

# Assessing Urban Resource Consumption and Carbon Emissions from a Food–Energy–Water Nexus Perspective



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**Abstract** This chapter aims to analyze the carbon emissions in the food–energy–water (FEW) nexus from an urban supply-and-demand perspective by quantifying resource consumption flows in FEW supply chains so that carbon dioxide (CO<sub>2</sub>) emissions from supply and consumption, as well as the contributions of FEW to urban systems, can be calculated quantitatively. By using monetary input–output tables of the Tokyo Metropolitan Government’s Statistics Division, we tracked the flows of water, energy, and CO<sub>2</sub>; visualized energy and water consumption and carbon emissions in each sector; and assessed resource efficiency in different sectors. We then defined the elements in the food nexus system and established the relationships among the elements of supply and demand, 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. We also calculated water, energy, and carbon flows in the food system. Finally, we allocated reduction targets to specific sectors according to the results of emissions at different scales through embodied flow analysis. The results show that in Tokyo, services have the greatest food-energy-water consumption and carbon emissions. There is considerable potential to conserve resources and reduce emissions in these sectors. This research shows that FEW makes a significant contribution to carbon emissions, and more effort is required to achieve the “Zero Emission Tokyo Strategy” for 2050.

**Keywords** Food-energy-water nexus · CO<sub>2</sub> emissions · Environmental input-output analysis · Tokyo

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## 1 Introduction

Food, energy, and water are essential for human social development, and the food–energy–water (FEW) nexus has huge impacts on resource consumption, CO<sub>2</sub> emissions, and the security of FEW supplies (Ramaswami et al. 2017). Currently, about 70% of freshwater consumption (Gleick 2003) and 30% of carbon emissions (Vermeulen et al. 2012) are associated with the supply of food. According to UN World Urbanization Prospects projections (<https://population.un.org/wup/>), more than half the world's population is living in cities now, and by 2050, the urban population will reach 68%. This means that cities will face significant challenges from the rapidly growing demand for food, energy, and water, and a range of urban environmental issues, such as resource depletion, environmental pollution, garbage, and ecosystem damage (Xu et al. 2021). Tokyo, the largest metropolis in the world, with high population density and a concentration of industry, also faces urban environmental problems such as insufficient local food supplies due to an aging population and labor shortages, therefore being unable to meet all the food needs of the local population. Global warming has had a negative impact on Tokyo's water quality and quantity, while dramatic changes have occurred in the structure of its energy supply because of the Great East Japan Earthquake in 2011. Final energy consumption dropped by about 12% from 2010 to 2015, but Tokyo's carbon emissions returned to 2011 levels in 2015.

In mega-cities like Tokyo, sectoral linkages inevitably affect the city's inputs and outputs (Wang et al. 2019). Food, energy, and water are the main areas of physical and energy flow in the inputs and outputs through cities. Thus, the functioning of these sectors is key to resource use efficiency and reducing carbon emissions. It remains critical to find approaches to quantify material and energy flows; that is to assess the resource consumption and carbon emissions in terms of sectoral linkages, in order to identify key sectors and productive ways to achieve resource savings and emissions reductions. In recent years, input–output analysis (IOA) has become a primary method used to analyze these problems, as it is useful 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 into physical flows using value flows (Dong et al. 2014; Tan et al. 2018), and can reflect the resource consumption and emissions embodied in the trade of goods (Zheng et al. 2020).

An increasing amount of research focuses on input–output analysis at the national, urban agglomeration, and city scales. At the national scale, Xu et al. (2021) assessed water use, energy consumption, and carbon emissions in China based on environmental input–output analysis and ecological network analysis for the years 2007, 2012 and 2017. They found that advanced manufacturing and agriculture played important roles in resource conservation and emissions reduction. Advanced manufacturing was the largest energy consumer and carbon emitter, and agriculture was the bigger water user. Owen et al. (2018) explored the food–energy–water nexus in the UK by input–output analysis and structural–path analysis. They

found that demand-side policies can help governments to reduce food, energy, and water consumption. At the urban agglomeration scale, Zhang et al. (2016) identified regional energy consumption features and their ecological roles in the energy metabolic system to advance coordinated development by combining multi-region input–output (MRIO) and ecological network analysis (ENA) in Beijing–Tianjin–Hebei (Jing–Jin–Ji). Liu et al. (2020) compiled an urban multi-regional input–output table for analyzing the energy–water nexus in the Pearl River Delta urban agglomeration. At the interprovincial level, many suggestions and measures for energy conservation and emissions reduction have been put forward. At the city scale, Chen and Chen (2016) proposed a system-based framework for assessing water and energy use in Beijing. They found that services consumed the most energy and that manufacturing was the largest water consumer. Yang et al. (2018) assessed the energy–water–carbon nexus in Shanghai and Beijing in 2012 using an environmental input–output model, and found that the services sector consumes the most resources and emits the most carbon in Shanghai and Beijing. Compared to Beijing, Shanghai faced greater environmental challenges, they found.

