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Research Title	Assessing the energy-water-CO2 emission in food nexus system by I-O analysis
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Research Overview	The sustainability of Tokyo relies on a big food supply chain to meet the huge demands of a population of 14 million people. The production of food consumes enormous amounts of water and energy along with producing the accompanying vast amount of CO2 emissions. Excessive emissions create serious downward pressure on reaching the goal of being a carbon-neutral society by 2050. This paper aims to develop a framework to visualize direct and indirect resource consumption and emissions in the food system, from food supply to food demand, and identify the key nodes and paths to achieve reduction targets using input-output tables at different scales.

	The result shows that the services sector has the greatest food-energy-water consumption and carbon emissions in Tokyo. So there is great potential to conserve resources and reduce emissions from this sector. The manufacturing sector is the largest great embodied energy, water, and CO2 supplier in the 11 sectors, and services are the biggest beneficiary. In the food system, more than 80% of consumption and emissions come from food demand, especially in the catering service. Energy-related policies have had a positive impact on energy conservation and emission reduction. One important conclusion is that Tokyo citizens should buy local, seasonal produce and eat a healthy balance of plant-based foods to relieve environmental stresses caused by food manufacturing.

🏆 *reviewed paper*

Using Environmental Input-Output Analysis to Assess Energy, Water, and CO_2 Emissions in Tokyo's Food System

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1 ABSTRACT

The sustainability of Tokyo relies on a big food supply chain to meet the huge demands of a population of 14 million people. The production of food consumes enormous amounts of water and energy along with producing the accompanying vast amount of CO_2 emissions. Excessive emissions create serious downward pressure on reaching the goal of being a carbon-neutral society by 2050. In order to relieve this pressure, it is required to first evaluate the CO_2 emissions quantitatively and then identify the main emitters exactly. Most of the previous studies focused on the emissions by industrial sectors, ignoring nexus effects across sectors. They also ignored the contribution of carbon emissions in the entire food supply chain, from supply industries to final consumption. This paper aims to develop a framework to visualize direct and indirect resource consumption and emissions in the food system, from food supply to food demand, and identity the key nodes and paths to achieve reduction targets using input-output tables at different scales. First, we define the elements in the food nexus system and establish the relationships among elements, in which the supply-side includes agriculture, animal husbandry, fisheries, and food manufacturing, while the demand-side includes food wholesale and retail, catering, and households. Then by using a monetary input-output table compiled from the statistics from the Tokyo Metropolitan Government, direct and indirect resource utilization and emissions are calculated to identify the sources of environmental stress through combining environmentally-extended input-output analysis and energy-water-CO_2 flow analysis. Finally, the reduction targets could be allocated to specific sectors and districts according to the results of emissions at different scales. The results show that the manufacturing and services sectors played the top roles of direct and indirect energy consumption and carbon emission, with manufacturing as the largest embodied energy consumer and CO_2 emitter, and services as the largest direct and embodied water user. These results indicate that the Tokyo Metropolitan Government could provide more measures on energy conservation and reduction in manufacturing and services. In addition, government should promote the wide use of zero emission vehicles to reduce emissions in transportation. It was found that the food system emits 10.73% of total CO_2 emissions and the embodied resource consumption and carbon emissions triggered by households is nearly a quarter of total embodied household consumption and emissions. Also, more than 80% of direct consumption and emissions comes from food demand. For embodied energy and CO_2 emissions, the main sectors with a strong correlation effect were manufacturing–services, manufacturing–transport/post, and services–transport/post, while manufacturing–services, telecommunication–services, and services–telecommunications were the major sectors for embodied water use. These sector pairs are the key paths for formulating energy conservation, water saving, and reduction measures. Our findings show that the food-energy-water (FEW) system is a significant contributor of CO_2 emissions in Tokyo. Thinking and acting on the FEW nexus across sectors could help the government to roll out its "Zero Emission Tokyo Strategy 2050" more effectively.

Keywords: Food systems, energy-water- CO_2 emissions, environmental input-output analysis, Tokyo

2 INTRODUCTION

With increasing demand for food, energy and water (FEW), driven by population growth, urbanization, and economic development, the supplies of these three resources face significant challenges (Xiao et al., 2018), while the production and consumption of these resources is accompanied by production of a vast amount of CO_2 emissions. Excessive emissions contribute to the frequent occurrence of extreme climatic events and serious damages to the security of FEW services in cities. Traditional thinking analyzes food, energy, and water individually, and ignores the impact of emissions (Owen et al., 2018). In fact, these four factors are relevant. It is clear that water and energy are the crucial inputs along the whole food supply chain. The energy production process consumes a large amount of water, while a lot of energy consumption is embodied during the production and distribution of water (Xiao et al., 2018), and all these processes are accompanied by carbon emissions. The interrelationships and interdependence between them are important areas of study. Nexus thinking is a sustained endeavor to understand the relationships between the four variables and applies an integrated management approach (Al-Saidi and Elagib, 2017; Sharmina et al., 2016).

