysing the embodied water consumption, embodied energy consumption, embodied CO_2 emissions in different regions of the EU27, as well as different sectors of China. Table 1 shows the framework of EEIO.

Table 1: The input-output table of the EEIO model.

		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		
Energy input		E_j		
Water input		W_j		
CO_2 emissions		C_j		

Where Z_{ij} is the flow from sector/region *i* to sector/region *j*, F_i means the final demands of sector/region *i*, V_j represents the value added for sector/region *j*; X_i is the total output from sector/region *i*, X_j is the total input of sector/region *j*, E_{kj} is the amount of energy (type k) that directly consumed by sector/region *j*, W_j means the sector/region (*j*) direct water consumption. C_j represents direct carbon emissions of sector/region j. z_{ij}, F_i, X_i, X_j and V_j are with the monetary units. E_{kj} , W_j, and C_j are with physical units.
The direct water consumption coefficient c_j^w and the direct consumption coefficients c_{ij} are given as follow:

$$c_j^w = W_j/X_j\,, (j = 1, 2, 3, \dots, n) \quad (1)$$

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

The embodied water consumption W^{em} is calculated as follows. Embodied water consumption is the sum of all water embodied in creating the product or providing the services. It is a tool for measuring the amount of water which is affected by the manufacturing of products or services (Wang et al., 2020b). It includes the whole process of production, from the raw material to the final output. It includes several or even dozens of different countries or sectors which are involved in the entire process.

$$W^{em} = C^w (I - C)^{-1} F^{diag} \quad (3)$$

where C^w means the matrix of direct water consumption coefficient with elements c_j^w, *I* is the identity matrix, *C* is the matrix of the direct consumption coefficients, F^{diag} is the diagonal matrix transformed from the column vector of total output, F_i.
Then embodied energy consumption and embodied CO_2 emissions are allocated in the same way:

$$c_j^e = E_j/X_j\,, (j = 1, 2, 3, \dots, n) \quad (4)$$

$$E^{em} = C^{e}(I - C)^{-1} F^{diag} \quad (5)$$

$$c_j^c = C_j / X_j (j = 1, 2, 3, \ldots, \mathrm{n}) \quad (6)$$

$$C^{em} = C^{c}(I - C)^{-1} F^{diag} \quad (7)$$

where c_{kj}^e is the direct energy consumption ecoefficiency, E^{em} means the matrix of embodied energy with elements E_{kj}^{em}, C^e is the matrix of direct energy consumption coefficient with elements c_{kj}^e, c_j^c is the direct CO_2 emissions coefficients, C^{em} are the embodied CO_2 emissions, C^c is the row vector of direct CO_2 emissions with elements c_j^c.

Embodied energy consumption indicates the sum of all consumed energy that embodied in manufacturing the product or providing the service itself. Embodied carbon emissions mean the sum of CO_2 emitted during manufacturing products or providing services. 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 countries or sectors (Ifaei and Yoo, 2019). The indicators can represent the significance of the life cycle water and energy requirements as well as carbon emissions estimates, which are from the supply chain perspective.

2.2 Data

The main data of this study include the input-output table of the EU27 in 2014 (Amores et al., 2019) and the input-output table of China in 2012 (National Bureau of Statistics of China, 2019), which are the latest data can be obtained. The water consumption data of the EU27 were obtained and proceeded from the water balance table database (Eurostat, 2020). High-quality statistics of European level are provided by Eurostat. The data of CO_2 emissions and energy consumption of different countries are obtained and proceed from the WIOD database (Amores et al., 2019). The data on water consumption and energy consumption of China is from the Energy Balance table (China Energy Statistical Yearbook, 2019). The average caloric value and carbon emission factors were obtained from China's National Development and Reform Commission (NDRC) documents (2019) and the IPCC guidelines (2019).