Previous studies, whether at the national or city scale, have tended to focus on the energy–water nexus at the sectoral level, including agriculture, commerce, industry, so they had limited value for developing resource conservation and emissions reduction policies specific to local conditions, such as what products or services in the agricultural sector need to have energy efficiency and emissions reduction targets. Detailed analysis (e.g., agriculture sector includes grain, meat, and vegetables) could support policymaking. In food research, previous work tended to concentrate on the food supply (agriculture and food manufacturing), ignoring the contribution of food demand, such as catering, because current statistics in cities are generally not detailed enough to characterize specific products. In addition, some studies were only snapshots of one statistical year, whereas dynamic assessments of multiple years over time could be more useful for macro-level policymaking.

Thus, the objective of this research was to assess the food–energy–water nexus and CO<sub>2</sub> emissions through an environmental input–output model based on Tokyo’s input–output tables (2011 and 2015). The study area for this research consists of the 23 wards covered by the Tokyo Metropolitan Government. First, we calculated direct and indirect consumption and emissions at the sector level to identify the relationship between economic sectors and energy consumption, water use and CO<sub>2</sub> emissions. Then, we visualized resource utilization and carbon emissions in the food system, from food supply to food demand, and identified the vital food products which have high consumption and emission levels based on an input–output table at the product level. Finally, we used embodied flow analysis to identify key elements for resource conservation and emissions reduction, and to facilitate policy recommendations to effectively reach the goals of the “Zero Emission Tokyo Strategy” for 2050.

## 2 Methods

### 2.1 Environmental Input–Output Analysis

Environmental input–output models can be used to calculate the resource consumption of different industries based on economic input–output tables. They can be used for assessing the ecological footprint (Bicknell et al. 1998; Wiedmann et al. 2006; Galli et al. 2013), the water footprint (Hoekstra and Chapagain 2006; Hoekstra and Mekonnen 2012), energy consumption (Chen and Chen 2016), and CO<sub>2</sub> emissions (Xu et al. 2021). The calculation is shown in Eq. (1):

$$C + \varepsilon A = \varepsilon O \quad (1)$$

where  $C$  represents a  $1 \times n$  vector that indicates the FEW consumption and carbon emissions for each sector, respectively. The units are petajoules (PJ), cubic meters (m<sup>3</sup>) and tonnes (t), respectively.  $A$  is the economic input–output matrix and  $O$  is the economic output in each sector, in unit of one million yen. Meanwhile,  $\varepsilon$  is a  $1 \times n$  embodied resources intensity vector used to calculate the embodied resource flows from sector  $i$  to sector  $j$ .

### 2.2 Direct Consumption and Emissions

Different types of energy consumption can be calculated directly in each sector. The types of energy in the Final Energy Consumption and Greenhouse Gas Emissions report (<https://www.kankyo.metro.tokyo.lg.jp/en/climate/index.html>) mainly include electricity, city (natural) gas, liquified petroleum gas (LPG), and fuel oil. In this chapter, carbon emissions were calculated based on these four types of energy resources, as shown in Eqs. (2) and (3):

$$e_i = E_{ele,i} \times \frac{T_{ele,i}}{\sum_{i=1}^m T_{ele,i}} + E_{gas,i} \times \frac{T_{gas,i}}{\sum_{i=1}^m T_{gas,i}} + E_{oil,i} \times \frac{T_{oil,i}}{\sum_{i=1}^m T_{oil,i}} \quad (2)$$

$$c_i = C_{ele,i} \times \frac{T_{ele,i}}{\sum_{i=1}^m T_{ele,i}} + C_{gas,i} \times \frac{T_{gas,i}}{\sum_{i=1}^m T_{gas,i}} + C_{oil,i} \times \frac{T_{oil,i}}{\sum_{i=1}^m T_{oil,i}} \quad (3)$$

where  $e_i$  and  $c_i$  are direct energy consumption (PJ) and CO<sub>2</sub> emissions (t) of each sector.  $E_{ele,i}$ ,  $E_{gas,i}$ , and  $E_{oil,i}$  represent total industrial consumption of electricity, city gas, and oil, respectively (units are PJ).  $T_{ele, gas, oil, water, i}$  are the intermediate use (million yen) of sector  $m$  (production and distribution of electricity, gas, oil and

water) in sector  $i$ .  $C_{ele,i}$ ,  $C_{gas,i}$ , and  $C_{oil,i}$  represent the total CO<sub>2</sub> emissions from industrial electricity, city gas use, and oil use.

According to the Tokyo Metropolitan Government' Bureau of Waterworks, 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 in Eq. (4):

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

where  $w_i$  is direct water use (m<sup>3</sup>) in each sector and  $W_{water, i}$  is the total water consumption of industry  $i$  in Tokyo.

### 2.3 Indirect Consumption and Emissions

In addition to direct usage of energy and CO<sub>2</sub> emissions, production sectors will impact consumption and emissions through sector interlinkages called indirect or embodied consumption and emissions. This represents the nexus impact of urban systems from a consumption perspective. The embodied consumption and emissions are triggered by urban final demand (Chen and Chen 2016). First, direct intensities are calculated as shown in the Eqs. (5) and (6),

$$ewc_j^d = ewc_j/x_j \quad (5)$$

$$a_{ij} = z_{ij}/x_j \quad (6)$$

where  $ewc_j^d$  is the direct intensity of energy, water, and CO<sub>2</sub> in sector  $j$ . Finally,  $a_{ij}$  is the coefficient of direct consumption and  $x_j$  is the economic output of sector  $j$ , as shown in Eq. (7),

$$EWC_{em} = EWC_d(I - A)^{-1}Y \quad (7)$$

where  $EWC_{em}$  is the row vectors of direct intensities,  $A$  is the coefficient matrix of direct use,  $I$  is the identity matrix, and  $Y$  is the final demand.