Tokyo, Japan's capital and the largest metropolis in the world, with a high density of population and industries, is a good research case because it is an urban area with huge demand for food supply and the Tokyo Metropolitan Government has set the goal of net zero CO_2 emissions by 2050. Therefore, it is particularly important to have ways to to accurately evaluate resource consumption and emissions in the food supply chain. Input-output analysis is a valuable method for illustrating the supply and consumption processes of FEW resources in various economic systems (Zhang et al., 2014; Chen et al., 2017). In general, IOA can translate economic and environmental data in physical flows using value flows (Dong et al., 2014; Tang et al., 2018), and it can reflect the resource consumption and emissions that are embodied in the trade of goods (Zheng et al., 2020).

Input-output analysis is also an effective technique of evaluating supply and demand links between food, energy and water resources from a nexus viewpoint (Xiao et al., 2018). Owen et al. (2018) explore the relationship between products' energy, water, and food impacts by using input-output analysis in the UK, and finds that relieving environmental pressure cannot be achieved by reducing social welfare. Chen and Chen (2015) in a Beijing study find that the energy nexus impact is greater than water and a great majority sectors depend on manufacturing. Using a modified input-output analysis, Wang et al. (2017) find that manufacturing is the biggest supplier of embodied energy . Yang et al. (2018) find that Shanghai has similar and even greater environmental issues.

In this study, we first calculated direct and indirect resource consumption and emissions based on the input-output table (2011) of Tokyo at the sector level to identify the relationship between economic sectors and energy-water-CO_2 emissions. Then, we visualized direct and embodied resource utilization and carbon emissions, from food supply to food demand, and identity the key nodes which have high consumption and emissions based on an input-output table at the product level. Finally, the reduction targets were allocated to specific sectors and districts according to the results of emissions assessed at different scales.

3 DATA AND METHODS

3.1 EIO model construction and technical framework

The environmentally input-output mode can evaluate the relationship between environmental factors (energy, water, and CO_2) and socioeconomic activities by transforming a monetary input-output table to a physical input-output table, as shown in Equations: (1) and (2) (Zhang et al., 2014; Xu et al., 2021)

$$P + \varepsilon Z = \varepsilon X \tag{1}$$

$$\varepsilon = P[X - Z]^{-1} \tag{2}$$

where, $P = [p_i]_{1\times n}$, p_i is direct consumption and emissions in the *i*th sector; $Z = [z_{ij}]_{n\times n}$, z_{ij} is the I-O table currency flows matrix; X is a diagonal matrix consisting of each sector's overall economic output; $\varepsilon = [\varepsilon_i]_{1\times n}$, ε_i is the embodied resource intensity of the *i*th sector.

Fig.1 shows the data description and technical framework.

3.2 Direct consumption and emissions

For different types of energy, the direct energy consumption can be calculated in each sector. The types of energy in the Final Energy Consumption and Greenhouse Gas Emissions report in Tokyo mainly include electricity, city (natural) gas, liquified petroleum gas (LPG), and fuel oil. Therefore, CO_2 emissions were calculated based on four types of energy resources in this research. According to the Bureau of Waterworks, Tokyo Metropolitan Government, domestic water consumption consists of industrial consumption, urban activities consumption and daily life consumption. Sub-sectoral direct water use can be obtained from the total amount based on the economic output of the production and distribution of water (Xu et al., 2021). The direct consumption and emissions are formulated as follows:

$$e_i = E_{ele,i} \times \frac{T_{ele,i}}{\sum_{i=1}^{m} T_{ele,i}} + E_{gas,i} \times \frac{T_{gas,i}}{\sum_{i=1}^{m} T_{gas,i}} + E_{oil,i} \times \frac{T_{oil,i}}{\sum_{i=1}^{m} T_{oil,i}} \tag{3}$$

$$w_i = W_{water,i} \times \frac{T_{water,i}}{\sum_{i=1}^{m} T_{water,i}} \quad (4)$$

$$c_i = C_{ele,i} \times \frac{T_{ele,i}}{\sum_{i=1}^{m} T_{ele,i}} + C_{gas,i} \times \frac{T_{gas,i}}{\sum_{i=1}^{m} T_{gas,i}} + C_{oil,i} \times \frac{T_{oil,i}}{\sum_{i=1}^{m} T_{oil,i}} \quad (5)$$

where e_i, w_i, and c_i mean direct energy consumption (petajoules, or PJ), direct water use (m^3), and CO_2 emissions (t) of ith sector, respectively. $E_{ele,i}$, $E_{gas,i}$ and $E_{oil,i}$ represent the total electricity consumption of industry (PJ), total city gas consumption of industry (PJ) and total oil consumption of industry (PJ), respectively. $T_{ele,\ gas,\ oil,\ water,\ i}$ means the intermediate use (million yen) of sector m (production and distribution of electricity, gas, oil and water) in sector i. $W_{water,i}$ is the total water consumption of industry in Tokyo. $C_{ele,i}$, $C_{gas,i}$ and $C_{oil,i}$ represent the total emissions from electricity of industry (t), total emissions from city gas use (t) and total industrial emissions from oil use (t), respectively.