3. Results

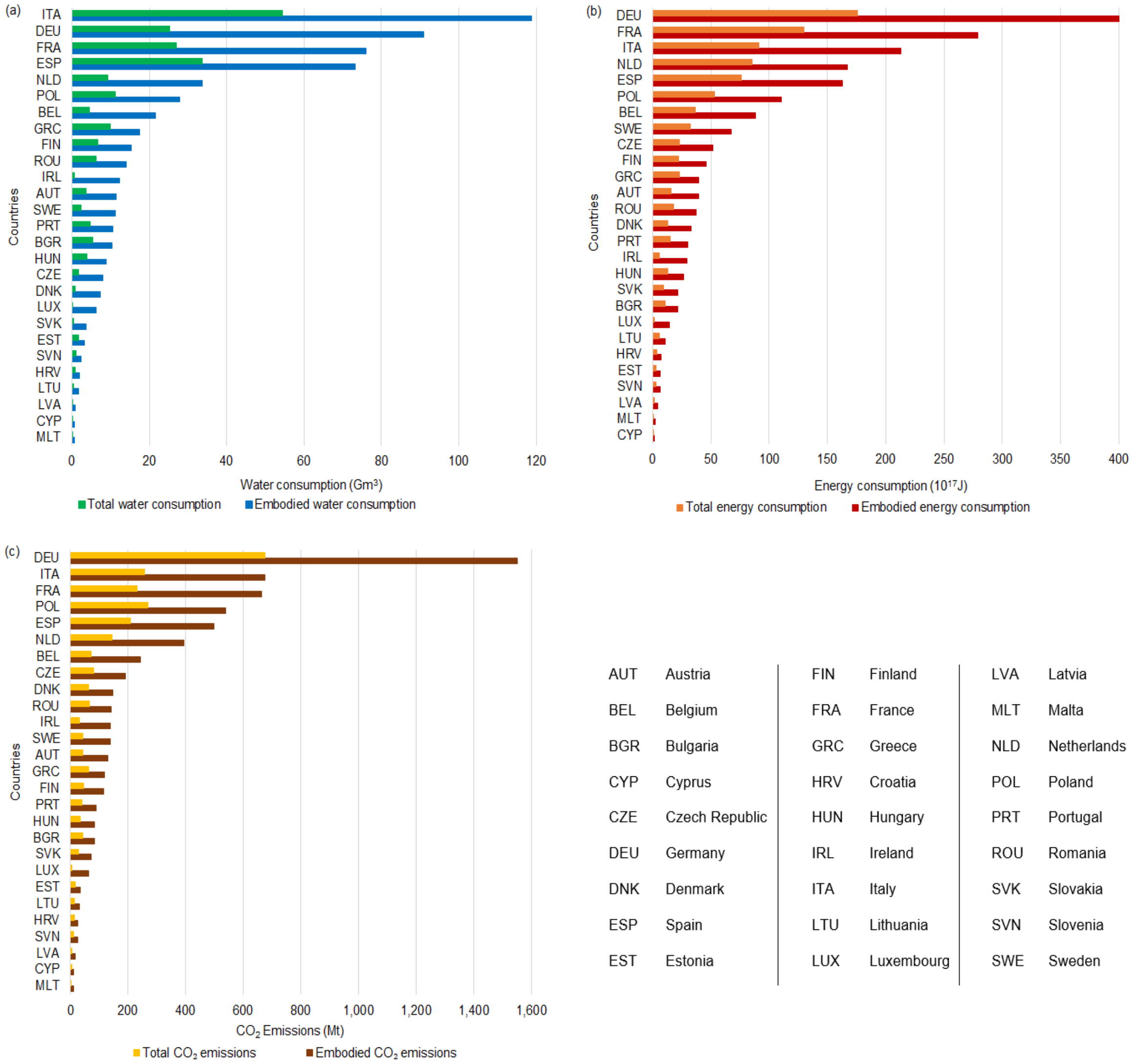
This section shows the WECN of the EU27 and different sectors in China. It includes the embodied water consumption, embodied energy consumption and embodied CO_2 emissions of the above objectives.

3.1 WECN of the EU27

Figure 2 shows the WECN of the EU27. Each of them, water consumption (a), energy consumption (b) and CO_2 emissions (c), includes two parts, embodied amount and total amount. The embodied amount has been explained in section 2. The total water/energy consumption means the sum of the direct and indirect water/energy input within a specific region or sector. The total CO_2 emissions are the total amount of direct and indirect CO_2 emissions within a specific country or sector.