### 2.4 Embodied Flow Analysis

By measuring the embodied flows between urban sectors, the efficiencies and mechanisms of the urban system can be quantified and analyzed (Zhang 2013). We can determine the vital sectors and pathways for resource conservation and emissions reduction by analyzing embodied flows of energy, water, and carbon 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 carbon emissions embodied in the trade of goods. Embodied flows can be quantified based on environmental input–output analysis (Tang et al. 2019; Xu et al. 2019; Wang et al. 2019), as shown in Eq. (8),

$$F_{ij}^{ewc} = \left[ f_{ij}^{ewc} \right] = \varepsilon^{ewc} Z \tag{8}$$

where  $f_{ij}$  is the embodied flows from sector  $i$  to sector  $j$  and  $\varepsilon$  is the diagonal matrix of embodied intensity.

### 3 Data Processing

To assess resource consumption and CO<sub>2</sub> emissions, we used the Tokyo Metropolitan Government Statistics Division’s economic input–output table (IO table) with different structures (38 sectors and 191-sector structures) for 2011 and 2015. The IO tables include intermediate demand, intermediate supply, final demand, imports, gross value-added, and total production value (Fig. 1). Intermediate sectors include many industries, such as agriculture, mining, and manufacturing. Final demand includes households, government, and export. Energy use data, including four types of fuel, were gathered from the Tokyo Metropolitan Government’s Bureau

| Supply Sector       | Demand Sector              | Intermediate demand |            |            |     |       | Final demand |            |        |       | Import | Total production value |
|---------------------|----------------------------|---------------------|------------|------------|-----|-------|--------------|------------|--------|-------|--------|------------------------|
|                     |                            | 1.Sector 1          | 2.Sector 2 | 3.Sector 3 | ... | Sum A | Household    | Government | Export | Sum B |        |                        |
| Intermediate Supply | 1.Sector 1                 |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | 2.Sector 2                 |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | 3.Sector 3                 |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | ...                        |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | Sum D                      |                     |            |            |     |       |              |            |        |       |        |                        |
| Gross value added   | Compensation of employees  |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | Indirect taxes             |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | ...                        |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | Sum E                      |                     |            |            |     |       |              |            |        |       |        |                        |
|                     | Total production value D+E |                     |            |            |     |       |              |            |        |       |        |                        |

Fig. 1 Tokyo economic input–output table

of Environment. Information on water use of each sector was acquired and analyzed from the Tokyo Metropolitan Government's Waterworks Bureau.

Tokyo's monetary input-output tables (38-sectors) were aggregated to an 11-sector table for assessing urban energy-water-CO<sub>2</sub> emissions, as follows: Agriculture (Agr), Mining (Min), Manufacturing (Man), Construction (Con), Electricity, Gas and Water (EGW), Wholesale and Retail Trade (WR), Finance and Insurance (FI), Real Estate (RE), Transport and Post office (TP), Telecommunications (Tel), and Services (Ser).