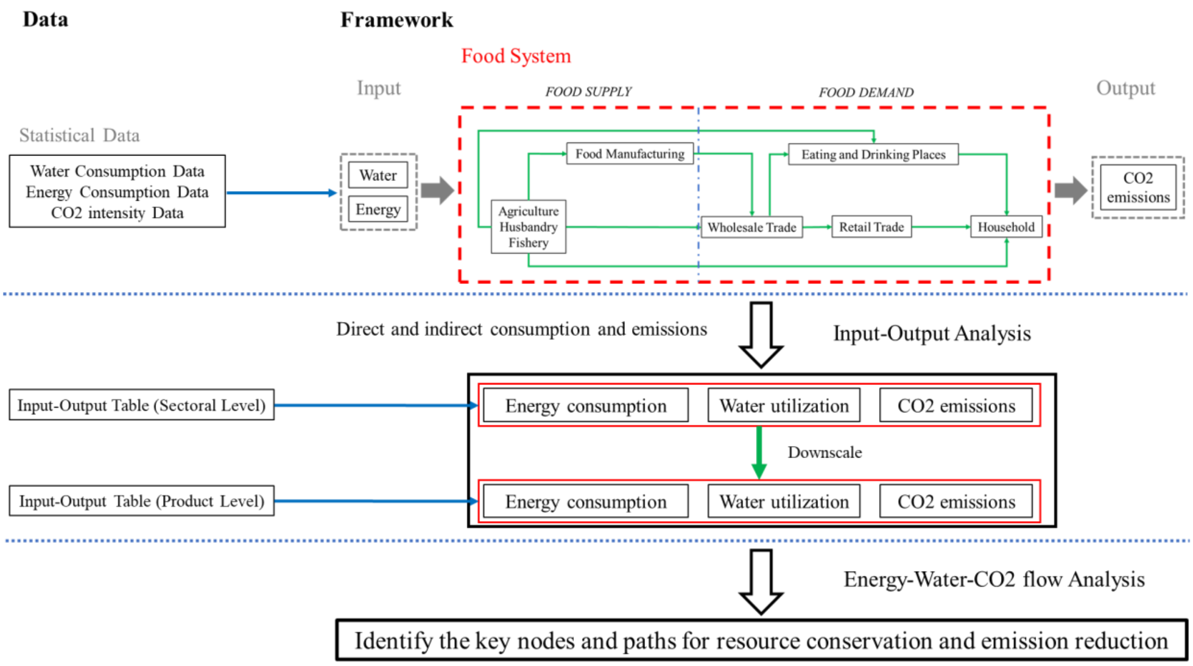


Fig. 1: Research framework

3.3 Indirect consumption and emissions

In addition to direct energy use and CO_2 emissions, sectoral production activities will create consumption and emission impacts as a result of sectoral linkages, which is referred to as indirect or embodied consumption and emissions. It represents the nexus impact of urban systems from a consumption perspective. The embodied consumption and emissions are triggered by urban final demand (Chen et al., 2016). Indirect consumption and emissions are calculated and analyzed based on the direct consumption and emission intensities as shown in Equations (7), (8), (9), and (10).

$$e_j^d = e_j / x_j \quad (7)$$

$$w_j^d = w_j / x_j \quad (8)$$

$$c_j^d = c_j / x_j \quad (9)$$

$$a_{ij} = z_{ij} / x_j \quad (10)$$

where e_{jd}, w_{jd} and c_{jd} are the direct consumption and emission intensity of energy, water, and CO_2 in sector *j*.

a_{ij} is the coefficients of direct consumption and x_j is the economic output of sector *j*.

Equations (11), (12), and (13) were used to determine the energy and water consumption as well as the CO_2 emission row vectors.

$$E_{em} = E_d(I - A)^{-1}Y \quad (11)$$

$$W_{em} = W_d(I - A)^{-1}Y \quad (12)$$

$$C_{em} = C_d(I - A)^{-1}Y \quad (13)$$

where E_d, W_d and C_d are the row vectors of direct consumption and emissions intensities, respectively. A is the coefficients matrix of direct use. I is the identity matrix, and Y is the diagonal matrix transformed from the final demand.

