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Estimation of Direct and Indirect Household CO_2 Emissions in 49 Japanese Cities with Consideration of Regional Conditions

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Abstract: We conducted a detailed estimation of direct and indirect CO_2 emissions related to multi-person households in 49 Japanese cities. Direct energy consumption was decomposed into energy use in order to consider the relationship with regional conditions. The results showed that CO_2 emissions from direct energy consumption were almost as large as indirect CO_2 emissions induced by consuming products and services, suggesting that lifestyle improvements are important for both energy savings and reducing CO_2 emissions relating to product and service consumption. In addition, CO_2 emissions from direct energy consumption varied widely between cities, making them susceptible to regional conditions. We also calculated CO_2 emissions from direct energy consumption and examined the regional conditions for individual forms of energy use. CO_2 emissions were higher in cold regions and lower in larger cities. In Japan, large cities are often located in relatively warm areas, so we conducted an analysis to distinguish the effects of climatic conditions from those of urbanization. This analysis allowed us to clarify the effects of regional conditions on factors such as heating/cooling and the ratio of detached houses to apartments.

Keywords: household energy consumption; consumption behaviors; indirect CO_2 emission; regional characteristics; lifestyles; low-carbon society

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1. Introduction

The growing severity of global warming has made reducing CO_2 emissions resulting from daily human activities an increasingly important issue [1–3]. In recent years, local governments have been required to take detailed measures [4], and it is necessary to further consider effective CO_2 reduction measures at the individual level.

In the residential sector, a large proportion of total CO_2 emissions originate from the use of heating/cooling units and hot water, highlighting that climate is an important factor in such assessments [5–7]. The size and density of urban areas is also important as residential housing characteristics and availability of city gas have significant effects. As such factors vary widely between different cities and regions, it is important to better define CO_2 emissions from residential housing according to regional characteristics and introduce regionally appropriate measures. Whilst many studies have considered energy consumption and CO_2 emissions at the household scale [8–11], these are insufficient to understand the broader effects of urban conditions, such as climate and housing density. Individual surveys of energy consumption at home can provide detailed information on energy usage and construction style, but these require significant cost and labor, making it difficult to conduct

widespread surveys in multiple cities. Therefore, it is necessary to establish a method to macroscopically assess CO_2 emissions from various urban conditions based on existing statistical information.

It is also important to better define indirect CO_2 emissions resulting from daily human activities [12–14]. Many urban environmental studies have focused on analyzing the effects of human behavior on energy consumption to propose low-carbon and energy-saving lifestyles [15–30]. Although this knowledge has been incorporated into environmentally conscious citizen behavior and government awareness campaigns [31,32], most of these studies have focused only on direct energy consumption behaviors, such as air-conditioning or public transportation usage. In contrast, CO_2 emissions in the industrial sector are higher than those in the building and transportation sectors [33]. Thus, serious consideration should be given to reducing indirect CO_2 emissions from consumer activity, such as suppressing excessive waste of products and services [34–38].

Such studies require an understanding of CO_2 emissions for the entire supply chain and should consider measures to reduce CO_2 emissions from consumption behavior across multiple sectors [39]. In many instances, alternative consumption behaviors extend beyond individual sectors. For example, meals may involve home cooking (residential sector), food processing facilities (industrial sector), or restaurants (commercial sector), while bathing may involve home water heaters (residential sector) or public baths (commercial sector). Therefore, studies of consumption must consider both direct and indirect CO_2 emissions for equal comparison. However, compared to the vast amount of existing research aimed at reducing CO_2 emissions due to direct energy consumption, few studies have evaluated indirect CO_2 emissions in the context of individual behavior. This makes it necessary to further define human behavioral factors related to CO_2 emissions and low-carbon lifestyles, including indirect CO_2 emissions, and propose realistic measures for further CO_2 reduction.

In this study, we conducted detailed estimates of direct and indirect CO_2 emissions on a regional scale using data from 49 Japanese cities (Figure 1). In these cities, energy consumption could be determined using the Family Income and Expenditure Survey [40]. We also decomposed direct energy consumption into energy use by using the methods given in Hirano et al. [41] in order to consider relationships with regional conditions. In order to best consider consumer energy conservation measures, we regarded CO_2 emissions associated with energy consumption as CO_2 emissions due to direct energy consumption. For this reason, CO_2 emissions from power plants were considered to be CO_2 emissions from direct energy consumption by consumers. Similarly, CO_2 emissions from gas and kerosene consumption, as well as consumption-induced CO_2 emissions from refining and transportation, were considered to be CO_2 emissions from direct energy consumption. As the Family Income and Expenditure Survey does not contain data for single-person households at the city scale, only CO_2 emissions from multi-person households were considered in this study.
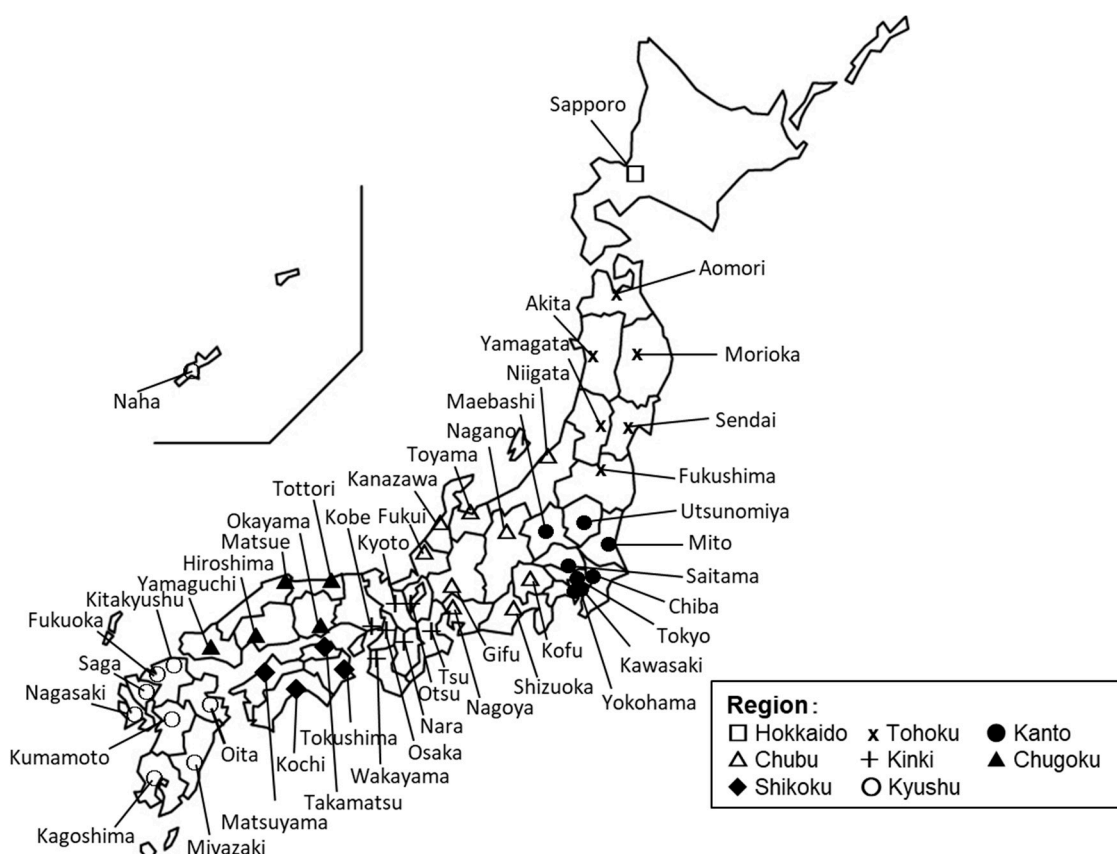
Sapporo