Figure 2 (a) shows the water consumption of different countries in the EU27. The embodied water consumptions of all these countries are more than their total water consumption. It means all of these countries import a huge amount of embodied water during international trade. These countries place downstream from the worldwide supply chain perspective. Italy has the most embodied water consumption, 119 Gm^3, followed by Germany, France and Spain. These countries also have the biggest difference between embodied water consumptions and total water consumption. It means that these countries extremely rely on import for supporting the sustainability of national society and economy. Figure 2 (b) shows the embodied energy consumption of different countries in the EU27. It has a similar characteristic that the embodied energy consumptions of these countries are more than their total energy consumption. Germany has the most embodied energy consumption, 4×10^{19} J, followed by France, Italy and Netherlands. These countries have very highly developed industries and renewable energy utilisation, for example, 19.5 % of the electricity in France is from renewable energy (France Annual Electricity Reports, 2015). Figure 2 (c) shows the embodied and total CO_2 emissions of different countries in the EU27. The embodied CO_2 emissions amount of each country is larger than the total amount as well. It means these countries transfer big environment pressure to the upstream countries during international trade. These countries benefit from import in terms of environmental footprints.

From Figure 2, all EU27 countries place downstream in terms of water consumption, energy consumption and CO_2 emissions, from the worldwide supply chain perspective. The EU27 benefit from the import from the whole world and at the same time, transfer CO_2 emissions to upstream countries, significantly decreasing their environmental pressure.



AUT	Austria	FIN	Finland	LVA	Latvia
BEL	Belgium	FRA	France	MLT	Malta
BGR	Bulgaria	GRC	Greece	NLD	Netherlands
CYP	Cyprus	HRV	Croatia	POL	Poland
CZE	Czech Republic	HUN	Hungary	PRT	Portugal
DEU	Germany	IRL	Ireland	ROU	Romania
DNK	Denmark	ITA	Italy	SVK	Slovakia
ESP	Spain	LTU	Lithuania	SVN	Slovenia
EST	Estonia	LUX	Luxembourg	SWE	Sweden

Figure 1: WECN of the EU27

3.2 WECN of China

Figure 3 shows the WECN of different sectors in China. Nine sectors have been involved in this study. Figure 3 (a) illustrates the water consumption of different sectors, including embodied water consumptions and total water consumption. It is ordered by the amount of embodied amount. Light industry leads the list of embodied water consumption, 176 Gm^3, followed by agriculture, heavy industry, construction and service industry. China is the top country with the output of these sectors. They are the main embodied water consumers, accounting for the overwhelming bulk of embodied water consumption, which was 96.83 % in total. These sectors significantly rely on the upstream sectors to be as the water source (Lu et al., 2018). Agriculture has much more total water consumption than embodied water consumption. Most of the direct water consumption is not transferred to embodied water. Figure 3 (b) shows the energy consumption of different sectors in China. Heavy industry and light industry are the top sectors of embodied energy consumption at 6.5×10^{19} J and 5.1×10^{19} J, followed by construction and service industry. These sectors contribute the most GDP of China and consume a huge amount of energy (National Bureau of Statistics of China, 2019). These sectors also have more embodied energy consumption than total energy consumption, which means the environmental performance of them highly depend on the upstream sectors from the supply chain perspective. Figure 3 (c) shows the CO_2 emissions, including the total amount and embodied amount. It shows a similar characteristic of energy consumption. Heavy industry (4.7 × 10^9 t), light industry (3.5 × 10^9 t), construction (2.7 × 10^9 t) and service industry (2.1 × 10^9 t) are the top four sectors of embodied CO_2 emissions. They also have higher embodied amount than the total amount. It means they transfer a huge amount of CO_2 emissions to the upstream sectors. On the contrary, the sector of energy generation and supply has much higher total CO_2 emissions than the embodied number. It is consistent with the profile of this sector, which play the key role of energy supplier for other sectors.