3.4 Embodied flow analysis

By measuring the embodied flows between urban sectors, the efficiency and mechanism of the urban system can be quantified and analysed (Zhang, 2013). We can determine the vital sectors and pathways for resource conservation and emission reduction through analyzing embodied flows of energy, water, and CO_2 in the urban system (Li et al., 2017; Cai et al., 2019). Therefore, sectoral embodied flows of consumption and emissions must be considered (Fang and Chen, 2017). The embodied flows reflect the resource consumption and emissions embodied in goods trade. The embodied flows can be quantified based on the environmentally input-output mode through Equation (1)–(2) as follows (Tang et al., 2018; Xu et al., 2019; Wang et al., 2019):

$$F_{ij}^{ene} = \left[f_{ij}^{ene}\right] = \varepsilon^{ene} Z \quad (14)$$

$$F_{ij}^{wat} = \left[f_{ij}^{wat}\right] = \varepsilon^{wat} Z \quad (15)$$

$$F_{ij}^{CO2} = \left[f_{ij}^{CO2}\right] = \varepsilon^{CO2} Z \quad (16)$$

where f_{ij} is the embodied flows from sector *i* to sector *j*. ε is the diagonal matrix transformed from the row vector of embodied intensity.

3.5 Data sources

In this research, in order to assess resource consumption and CO_2 emissions at the sectoral level and product level (38-sector and 191-sector structures), Tokyo economic input-output table (2011) were available from Statistics of Tokyo. Energy use data including four types of fuel were gathered from the Bureau of Environment Tokyo Metropolitan Government. Information on the use of water in each sector has been acquired and analyzed from the Tokyo Metropolitan Government Waterworks Bureau. In addition, Tokyo's monetary input–output table (38-sector structure) is aggregated to a 11-sector table for assessing urban energy–water-CO_2 emissions, that are Agriculture (Agr), Mining (Min), Manufacture (Man), Construction (Con), Electricity, Gas and Water (EGW), Wholesale and Retail Trade (WR), Finance and Insurance (FI), Real Estate (RE), Transport and Post (TP), Telecommunications (Tel) and Service (Ser).

4 RESULTS

4.1 Sectoral energy and water consumption and CO_2 emissions in Tokyo

Fig. 2 shows sectoral energy consumption, water utilization, and CO_2 emissions in 2011. The total indirect consumption and emissions are higher than the direct consumption and emissions, where embodied energy consumption and carbon emissions are nearly two times the city's direct consumption and emissions. The reason for this phenomenon is that as the population grows there is a decrease in traditional production sectors, rapid tertiary industry development, and implementation of "Zero Emission Tokyo Strategy" policies, while the increase in citizen demand for goods resulted in an indirect consumption increase.

Fig. 2 (a) presents the direct and indirect energy consumption of each sector. The direct energy consumption of Tokyo in 2011 is 453.36 PJ. The biggest proportion of energy is consumed by the transport and post (TP) sector (36% of total energy consumption). Tokyo is a typical example of a railway-oriented city and 76% of total fuel consumption comes from transport. Services (Ser) is the second most energy-intense sector (27.6%), which includes education and scientific research, medical services, and various business services (accommodation business, eating and drinking services, and entertainment services, etc.). Manufacturing (Ma) consumed 9.7% of the energy, and the remaining sectors consumed another 26.7%. The total embodied energy consumption triggered by final demand is 1,008.37 PJ, in which the contributions of Manufacturing (Ma), Services (Ser) and Transport and Post (TP) are 28.67%, 27.34% and 13.69%, respectively. Compared with Fig. 2(c), the same trend was observed in energy consumption and carbon emissions. The biggest proportion of CO_2 emissions is Transport and Post (TP).

Fig. 2 (b) shows the sectoral direct/indirect water utilization of each sector. The direct water consumption of Tokyo is 4.029 billion m^3. About 2.38 billion m^3 of the water is consumed by Services (Ser) due to high demand in the food and beverage services and public bath services, accounting for 59% of the total water use, while 2.1% is used by Manufacturing (Ma). The total embodied water utilization triggered by final demand is 4.92 billion m^3, in which the contributions of Services (Ser), Wholesale and Retail Trade (WR), and Manufacturing (Ma) are 57.5%, 11.95% and 11.8%, respectively.