Aomori
Akita
Yamagata
Niigata　　Morioka
Maebashi
Nagano　　Sendai
Toyama
Tottori　Kanazawa　　Fukushima
Okayama　Kobe Fukui　Utsunomiya
Matsue　　Kyoto　Mito
Hiroshima　　　Saitama
Yamaguchi　　Chiba
Kitakyushu　　Tokyo
Fukuoka　　Gifu　Kofu　Kawasaki
Saga　　Tsu
Nagasaki　Otsu　Shizuoka　Yokohama
Nara　Nagoya
Kumamoto　Oita　Kochi　Osaka
Tokushima　Wakayama
Takamatsu
Kagoshima　Matsuyama
Miyazaki

Naha

Region:
□ Hokkaido　x Tohoku　● Kanto
△ Chubu　　+ Kinki　　▲ Chugoku
◆ Shikoku　○ Kyushu

Figure 1. Distribution of the 49 Japanese cities considered in this study.

2. Estimation Method

We estimated CO_2 emissions using the workflow shown in Figure 2. Previous studies have estimated CO_2 emissions from consumer behavior using various types of statistical data, such as input–output tables and consumption expenditure data [39,42,43]. In this study, we incorporated a usage decomposition method that considered the influence of regional conditions on direct energy consumption [41] and applied these to the consumption data for the 49 cities. This approach is based on Hirano et al. [43] and uses CO_2 emissions per unit of value estimated using input–output tables and the Embodied Energy and Emission Intensity Data for Japan (3EID) [44]. We used the input–output table from the basic classification table in the basic input–output table of 2005, similar to Hirano et al. [43]. As it is difficult for wholesale and retail data in the input–output table to correspond to specific household consumption expenditures, the industrial sector margin (commercial margin) was set, and the total output was allocated based on the wholesale/retail margin of each industrial sector. As the input–output table was composed of 520 rows and 407 columns, these were aggregated into a square matrix to calculate the inverse matrix. The industrial sector classification was then set to 403, in accordance with 3EID. Based on the resulting input–output table, we calculated the inverse matrix coefficient of the $[I-(IM)A]^{-1}$ type, then multiplied this by the direct CO_2 emission intensity from 3EID. This provided the indirect CO_2 emission intensity from household consumption expenditure. Direct CO_2 emissions were calculated from the direct CO_2 emission intensity based on the 3EID and domestic production values. We then calculated the indirect CO_2 emission for each item of consumption expenditure using indirect CO_2 emission intensity and household consumption expenditures.

The CO_2 estimation model of Hirano et al. [41] was used to develop a sub-model to estimate CO_2 emissions when direct energy consumption was decomposed into energy use based on regional conditions. In this model, estimation equations created individually or known estimation equations for various factors related to CO_2 emission are incorporated into the calculation. Then, by combining these