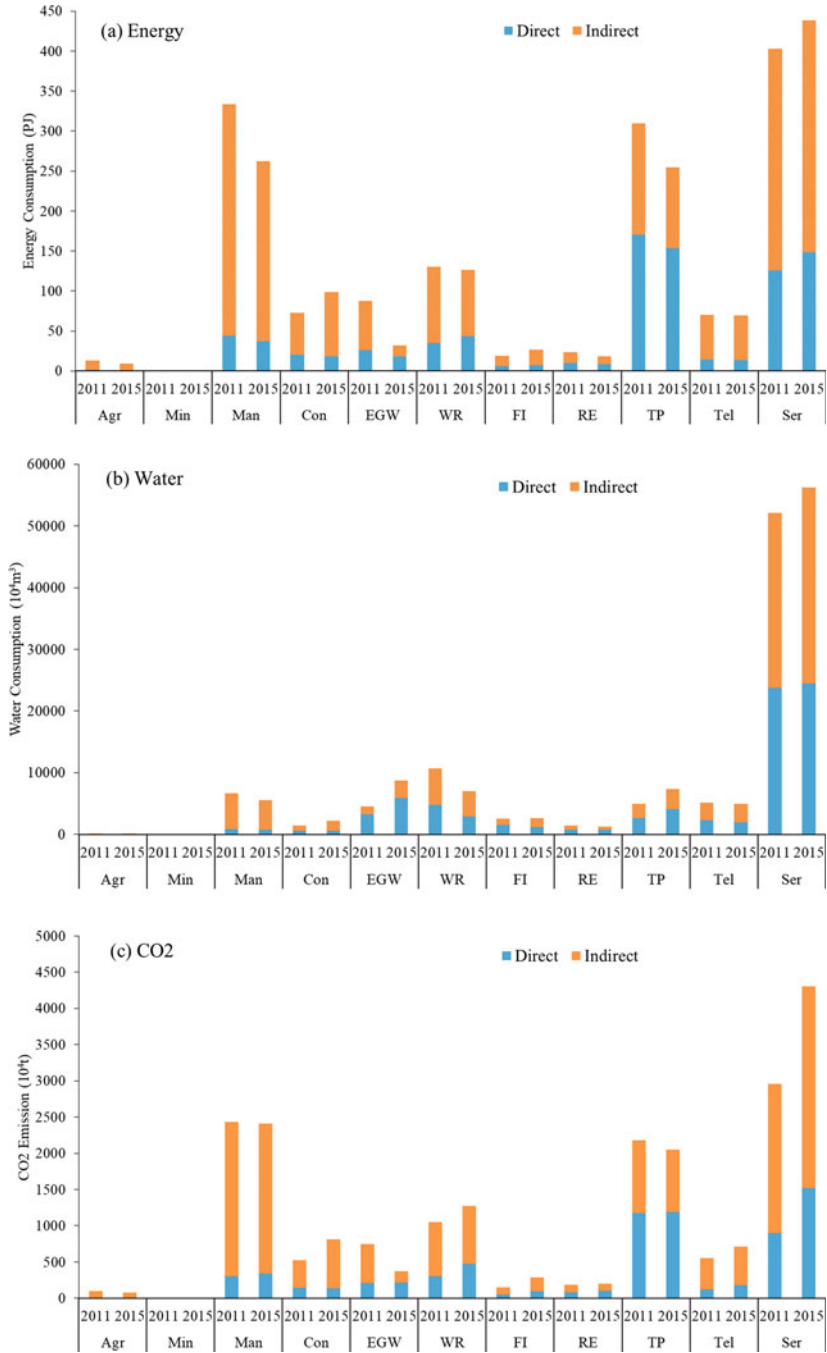
## 4 Results

### 4.1 Energy and Water Consumption and CO<sub>2</sub> Emissions in Tokyo

Figure 2 shows sectoral energy consumption, water utilization, and CO<sub>2</sub> emissions in 2011 and 2015. Figure 2a presents the direct and indirect energy consumption of each sector. It shows that Service (Ser), Transport and Post (TP), and Manufacture (Man) were the top three energy consumers. However, only the energy demand of Service (Ser) has increased. The biggest proportion of energy is directly consumed by Transport and Post (TP) (more than 30% of total energy consumption). In addition, Manufacture (Man) has extremely high indirect consumption, because products from this sector are typically the raw materials for other industries, and there is big demand in Tokyo. The percentage of indirect energy and water consumption in Agriculture (Agr) and Manufacture (Man) remained at more than 80%. In addition, the proportion of embodied energy use in Mining (Min) and Electricity, Gas and Water (EGW) dropped by 35% and 28%, respectively, while at the same time it rose 10% in Construction (Con). The reason for this situation was that the 2011 earthquake destroyed the energy supply system, and many buildings had to be repaired and rebuilt.

Figure 2b describes the direct/indirect water utilization of each sector. In 2011, about 2 billion m<sup>3</sup> of the water is consumed by Services (Ser) due to high demand in the food and beverage services and public bath services, accounting for more than 55% of total water use. Electricity, Gas, and Water (EGW) was the second largest direct water consumer, using 31.98 million m<sup>3</sup> and 59.32 million m<sup>3</sup> in 2011 and 2015, respectively. The total embodied water utilization triggered by final demand was more than 4 billion m<sup>3</sup>, in which the consumption in Services (Ser), Wholesale and Retail Trade (WR), and Manufacture (Ma) were 57.5%, 11.95% and 11.8%, respectively, in 2011.

Figure 2c shows the direct/indirect carbon emissions of each sector. Transport and Post (TP) was the biggest direct carbon emitter, at more than 11 million t. Apart from Agriculture (Agr) and Manufacture (Man), carbon emissions have increased in the rest of the industries, especially Ser, which increased by more than six million



**Fig. 2** Sectoral energy consumption (a), water resources utilization (b), and CO<sub>2</sub> emissions (c) in Tokyo



t. Moreover, the indirect emissions in Man remained at the highest level, because other sectors had the largest demand for manufacturing supply.

### 4.2 Energy and Water Consumption and CO<sub>2</sub> Emissions in the Food System

Figure 3 shows resource use and carbon emissions in the food system in 2011 and 2015. In 2011, the food supply consumed 15.3% of energy and 3.9% of water and emitted 15.2% of total carbon emissions, and it was a similar situation in 2015. In addition, we find that more than 80% of energy use and carbon emissions, and more than 90% of water use, came from food demand.

Figure 4 shows direct consumption and emissions in Agriculture and Food Manufacturing. Marine fisheries are the industries with high-energy consumption and high emissions, as they consume more than 50% of the energy and emit more than 40% of CO<sub>2</sub>. Non-edible foods consumed 40% of the water in 2011, because seeds, flowers, and tobacco require much water to grow.