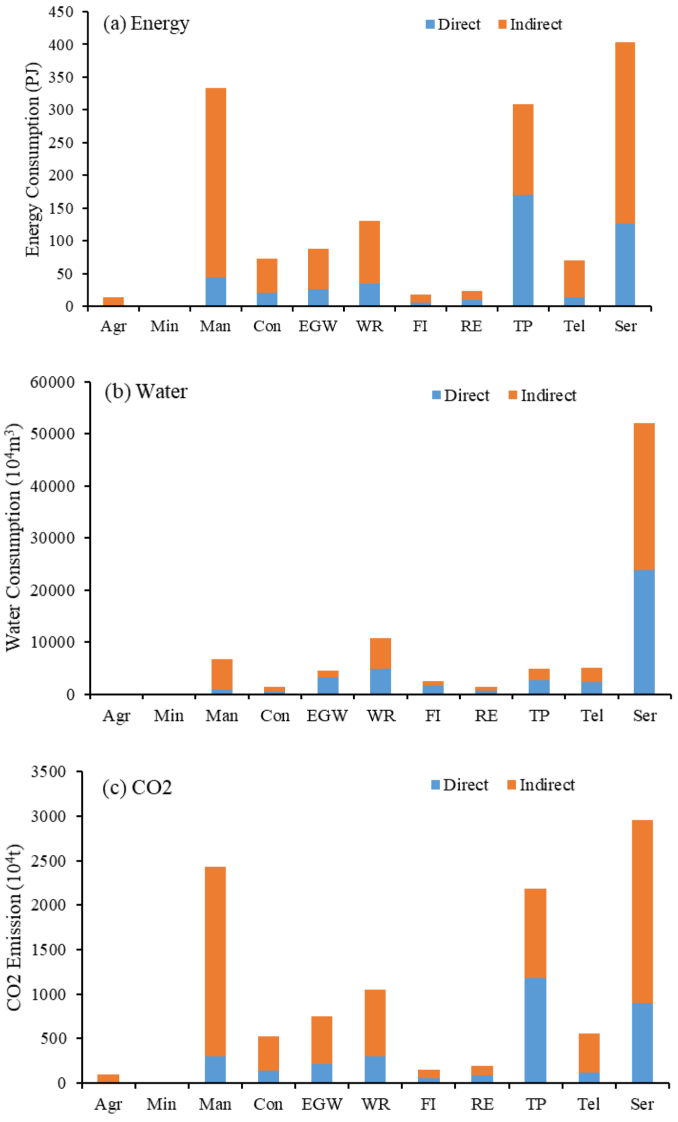


Fig. 2: Sectoral direct and indirect energy consumption, water resources utilization, CO_2 emissions in Tokyo

4.2 Energy and water consumption and CO_2 emissions in the food system

Fig. 3 shows that the food system consumes 19.89% of direct water and 11.64% of direct energy and emits 10.73% of total CO_2 emissions. The embodied consumption and emissions triggered by households are 22.85% of embodied water, 28.57% of embodied energy, and 26.97% of embodied emissions, respectively. In the food system, more than 80% of direct consumption and emissions come from food demand.