estimation equations, total CO_2 emissions for each energy use are estimated (Figure 3). However, for fuel, The CO_2 estimation model [41] only counted in situ CO_2 emissions calculated from fuel consumption and CO_2 emission intensity of each fuel. For power, it only counted CO_2 emissions from power plant efficiency calculated from power generation efficiency and CO_2 emission intensity. On the other hand, our estimation method counted CO_2 emissions related to fuel refining and transportation, and CO_2 emissions associated with power consumption at power plants, as CO_2 emissions due to direct energy consumption. Therefore, when incorporating these into total CO_2 emissions, including indirect CO_2 emissions (Section 3), we divided them into energy use by proportional allocation. The full details of this method are provided in Hirano et al. [41].
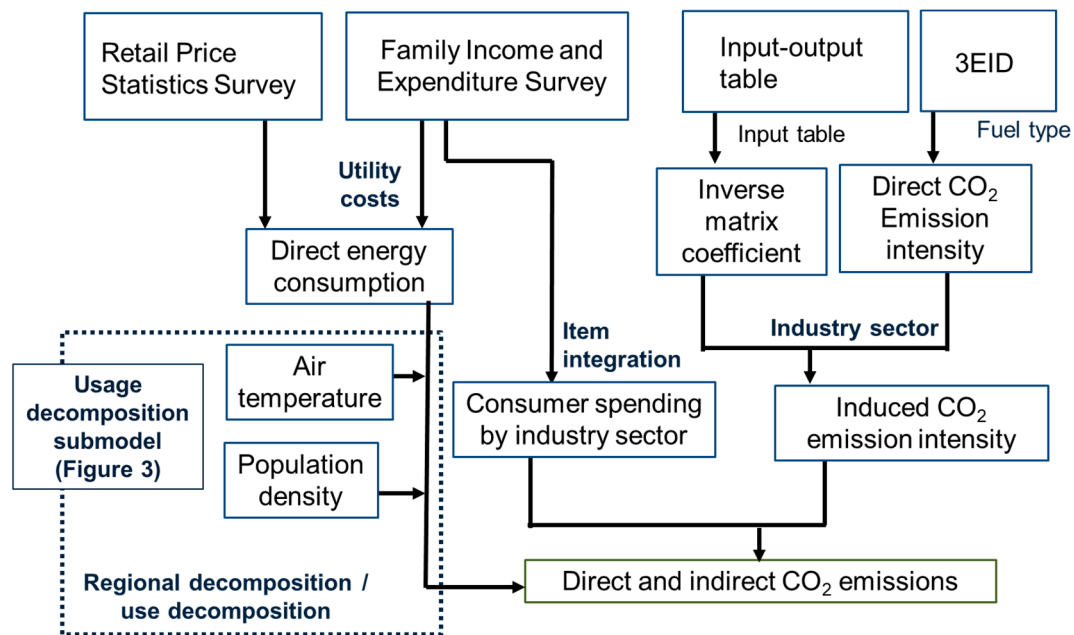

Figure 2. CO_2 emission estimation workflow used in this study.

First, for space heating and cooling, energy consumption was estimated based on estimation equations by Sawachi et al. [9]. They investigated residential energy consumption in major cities across Japan with the number of valid samples of 2169 in the summer survey and 1675 in the winter survey. Based on the survey data, they analyzed the relationship between heating/cooling energy consumption and climatic conditions, and obtained the following equation by non-linear regressions (Equations (1)–(4)):

$$E_{dh} = 1.25 \cdot 10^{-14} \cdot D_h{}^5 - 3.49 \cdot 10^{-4} \cdot D_h{}^2 + 2.15 \cdot D_h - 155 \tag{1}$$

$$E_{ah} = 2.26 \cdot 10^{-11} \cdot D_h{}^4 - 1.01 \cdot 10^{-4} \cdot D_h{}^2 + 0.748 \cdot D_h + 25 \tag{2}$$

$$E_{dc} = 1.12 \cdot 10^{-3} \cdot D_c{}^2 + 0.621 \cdot D_c + 18 \tag{3}$$

$$E_{ac} = 1.91 \cdot 10^{-4} \cdot D_c{}^2 + 0.798 \cdot D_c + 21 \tag{4}$$

where E is secondary energy consumption (Mcal/year) (*dh*, detached house heating; *ah*, apartment heating, *dc*, detached house cooling; *ac*, apartment cooling), D_h is heating degree days ($D_{18–18}$), and Dc is cooling degree days ($D_{24–24}$). The heating degree days ($D_{18–18}$) was defined as the cumulative total of the difference between 18 °C and the average daily temperature on days when the average daily temperature was less than 18 °C. The cooling degree days ($D_{24–24}$) was defined as the sum of the difference between 24 °C and the daily average temperature on days when the daily average temperature exceeds 24 °C. In the regression analysis of Sawachi et al. [9], multiple correlation coefficients $R = 0.99$, 0.91, 0.94, and 0.78 were obtained in Equations (1)–(4), respectively. In Japan, although district heating and cooling are installed in some dense commercial and business areas,

they are rarely installed in residential areas. As such, district heating and cooling was not considered in this model.
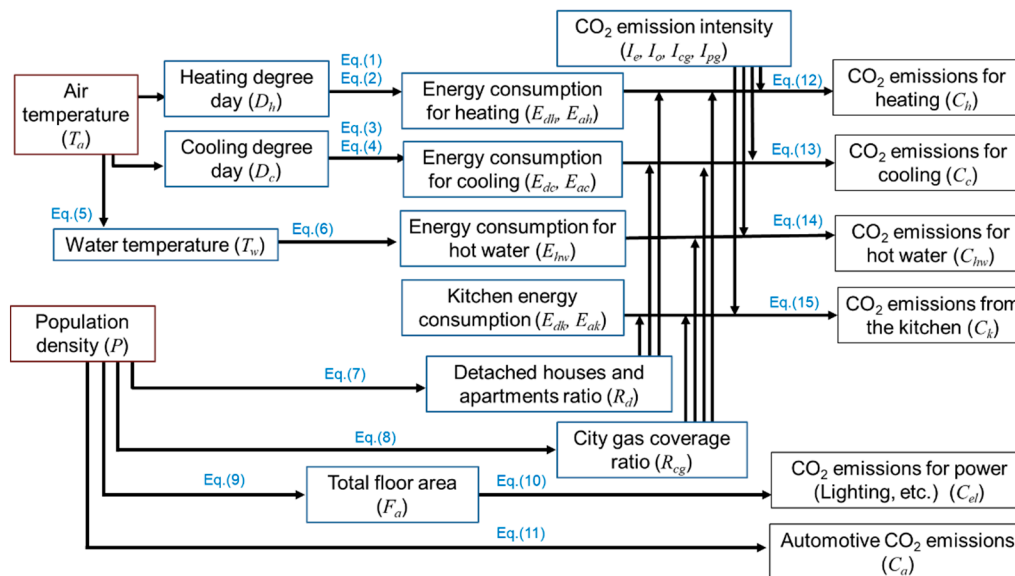

Figure 3. Calculation workflow of the direct CO_2 emissions estimation sub-model.