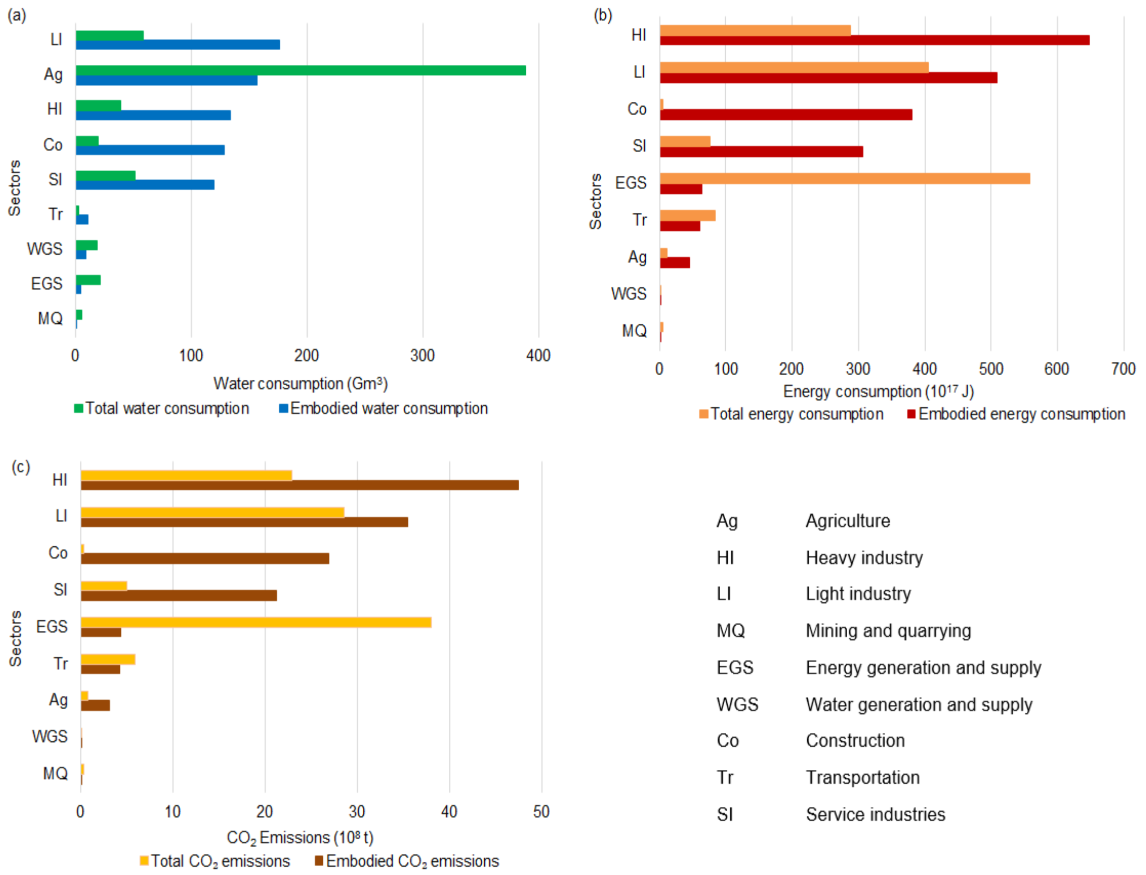


Figure 2: WECN of China

4. Conclusions

This study analysed the WECN of different countries in the EU27 and different sectors in China. The Environmental Extended Input-Output model has been employed to assess water consumption, energy consumption and CO_2 emissions. All indicators above include two more specific terms, which are the total amount and embodied amount. The main conclusions are as follows:

(i) The embodied amount of WECN of all countries in the EU27 is more than that of the total amount. All EU27 countries highlight depend on import goods and services from the global chain. They import a huge amount of embodied water and embodied energy, as well as transfer a huge amount of embodied CO_2 emissions to the upstream sectors during the international trade. EU27 members locate downstream from the worldwide supply chain perspective. Italy is with the most embodied water consumption, 119 Gm^3. Germany, France and Spain also consumed a mass of embodied water during the international trade.