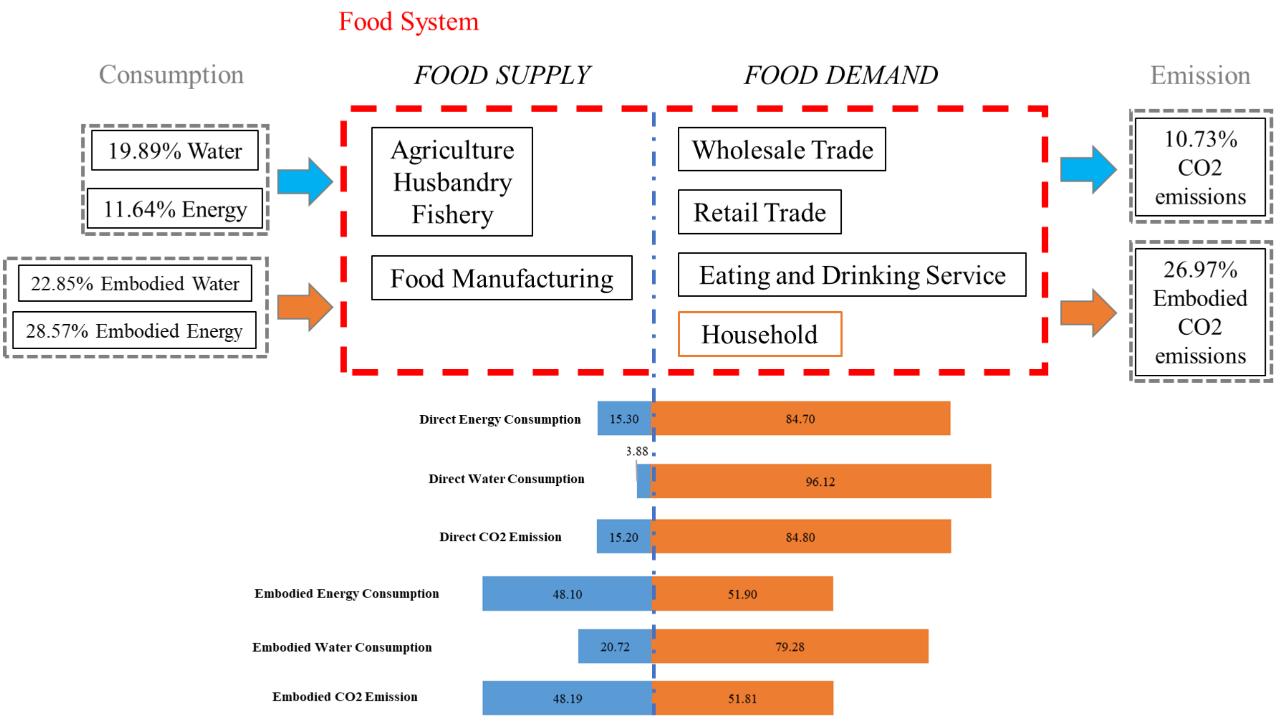


Fig. 3: Direct and embodied consumption and emissions in the food system

Fig. 4 shows direct consumption and emission in Agriculture (Agr) and Food Manufacturing (F Man). Marine fisheries are very developed, because they consume 71% of the energy in this sector. Agricultural services and non-edible foods consume 76% of the water, because seeds, flowers, and tobacco require much water to grow. Although there is little cultivated land in Tokyo, there are still professional farmers, mainly producing vegetables and fruits. Vegetable growing consumes 11% of water and energy, as shown in Fig. 4(a). Water and energy consumption are mainly concentrated in staple foods, condiments and other grocery products (frozen foods, fast foods, etc.), as shown in Fig. 4(b). Because the food supply in Tokyo mainly depends on imports, in order to feed 14 million people, it is necessary to refrigerate a large amount of vegetables, fruits and meat. As a result frozen foods and fast foods consume more than 36% of energy and water.