For hot water, the water temperature was calculated from air temperature using Equation (5) [11], and energy consumption was calculated using Equation (6) [45]:

$$T_w = 0.7{\cdot}T_a + 7.0 \tag{5}$$

$$E_{hw} = V{\cdot}c_\rho{\cdot}(T_{hw} - T_w)/\eta \tag{6}$$

where T_a is temperature, E_{hw} is energy consumption for hot water, V is the amount of hot water used, T_{hw} is the hot water temperature, T_w is the water supply temperature, c_ρ is the volumetric heat capacity of water, and η is equipment efficiency. Although Equation (5) is an empirical formula, it is well known that the air temperature and the water temperature are linked, and it is a commonly used equation.

For cooking, the effect of air temperature was ignored, this was set as 4000 (MJ/household) for detached houses and 3700 (MJ/household) for apartments based on consumption per household, as presented in the existing survey data [9].

Urban density affects CO_2 emissions in a variety of ways, such as the proportion of detached houses to apartments and the coverage ratio of city gas. We used population density as the parameter best representing urban density. Relationship between the ratio of houses to apartments (derived from the Population Census [46]), and the coverage ratio of city gas (derived from the purchase frequency of purchased city gas and liquid petroleum (LP) gas in the Family Income and Expenditure Survey) and the population density of each city are shown in Figures 4 and 5, respectively. These relationships were approximated by the following estimation formulas (Equations (7) and (8)):
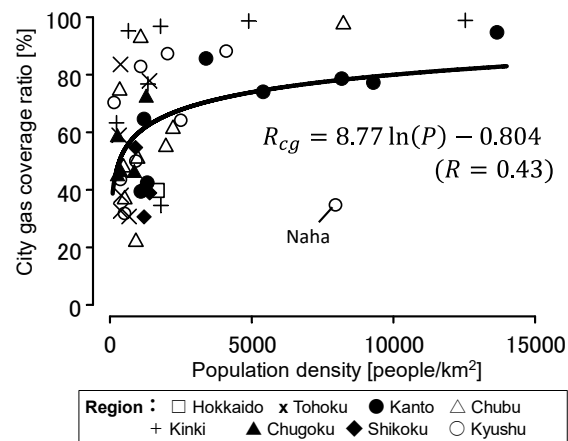
$$R_d = -9.09\ln(P) + 116 \tag{7}$$

$$R_{cg} = 8.77\ln(P) - 0.804 \tag{8}$$

where R_d is the detached house ratio (%), P is the population density (people/km^2), and R_{cg} is the city gas coverage ratio (%).
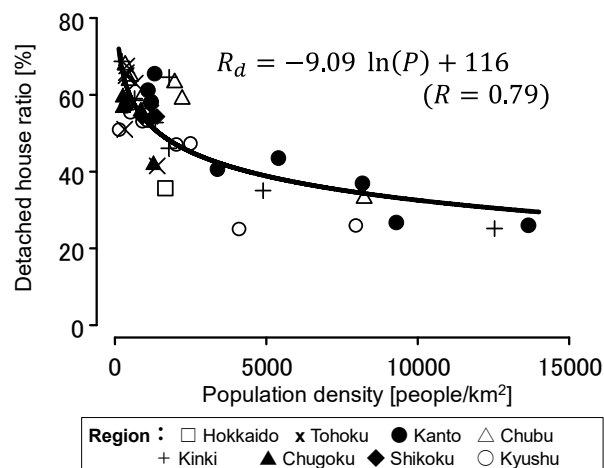
Figure 4. Relationship between the detached house ratio and the population density (modified from Hirano et al. [41]).
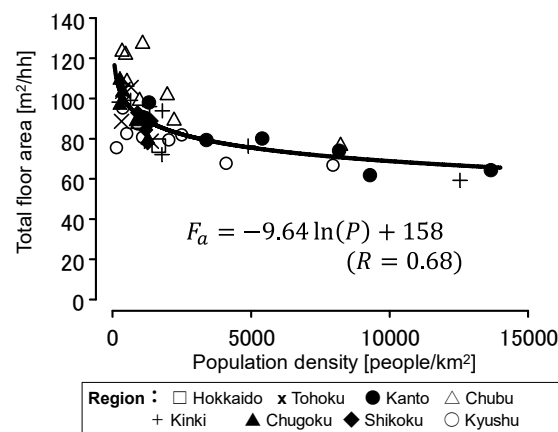

Figure 5. Relationship between the city gas coverage ratio and the population density (modified from Hirano et al. [41]).

For other types of power consumption (e.g., lighting), we excluded the heating and cooling usage previously measured by calculating electricity consumption during intermediate seasons (spring and fall) using monthly values from the Family Income and Expenditure Survey and applying these values to summer and winter. As mentioned above, population density is used as an index to represent the density of cities. Although it is possible to directly relate CO_2 emissions to population density empirically, it is more important to clarify the causal mechanisms for developing a general model. Therefore, we focused on the total floor area of the house, which is related to CO_2 emissions. The relationship between population density and floor area and the relationship between floor area and CO_2 emissions are shown in Figures 6 and 7, respectively. Estimation formulas were subsequently developed for power consumption based on the population density (Equations (9) and (10)):
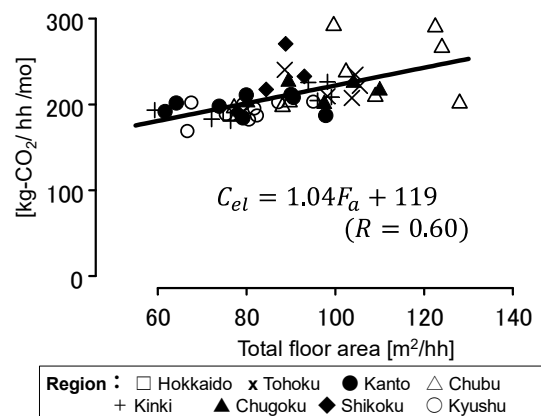
$$F_a = -9.64 \ln(P) + 158 \tag{9}$$

$$C_{el} = 1.04 F_a + 119 \tag{10}$$

where F_a is the total floor area per household (m^2/household), and C_{el} represents the CO_2 emissions from electricity consumption during intermediate seasons (kg CO_2/household/month).