(ii) Regarding China WECN, the heavy industry, light industry, construction and service industry are with high embodied water consumption, embodied energy consumption and CO_2 emissions. They are embodied- water-, energy-, CO_2- intensive sectors in China. Especially heavy industry and light industry, which are the top two sectors with the most embodied energy consumption at 6.5 × 10^{19} J and 5.1 × 10^{19} J, the most embodied CO_2 emissions at 4.7 × 10^9 t and 3.5 × 10^9 t, as well as the most embodied water consumption at 133 Gm^3 and 176 Gm^3. These sectors significantly contribute to the economy of China.

In future research, the more specific sectors classification and the transmission flows of water, energy and carbon emissions among them still need more in-depth exploration.

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References

Amores A.F., Arto I., Corsatea T.D., Lindner S., Neuwahl F., Román M.V., Rueda-Cantuche J.M., Velázquez Afonso A., European Commission, Joint Research Centre, 2019, World input-output database environmental accounts: update 2000-2016, <publications.jrc.ec.europa.eu/repository/bitstream/JRC116234/jrc116234_wiod_based_energy_and_co2_accounts_final_pubsy.pdf>, accessed 07.07.2020.

Fan W., Zhang P., Xu Z., Wei H., Lu N., Wang X., Weng B., Chen Z., Wu F., Dong X., 2018a, Life cycle environmental impact assessment of circular agriculture: a case study in Fuqing, China, Sustainability, 10(6), p.1810.

Fan W., Dong X., Wei H., Weng B., Liang L., Xu Z., Wang X., Wu F., Chen Z., Jin Y., Song C., 2018b, 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.

Ifaei P., Yoo C., 2019, The compatibility of controlled power plants with self-sustainable models using a hybrid input/output and water-energy-carbon nexus analysis for climate change adaptation, Journal of Cleaner Production, 208, 753–777.

IPCC - Task Force on National Greenhouse Gas Inventories, 2019, <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>, accessed 18.03.2020.

Li H., Zhao Y., Lin J., 2020, A review of the energy–carbon–water nexus: Concepts, research focuses, mechanisms, and methodologies, Wiley Interdisciplinary Reviews: Energy and Environment, 9(1), p.e358.

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.

Klemeš J.J., Varbanov P.S., Walmsley T.G. and Jia X., 2018, New directions in the implementation of Pinch Methodology (PM), Renewable and Sustainable Energy Reviews, 98, 439-468.

Nair S., George B., Malano H.M., Arora M., Nawarathna B., 2014, Water–energy–greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods, Resources, Conservation and Recycling 89, 1–10.

National Bureau of Statistics of China, 2019, <www.stats.gov.cn/english/> accessed 17.03.2020.

National Development and Reform Commission (NDRC) People’s Republic of China, 2019, <en.ndrc.gov.cn/> accessed 10.03.2020.

RTE France, 2015, Annual Electricity Reports. <https://www.rte-france.com/en/article/annual-electricity-reports>, accessed 01.03.2020.

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.

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.

Wang X.-C., Klemeš J.J., Long X., Zhang P., Varbanov P.S., Fan W., Dong X., Wang Y., 2020a, Measuring the environmental performance of the EU27 from the Water-Energy-Carbon nexus perspective, Journal of Cleaner Production, 121832.

Wang X.-C., Klemeš J.J., Wang Y., Dong X., Wei H., Xu Z., Varbanov P.S., 2020b, Water-Energy-Carbon Emissions nexus analysis of China: An environmental input-output model-based approach, Applied Energy 261, 114431.

Yang X., Wang Y., Sun M., Wang R., Zheng P., 2018, Exploring the environmental pressures in urban sectors: An energy-water-carbon nexus perspective, Applied Energy 228, 2298–2307.

Zeng S., Xia J., Chen X., Zou L., Du H., She D., 2020, Integrated land-surface hydrological and biogeochemical processes in simulating water, energy and carbon fluxes over two different ecosystems, Journal of Hydrology 582, 124390.