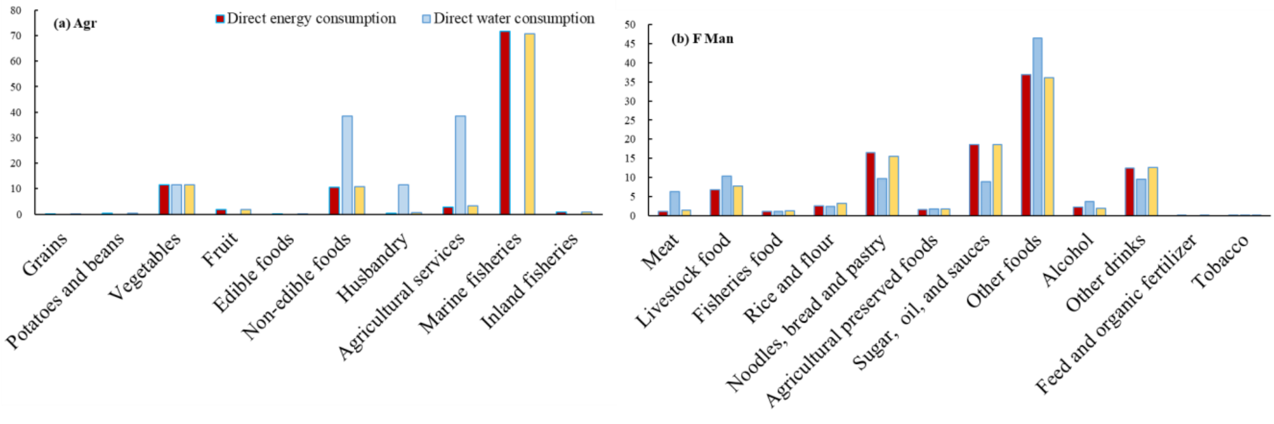
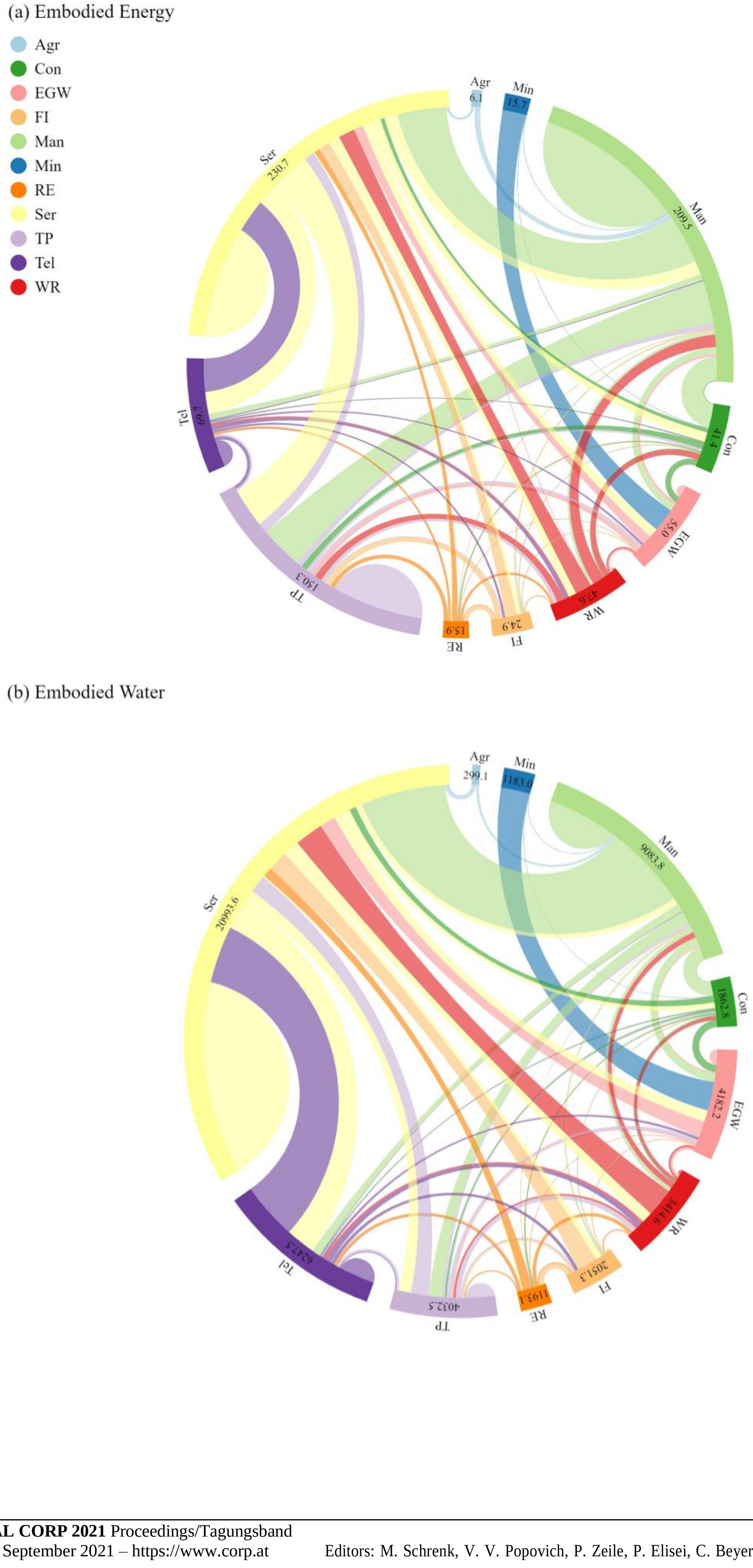


Fig. 4: Direct consumption and emissions in the food supply

4.3 Embodied flows for energy-water-CO_2

In Fig. 5 (a) and (c), Man is the largest embodied energy and CO_2 supplier, with the amount of 133.9 PJ and 947.8 (104t), respectively. Man, Ser, and TP were always the top three suppliers of embodied energy and CO_2. The largest embodied energy and CO_2 consumer in 2011 was Ser, followed by TP and Man, because of huge demand or goods trade. In Fig. 5 (b), Ser and EGW were the biggest water users with the functions of public bath services and cooling water for power generation facilities, respectively. The description of the energy, water and CO_2 flow interactions between the various sectors in 2011 is shown in Fig. 5. The top three embodied energy and CO_2 supply-consumption flows pairs all existed in Man-Ser, Man-TP, and Ser-

TP. Ser and TP were the biggest demanders of intermediate products from Man, in line with their sectoral features and raw materials demand. As the embodied CO_2 supplier, Ma has traditionally been the largest sector. The biggest supply-consumption flows pair is Man-Ser in embodied water.