Figure 6. Relationship between the total floor area per household and the population density (modified from Hirano et al. [41]).

Figure 7. Relationship between the CO_2 emissions during intermediate seasons and the total floor area (modified from Hirano et al. [41]).

We estimated CO_2 emissions from vehicle use based on the gasoline consumption calculated from the Family Income and Expenditure Survey. Relationship between the automotive CO_2 emissions and the population density is shown in Figure 8. An estimation formula was then developed for gasoline consumption by cars as a function of population density (Equation (11)):

$$C_a = -228 \ln(P) + 2780 \tag{11}$$

where C_a represents automotive CO_2 emissions from gasoline consumption (kg CO_2/household/year).

The source of energy used (i.e., electric or gas) was pre-determined by Hirano et al. [41] based on surveys of various existing sources (see Table 1). The CO_2 emission intensity for each energy source was also set with reference to Hirano et al. [41], as shown in Table 2.

Table 1. Setting values of energy source configuration [41].

Energy Applications	Households Using City Gas	Households Using LP Gas
Space heating	City gas: 30% Kerosene: 50% Electricity: 20%	Kerosene: 80% Electricity: 20%
Space cooling	Electricity: 100%	Electricity: 100%
Hot water	City gas: 100%	LP gas: 40% Kerosene: 60%
Cooking	City gas: 100%	LP gas: 100%
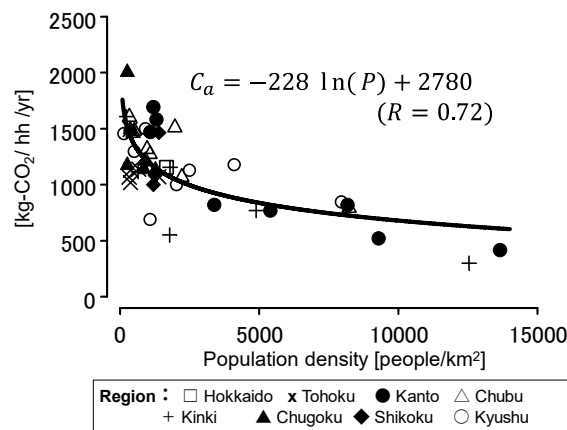
Figure 8. Relationship between the automotive CO_2 emissions and the population density (modified from Hirano et al. [41]).

Table 2. Setting values of CO_2 emission intensity.

Energy Source	CO_2 Emission Intensity (kg-CO_2/MJ)
Electricity (secondary energy)	0.1541
Kerosene	0.0678
City Gas	0.0511
LP gas	0.0600

Using the above values, we calculated the CO_2 emissions of heating, cooling, hot water, and kitchen by the following Equations (12)–(15).

$$C_h = E_{dh} \cdot R_d \cdot (0.8 \cdot I_o + 0.2 \cdot I_e) \cdot \left(1 - R_{cg}\right) + E_{dh} \cdot R_d \cdot \left(0.3 \cdot I_{cg} + 0.5 \cdot I_o + 0.2 \cdot I_e\right)$$
$$\cdot R_{cg} + E_{ah} \cdot (1 - R_d) \cdot (0.8 \cdot I_o + 0.2 \cdot I_e)$$
$$\cdot \left(1 - R_{cg}\right) + E_{ah} \cdot (1 - R_d) \cdot \left(0.3 \cdot I_{cg} + 0.5 \cdot I_o + 0.2 \cdot I_e\right) \cdot R_{cg} \quad (12)$$

$$C_c = E_{dc} \cdot R_d \cdot I_e + E_{ac} \cdot (1 - R_d) \cdot I_e \quad (13)$$

$$C_{hw} = E_{hw} \cdot \left(0.4 \cdot I_{pg} + 0.6 \cdot I_o\right) \cdot \left(1 - R_{cg}\right) + E_{hw} \cdot I_{cg} \cdot R_{cg} \quad (14)$$

$$C_k = E_{dk} \cdot R_d \cdot I_{pg} \cdot \left(1 - R_{cg}\right) + E_{dk} \cdot R_d \cdot I_{cg} \cdot R_{cg} + E_{ak} \cdot (1 - R_d) \cdot I_{pg} \cdot \left(1 - R_{cg}\right) E_{ak} \cdot (1 - R_d) \cdot I_{cg} \cdot R_{cg} \quad (15)$$

where C is CO_2 emissions (kg-CO_2/household/year) (*h*, heating; *c*, cooling; *hw*, hot water; *k*, kitchen), E is energy consumption (MJ/ household/year) (*dk*, detached house kitchen; *ak*, apartment kitchen), I is CO_2 emission intensity (kg-CO_2/MJ) (*e*, electricity; *o*, kerosene; *cg*, city gas; *pg*, LP gas). It should be noted that the model of this study cannot be extrapolated to areas with a lower population density than these 49 cities.

Details of Japan's direct energy consumption are provided in the literature [47–49].

Although the input–output table of 2005 was used to calculate indirect CO_2 emission, since the Family Income and Expenditure Survey [40] is a sample survey, there may be variations due to sampling. Therefore, the average value from 2003 to 2007 was used to develop this model formula. We selected data over this period for analysis, recognizing that there may be a slight time lag from current emissions. This is because Japan experienced significant impacts from the 2008 financial crisis, the 2011 Great East Japan Earthquake, the resulting Fukushima Daiichi nuclear disaster, and the subsequent wide-area evacuation. Although the evacuation areas are now gradually being lifted in the current situation, considering the time lag until statistical data become available, it is difficult to obtain general results in the latest situation. We also compared several datasets on direct energy

consumption in the residential sector [50] and found that inter-annual changes in the household sector were small prior to the financial crisis. Energy consumption may be decreasing due to the widespread use of light-emitting diodes (LEDs) and improved heating and cooling efficiencies of equipment. However, this change is not anticipated to be rapid as it takes time to replace buildings and equipment. In the long term, the model needs to be updated in consideration of the gradual diffusion of these new technologies.