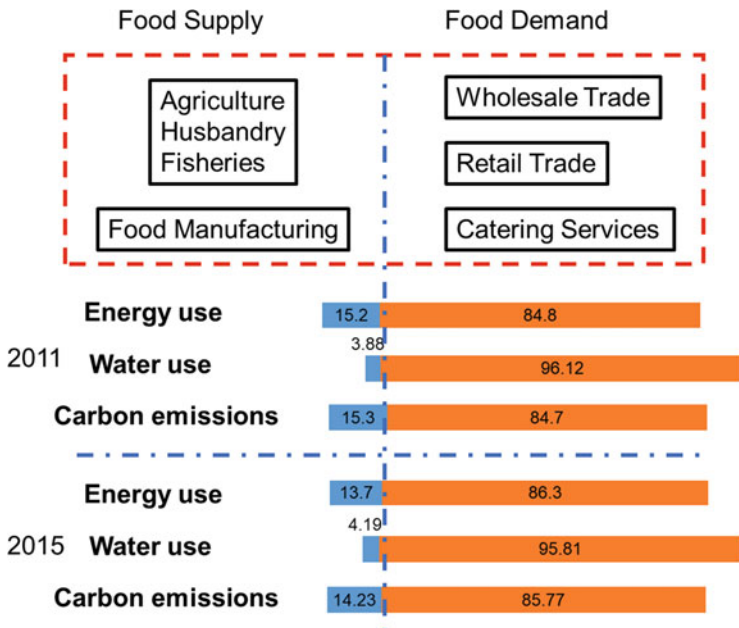
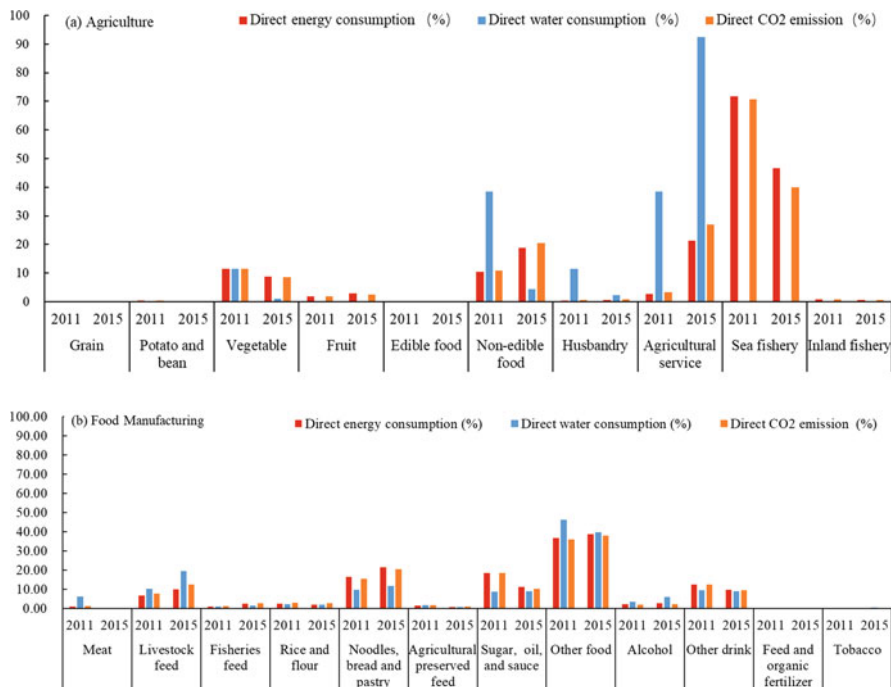


Fig. 3 Direct and embodied consumption and emissions in the food system



**Fig. 4** Direct energy use, water consumption, and CO<sub>2</sub> emissions in agriculture (a) and food manufacturing (b)

**Table 1** Top three embodied energy suppliers and consumers

| Energy | 2011    |                | 2015        |                |             |
|--------|---------|----------------|-------------|----------------|-------------|
|        | No.     | Supply-Consume | Amount (PJ) | Supply-Consume | Amount (PJ) |
| 1      | Man-Ser |                | 31.55       | Man-Ser        | 30.18       |
| 2      | Man-TP  |                | 25.55       | Man-TP         | 30.04       |
| 3      | Ser-TP  |                | 21.28       | Ser-TP         | 24.67       |

**Table 2** Top three embodied CO<sub>2</sub> suppliers and consumers

| CO <sub>2</sub> | 2011    |                | 2015                       |                |                            |
|-----------------|---------|----------------|----------------------------|----------------|----------------------------|
|                 | No.     | Supply-Consume | Amount (10 <sup>4</sup> t) | Supply-Consume | Amount (10 <sup>4</sup> t) |
| 1               | Man-Ser |                | 226.21                     | Man-Ser        | 293.16                     |
| 2               | Man-TP  |                | 190.11                     | Man-TP         | 238.24                     |
| 3               | Ser-TP  |                | 176.65                     | Tel-Ser        | 201.98                     |

### 4.3 Embodied Flows for Energy-Water-CO<sub>2</sub>

In Tables 1 and 2, Man is the largest embodied energy user and carbon emitter from 2011 to 2015. Manufacture (Man), Services (Ser), and Transport and Post (TP) have