(b) Embodied Water

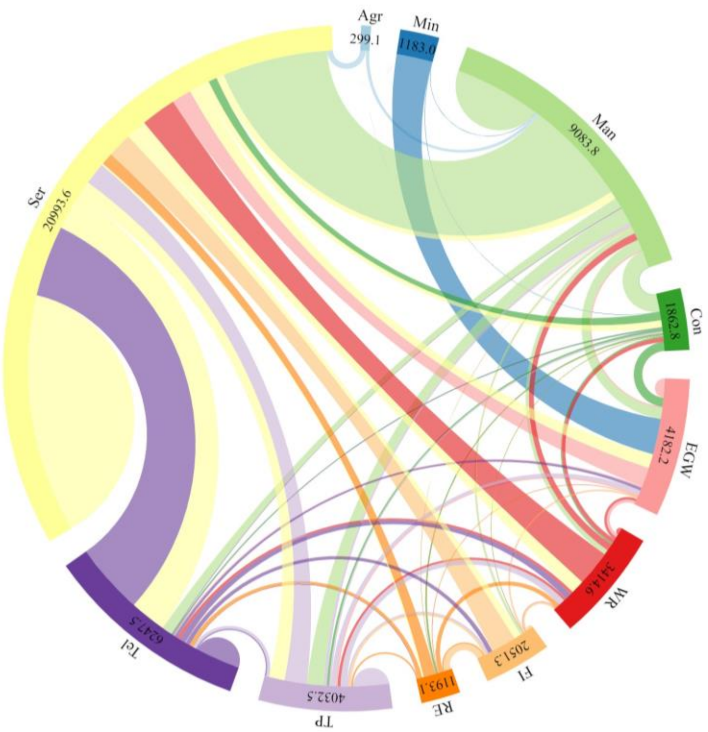


Fig. 5: Embodied energy, water, and CO2 flows between sectors in 2011.

Note: The units for energy, water, and CO2 are PJ, 104 m3, and 104t, respectively.

5 DISCUSSION

From the research results, the energy consumption of Ser and Man had a great difference in 2011. Indirect consumption was more than two times direct consumption. A similar result was seen in the water utilization and emissions of the two sectors. Therefore, in the Ser and Man sectors, there should thus be greater consideration of energy and water conservation and carbon reduction methods. Although the energy consumption of Con is not high, indirect consumption is 2.6 times that of direct consumption. There are many wooden houses in Tokyo, and research has showed that the average wooden house life expectancy is only 40 years, lower than a steel-concrete structure apartment (51 years). Because of the short average life expectancy of building structures, much energy and water were consumed, leading to high emissions. A key objective to minimize consumption and emissions of the Con sector should thus be to improve the technology and technical standards of housing construction. The largest direct emissions come from TP. Relieving environmental stress in TP can be effectively accomplished by promoting a new innovation in the motor industry through various subsidy policies.

From the standpoint of resource trading between sectors, suppliers and consumers assume various duties to save energy and water, and reduce emissions. For instance, the biggest embodied energy and CO_2 consumers in Tokyo have been Ser, TP, and Man. Therefore, Ser, TP, and Man are the sectors with the most opportunity to undertake steps to save energy and to reduce emissions. Meanwhile, Ser, EGW, Tel, and Man are the biggest embodied water consumers and have higher opportunities and responsibilities than other sectors for water saving. For embodied energy and CO_2, the main suppliers-consumers were Man-Ser, Man-TP, and Ser-TP, while Man-Ser, Tel-Ser, and Ser-Tel were the major suppliers-consumers pairs for embodied water. The significant correlation impact between these sectors reveals the main path to formulate energy conservation, water-saving, and carbon reduction methods.

6 CONCLUSION

This study evaluated energy, water, and CO_2 flows through environmental input-output analysis using 2011 data at the sector and product level in Tokyo. in the urban system, services prove to be one of the industries in Tokyo, and direct and indirect process analyses show that services have the greatest energy consumption and carbon emissions. Indirect water use by services is higher than by other sectors, so there is great potential to conserve resources and reduce emissions from this sector, especially in the catering and public bath industries. Efforts targeting these services could help meet emission reduction targets, guided by strategic policies established in the Tokyo 2050 goal. In addition, direct and indirect energy consumption and CO_2 emissions from manufacturing showed a great variance. Most energy consumption and carbon emissions are indirect, as most manufactured products are needed by households, governments and for exports. Transportation dominated the list of direct energy consumption, suggesting that a focus on promoting zero emission vehicles (ZEVs) could help reach reduction goals. Manufacturing and services were the main embodied energy and CO_2 suppliers and embodied water consumers. These sectors are critical points for achieving the objective of conserving resources and reducing emissions. In the food system, more than 80% of direct consumption and emissions come from food demand, especially in the catering industry. More than 25% of embodied CO_2 emissions in the food system were triggered by households. In the food supply sector, non-edible foods dominated direct water consumption. This finding suggests that a focus on increasing the efficiency of irrigation water use will help conserve water resources. Our study also found that marine fisheries had the highest percentages of energy consumption and carbon emissions. The top three items for consumption and emissions in food manufacturing were staple foods (noodles, bread, and rice), condiments, and other grocery products (frozen foods, fast foods, etc.). One important conclusion is that people should strive to purchase locally grown, seasonal produce and eat a healthy balance of plant-based foods to relieve environmental stresses caused by food manufacturing

7 ACKNOWLEDGEMENTS

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