To confirm the validity of the above equations, we compared our calculated CO_2 emissions with those calculated from the Family Income and Expenditure Survey for each city, achieving a correlation coefficient of $R = 0.822$ (Figure 9). The model presented by Hirano et al. [41] aimed to clarify the CO_2 emission structure by expressing it with essential elements rather than incorporating detailed elements in order to improve accuracy. For this reason, CO_2 emissions by use were estimated based only on temperature and population density. Given the approximate nature of such parameterization, this was considered to be a relatively good match. Next, we compared the average CO_2 emission values for the 49 cities by energy source, showing good correspondence (Figure 10).
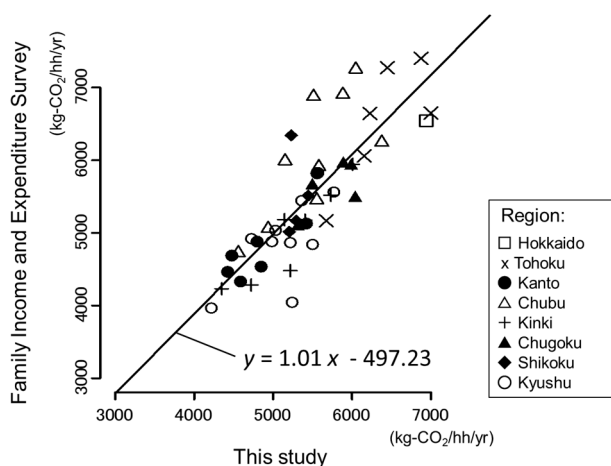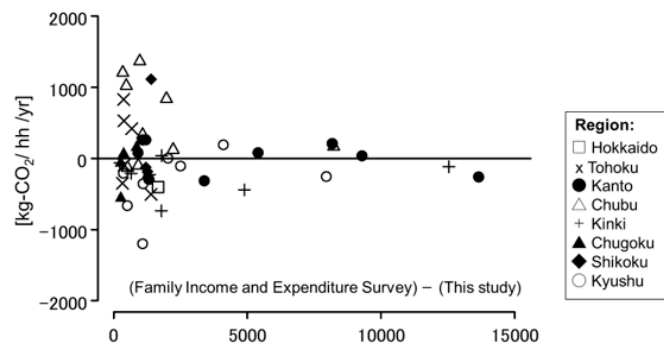

Figure 9. Correlation between CO_2 emissions calculated by this study and the Family Income and Expenditure Survey for 49 cities.
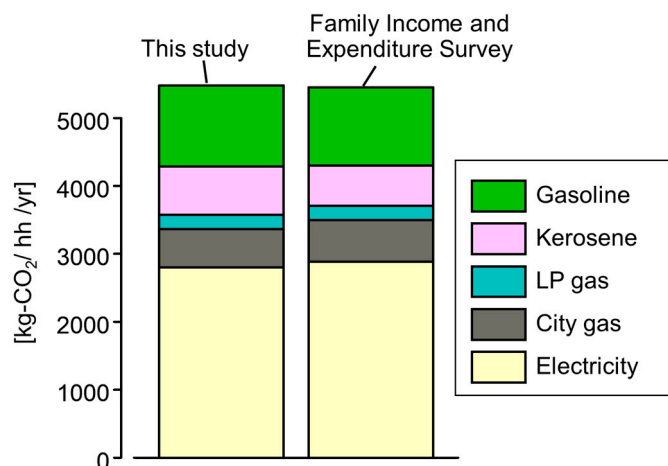
Figure 10. Comparison of CO_2 emissions calculated by this study and the Family Income and Expenditure Survey with the estimated value by energy source.

To confirm that the model is valid for all cities, we plotted the difference between the CO_2 emissions calculated by the model and the CO_2 emissions based on the Family Income and Expenditure Survey, and the population density (Figure 11). From this figure, it can be seen that there are relatively large variations in cities with a population density lower than 3000 (people/km^2). This is because random

variations due to various factors are relatively large in small cities. On the other hand, in medium and large cities with a high population density of more than 3000 (people/km^2), the random variation factors are averaged and the variation is relatively small. As a whole, no clear systematic bias can be seen in Figure 11. The difference between the CO_2 emissions calculated by the model and the CO_2 emissions based on the Family Income and Expenditure Survey are less than -500 (kg-CO_2/household/year) in 5, and more than 500 (kg-CO_2/household/year) in 7 of 49 cities. Other cities are in the range of -500 (kg-CO_2/household/year) to 500 (kg-CO_2/household/year), and it can be said that the results are generally good when compared with the overall variation range shown in Figure 9.

Figure 11. A plot of the difference between CO_2 emissions calculated by this study and the Family Income and Expenditure Survey versus the population density.