**Table 3** Top three embodied water suppliers and consumers

| Water No. | 2011           |                             | 2015           |                             |
|-----------|----------------|-----------------------------|----------------|-----------------------------|
|           | Supply-Consume | Amount ( $10^4\text{m}^3$ ) | Supply-Consume | Amount ( $10^4\text{m}^3$ ) |
| 1         | Man-Ser        | 3423.28                     | Man-Ser        | 3518.29                     |
| 2         | Tel-Ser        | 2308.38                     | Man-TP         | 2424.02                     |
| 3         | Ser-Tel        | 1178.2                      | Min-EGW        | 1661.21                     |

**Table 4** Resource use efficiency

| Sectors | Energy use efficiency (GJ/million yen) |       |       | Water use efficiency ( $\text{m}^3$ /million yen) |       |           |
|---------|--|-------|-------|---|-------|-----------|
|         | 2011                                   | 2015  |       | 2011  | 2015  | 2015–2011 |
| Agr     | 13.59                                  | 7.23  | −6.35 | 0.30  | 1.03  | 0.73      |
| Min     | 14.80                                  | 19.02 | 4.22  | 2.53  | 2.14  | −0.39     |
| Man     | 5.01                                   | 4.03  | −0.98 | 0.96  | 0.80  | −0.16     |
| Con     | 2.90                                   | 2.23  | −0.67 | 0.77  | 0.70  | −0.07     |
| EGW     | 11.18                                  | 9.03  | −2.15 | 13.81   | 28.99 | 15.18     |
| WR      | 1.81                                   | 1.80  | −0.01 | 2.47  | 1.21  | −1.26     |
| FI      | 0.55                                   | 0.66  | 0.11  | 1.42  | 1.01  | −0.41     |
| RE      | 0.68                                   | 0.58  | −0.11 | 0.50  | 0.48  | −0.02     |
| TP      | 27.65                                  | 20.33 | −7.33 | 4.31  | 5.41  | 1.11      |
| Tel     | 0.76                                   | 0.62  | −0.13 | 1.18  | 0.85  | −0.33     |
| Ser     | 2.61                                   | 2.54  | −0.07 | 4.94  | 4.18  | −0.76     |

always been the top three consumers of embodied energy and carbon emissions. The largest embodied energy user and carbon emitter in 2011 was Services (Ser), followed by Transport and Post (TP) and Manufacture (Man), because of huge demand for the goods trade. In Table 3, Service (Ser) and Electricity, Gas and Water (EGW) were the biggest water users because of the functions of providing public bath services and cooling water for power generation facilities, respectively. The top three embodied energy and carbon supply-consumption flows pairs all existed in Man-Ser, Man-TP, and Ser-TP. Ser and TP were the biggest source of demand for intermediate products from Man, in line with their sectoral features and raw materials demand. As a major embodied carbon emitter, Man has traditionally been the largest sector. The biggest supply-consumption flows pair is Man-Ser in embodied water.

#### 4.4 Resource Use Efficiency and Its Change

Resource use efficiency is calculated by taking resource consumption divided by total production value. This is calculated for 2011 and 2015, respectively. In Table 4, we find that the energy use efficiency of Transport and Post (TP), Agriculture (Agr) and Electricity, Gas, and Water (EGW) decreased quickly by 7.33, 6.35, and 2.15, respectively. However, the intensity of Mining (Min) and Finance and Insurance

**Table 5** Resource use efficiency per thousand employees

| Sectors | Energy use efficiency per thousand capita<br>(GJ/million yen/thousand employees) |        |           | Water use efficiency per thousand capita<br>(m <sup>3</sup> /million yen/thousand employees) |        |           |
|---------|--|--------|-----------|--|--------|-----------|
|         | 2011   | 2015   | 2015–2011 | 2011   | 2015   | 2015–2011 |
| Agr     | 3.3940   | 1.7524 | −1.6416   | 0.0756   | 0.2491 | 0.17342   |
| Min     | 6.4796   | 9.1026 | 2.62294   | 1.1069   | 1.0253 | −0.08160  |
| Man     | 0.0054   | 0.0056 | 0.00021   | 0.0010   | 0.0011 | 0.00008   |
| Con     | 0.0058   | 0.0048 | −0.00100  | 0.0015   | 0.0015 | −0.00004  |
| EGW     | 0.3083   | 0.3322 | 0.02398   | 0.3808   | 1.0665 | 0.68562   |
| WR      | 0.0009   | 0.0009 | −0.00004  | 0.0013   | 0.0006 | −0.00068  |
| FI      | 0.0013   | 0.0016 | 0.00028   | 0.0035   | 0.0025 | −0.00097  |
| RE      | 0.0020   | 0.0017 | −0.00029  | 0.0014   | 0.0014 | −0.00005  |
| TP      | 0.0543   | 0.0426 | −0.01171  | 0.0085   | 0.0113 | 0.00289   |
| Tel     | 0.0009   | 0.0007 | −0.00014  | 0.0014   | 0.0010 | −0.00036  |
| Ser     | 0.0006   | 0.0006 | −0.00007  | 0.0012   | 0.0010 | −0.00028  |