3. Estimated CO_2 Emissions for Each City

We calculated CO_2 emissions by consumption behavior for each city (Figure 12). CO_2 emissions were generally higher in colder regions and lower in large cities, including Tokyo and Osaka. When comparing consumption categories, the tendency for CO_2 emissions to be large (especially in cold districts) was well correlated with utilities (i.e., energy and water). Thus, the influence of heating demand for interior spaces and hot water supplies was larger in the relatively colder districts. The inclination of lower CO_2 emissions in large cities was for utilities (i.e., energy and water), and transportation/communication. This is likely due to a higher apartment ratio, widespread public transportation, and the shorter distances traveled. CO_2 emissions from public transport were included in indirect CO_2 emissions, and these were greater in large cities. However, compared to direct CO_2 emissions from automobiles, indirect CO_2 emissions from public transport were very small [51]. This meant that CO_2 emissions were lower in large cities for the transportation and transportation categories.
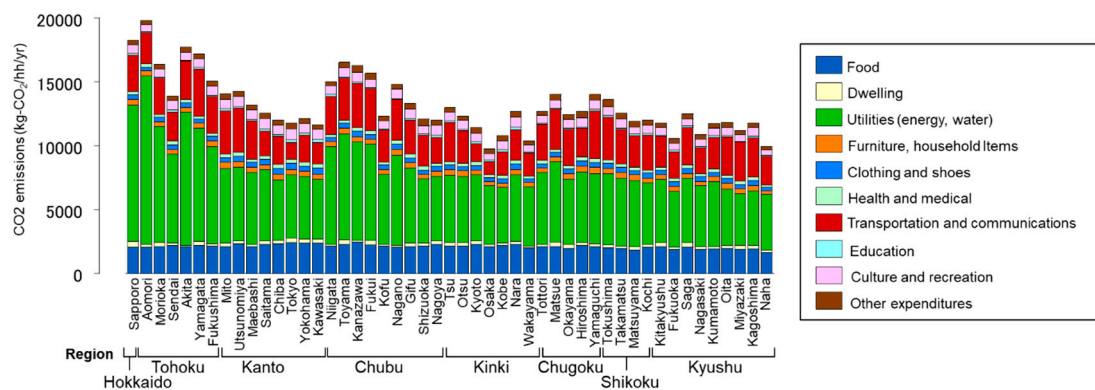
Figure 12. CO_2 emissions by consumption behavior for multi-person households.

A breakdown of direct and indirect CO_2 emissions by region and energy source of direct CO_2 emissions (Figure 13). When CO_2 emissions from electricity consumption and fuel consumption were

considered as CO_2 emissions due to direct energy consumption, there was some variation between cities, though on average, this was comparable to other indirect CO_2 emissions. Both energy saving and indirect CO_2 reductions were equally important in consumption behavior. Moreover, CO_2 emissions from direct energy consumption had greater regional differences than indirect CO_2 emissions. Particularly in cold regions, the level of CO_2 emissions due to kerosene consumption was remarkable. This was consistent with Figure 12, as high CO_2 emissions in cold regions mainly appear to be an effect of heat demand. In addition, CO_2 emissions from areas, including large cities, were lower than other areas due to a reduction in car usage.
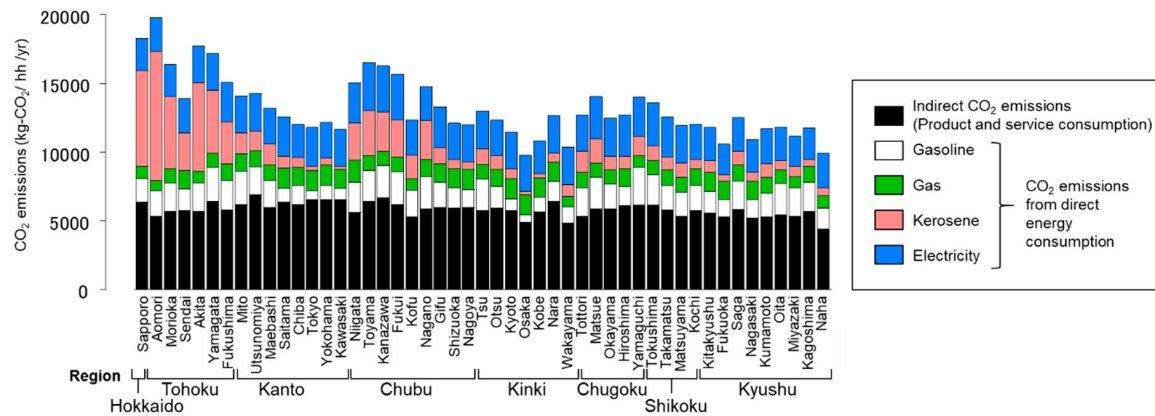
Figure 13. CO_2 emissions by energy source for multi-person households.

Figure 14 shows the results of decomposing CO_2 emissions from energy consumption by consumers into energy use. As described above, the original calculation approach (Figure 3) used only temperature and population density and excluded CO_2 emissions, such as refining and transportation, induced by energy consumption. For this reason, we adjusted the totals to the absolute amount defined in Figures 12 and 13, and only the distribution ratio for each application was calculated using the workflow in Figure 3.
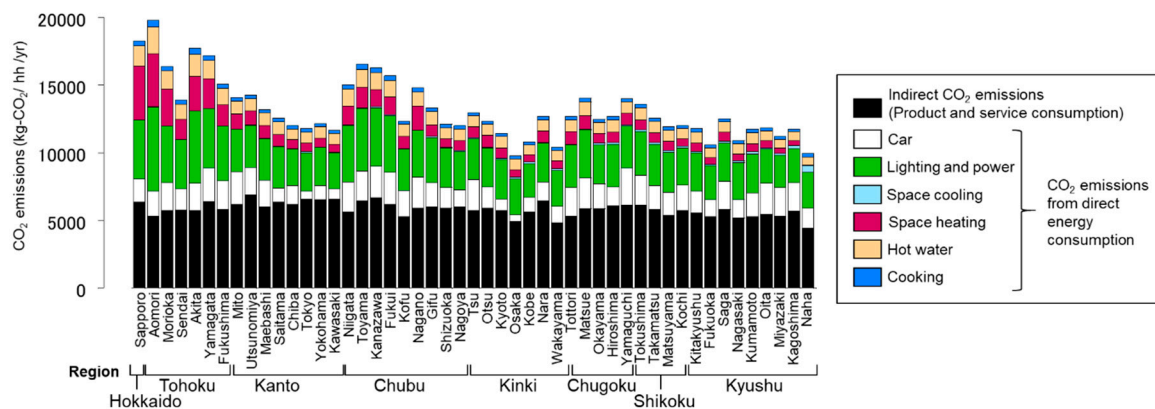
Figure 14. CO_2 emissions by energy use for multi-person households.