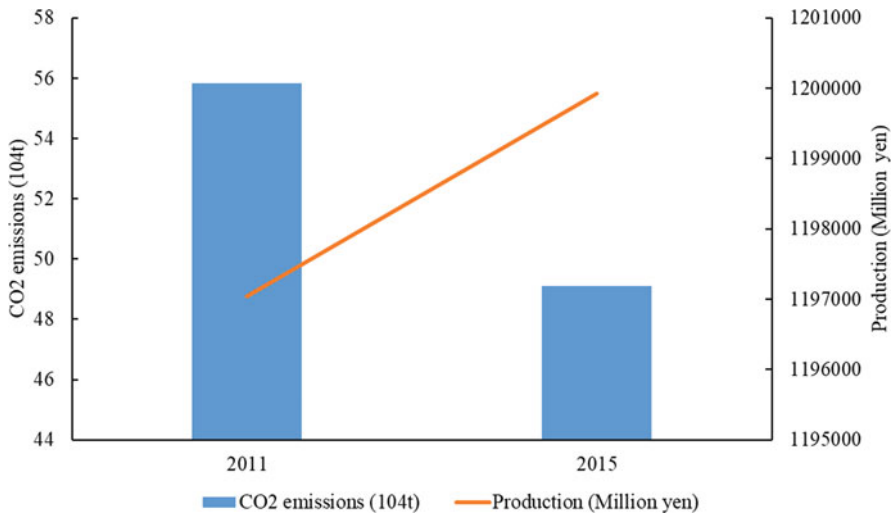
(FI) increased, especially Mining (Min), by 4.22. Water use intensity increased in Transport and Post (TP), Agriculture (Agr), and Electricity, Gas, and Water (EGW). Water use efficiency, particularly in Electricity, Gas, and Water (EGW) was also greatly increased, because the electricity supply of thermal power generation and the demand for cooling water increased rapidly.

Resource use efficiency also means how many resources are consumed per thousand employees for one million yen of production. It not only reflects resource efficiency but also automation level. In Table 5, energy use efficiency per thousand capita of Agriculture (Agr) and Transport and Post (TP) dropped quickly, especially Agriculture (Agr). The reason may be the decline in the urban agricultural population. And energy use efficiency per thousand capita in Mining (Min) and Electricity, Gas, and Water (EGW) increased. The water use efficiency per thousand capita and water use efficiency shows the same trend, except for Manufacture (Man). Compared with resource use intensity, resource use efficiency per thousand capita decreased in Manufacture (Man), because more than 50% of manufacturing companies with more than 100 employees have moved out of Tokyo to other areas (Bureau of Industrial and Labor Affairs 2006).

## 5 Discussion

### 5.1 Resource Consumption and Emissions in Tokyo

According to the Fig. 5, we find that from 2011 to 2015, resource use had a negative correlation with Tokyo's economic development, while carbon emissions had a positive correlation. Tokyo's total sector production value increased by 16.1% from 2011 to 2015, but total direct energy consumption decreased by 3.6%, water



**Fig. 5** Carbon emissions and production values in Tokyo from 2011 to 2015

use remained unchanged, and carbon emissions increased by 24.8%. These findings suggest that while Tokyo maintained economic growth, the energy structure changed because of the Great East Japan Earthquake, leading to increased carbon emissions. In addition, total indirect consumption and emissions are higher than direct consumption and emissions, and embodied energy consumption and carbon emissions are nearly two times the city's direct consumption and emissions. Factors in this phenomenon may be that traditional production sectors declined relatively as the population growth, tertiary industries developed rapidly, and increased citizen demand for goods results in increased indirect consumption, while Tokyo implemented its "Zero Emission Tokyo Strategy" policies.

More and more education and scientific research, medical services, and various service industries (accommodation, food and beverage, entertainment, etc.) have concentrated in Tokyo, resulting in increased electricity needs. It is a typical example of a railway-oriented city, where 76% of total fuel consumption comes from transport. In addition, there is a large environmental burden in agriculture and manufacturing; because the local food supply cannot meet local demand, so food must be imported from other areas. As for water consumption, thermal power generation increased due to the shutdown of nuclear power stations after the Great East Japan Earthquake. To maintain a steady supply of electricity, the thermal power generation needed a lot of water for cooling, resulting in a doubling of water consumption. And a large number of high-energy consumption products are consumed for manufacturing production in the typical process industries such as steel, brick and tile, and cement (Xu et al. 2021).

## 5.2 *Food System in Tokyo*

The average age of farmers has increased from 62 to 64 between 2000 and 2015, while the numbers of farmers and food manufacturing employees has decreased. As a result of this aging population and subsequent labor shortage, local food production decreased, while the population of Tokyo increased.

Although there is little cultivated land in Tokyo, there are still professional farmers, mainly producing vegetables and fruits. Vegetable growing consumed 11% of water and energy in 2011, as shown in Fig. 4a. And we can find that energy and water demand of agricultural service has increased rapidly from 2011 to 2015. This may be related to the promotion of smart agricultural technology in Tokyo, which, despite the large initial investment required, can greatly improve farming efficiency.

In food manufacturing, water and energy consumption are mainly concentrated in staple foods, condiments and other grocery products (frozen foods, fast foods, etc.), as shown in Fig. 4b. Because the food supply in Tokyo mainly depends on imports, in order to feed 14 million people, it is necessary to refrigerate a large number of vegetables, fruits, and meat. As a result, frozen foods and fast foods consume more than 36% of energy and water.

In the food system, especially in a mega-city, we should not only focus on the food supply, because local production is only a small part and the rest mainly comes from outside Tokyo. Food consumption is a vital research topic, because more than 80% of energy use, water use and carbon emissions comes from food demand, especially eating in the restaurant (Fig. 3). How to reduce resource consumption in the restaurant industry is crucial for carbon reduction in the Tokyo food system.

## 5.3 *Policy Recommendations*

According to the research results, the energy consumption of Service (Ser) and Manufacture (Man) showed a great difference: indirect consumption was more than two times direct consumption. A similar result was seen in the water utilization and carbon emissions of the two sectors. Therefore, in Service (Ser) and Manufacture (Man), there should be greater consideration of energy and water conservation and carbon emissions reduction methods. Although the energy consumption of Construction (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 buildings made of reinforced concrete (51 years). Because of the short average life expectancy of building structures, much energy and water are consumed, leading to high carbon emissions. A key objective to minimize consumption and emissions of the Construction (Con) sector should thus be to improve the technology and technical standards of housing construction.

In Electricity, Gas, and Water (EGW) supply, energy use and carbon emissions dropped, because the Tokyo Waterworks Bureau has been working to reduce energy consumption by replacing existing pumping equipment and lighting with high-efficiency equipment. At the same time, they have been reducing CO<sub>2</sub> emissions by installing power generation equipment that uses renewable energy sources such as solar power and small-scale hydroelectric power. For water consumption, Electricity, Gas, and Water (EGW) and Transport and Post (TP) display a tendency that is contrary to other sectors. For Electricity, Gas, and Water (EGW), the Great East Japan Earthquake is the main reason for the increase in water demand. Therefore, how to improve efficiency of electricity and water supply is a key point to reduce water use pressures.

The largest direct carbon emissions come from Transport and Post (TP). Relieving environmental stress from this sector can be effectively accomplished by promoting innovation in the automotive through various subsidy policies. According to the results of studying energy consumption, Transport and Post (TP), the largest the direct energy consumer, dropped 10% from 2011 to 2015. In 2010, the Japanese Ministry of Economy, Trade and Industry (METI) announced “Next-Generation Vehicle Strategy 2010,” it promoted hybrid electric vehicles and electric vehicles. It was projected that through private-sector efforts alone, next-generation vehicles would make up less than 20% of new passenger car sales in 2020, and 30% to 40% in 2030. Meanwhile, government targets based on implementation of effective incentives aimed for 20% to 50% by 2020 and 50% to 70% by 2030. The national government reported that the number of electric vehicles, fuel cell vehicles and plug-in hybrid vehicles increased by 370% from 2011 to 2015. In addition, the Tokyo government proposed its “Automotive Environmental Management Plan” in 2011, in which companies in Tokyo that have a fleet of more than 30 vehicles should replace their traditional cars with low-emission and fuel-efficient vehicles. During this period (2011–2015), the carbon emissions of these companies decreased 8%.

From the standpoint of resource trading between sectors, suppliers and consumers have respective roles to save energy and water, and to reduce carbon emissions. For instance, the biggest embodied energy and carbon consumers in Tokyo have been Service (Ser), Transport and Post (TP), and Manufacture (Man). These three sectors therefore have the most opportunity to undertake steps to save energy and reduce carbon emissions. Meanwhile, Service (Ser), Electricity, Gas, and Water (EGW), Telecommunications (Tel), and Manufacture (Man) are the biggest embodied water consumers and have larger opportunities and responsibilities than other sectors for water saving. For embodied energy and CO<sub>2</sub>, the main suppliers/consumers were Man-Ser, Man-TP, and Ser-TP, while Man-Ser, Tel-Ser, and Ser-Tel were the major supplier/consumer pairs for embodied water. The significant correlation impact between these sectors reveals the main paths to formulate energy conservation, water saving, and carbon-reduction methods.

## 6 Conclusions

This study evaluated energy, water, and CO<sub>2</sub> flows through environmental input–output analysis using 2011 and 2015 data at the sector and product level in Tokyo. Direct and indirect process analyses of the urban system showed 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 CO<sub>2</sub> emissions from this sector, especially in the catering and public bath industries. Efforts targeting these services could help meet emissions reduction targets, guided by strategic policies established in the Zero Emissions Tokyo Strategy for 2050. In addition, direct and indirect energy consumption and carbon emissions from manufacturing showed a great variance. Most energy consumption and CO<sub>2</sub> emissions are indirect, as most manufactured products are needed by households, governments and for exports. Transportation dominated the list of direct energy consumption sectors, suggesting that a focus on promoting zero emission vehicles (ZEVs) could help reach emissions reduction goals. Manufacturing and services were the main embodied energy users and CO<sub>2</sub> emitters 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. 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 CO<sub>2</sub> emissions in the food system. 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.

These findings prove that the contribution of carbon emissions from FEW is very large. If Tokyo wants to achieve the “Zero Emission Tokyo Strategy” for 2050, the government needs to consider how to reduce carbon emissions in the use of FEW resources.

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