CO_2 emissions from lighting and power accounted for approximately half of the CO_2 emissions from direct energy consumption, the largest of any category. Heating demand accounted for most of the rest, while cooling and cooking were relatively minor. These findings suggest that consideration should be given to measures to improve heating supply sources, such as solar heat or cogeneration.

4. Analysis of Regional Conditions for CO$_2$ Emissions from Direct Energy Consumption

The results so far demonstrated that the impact of regional conditions on CO$_2$ emissions from direct energy consumption was significant. Therefore, we analyzed the effects of regional conditions in more detail using the sub-model shown in Figure 3. Although large cities tended to emit less CO$_2$, in Japan, these cities tend to be located in relatively warm regions, making it necessary to distinguish between the effects of urbanization and those of climatic conditions when considering measures to reduce CO$_2$ emissions.

For urban conditions, the ratio of detached houses to apartments had a relatively large effect. However, these were not presented separately in Figures 12–14, preventing an assessment of their individual impact. Therefore, we selected specific major cities and calculated CO$_2$ emissions separately for detached houses and apartments using the same values obtained from the temperature and population density in the equations above (Figure 15). The results showed a large difference between detached houses and apartments in cold regions. This may be related to the relatively low exterior roof and wall area of apartment buildings, which lowers the heating load due to reduced conduction and ventilation. On the other hand, cooling load is significantly affected by factors other than outside air, such as internal heat generation and heat obtained from window surfaces. As a result, these differences did not occur as easily in warm regions as cold regions. In addition, in the average Japanese house, energy consumption for heating is larger than energy consumption for cooling, another factor contributing to the difference between warm and cold regions.
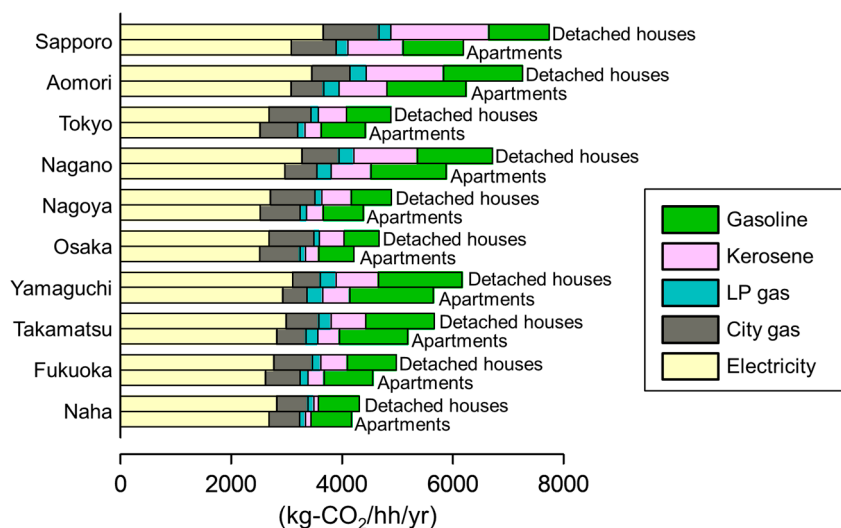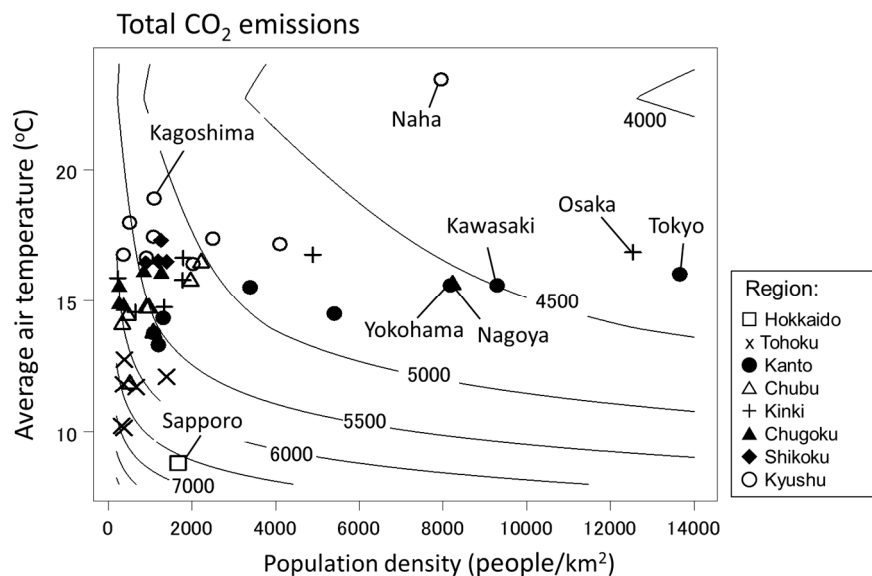

Figure 15. Estimated CO$_2$ emissions for detached houses and apartments.

To more clearly distinguish between the effects of climatic conditions and the effects of urbanization, we considered the relationship between the two on a two-dimensional axis of population density and average temperature. First, we created estimation equations from the average temperatures and degree days in the 49 cities (Figure 16), then used these to approximate the average temperature from the degree days. This made it possible to estimate CO$_2$ emissions in each city using only two variables, average temperature and population density (Figure 3).

We then plotted each city based on population density and average temperature, with the CO$_2$ emissions obtained from equations in Section 2 defined by isolines (Figure 17). Overall, total CO$_2$ emissions were lower in warmer regions because CO$_2$ emissions in Japanese residences were more influenced by heating needs than cooling, and the influence of temperature was more likely to be higher for the former. Above an average temperature of 24 °C, the effect of cooling exceeded the effect of heating, and the isolines changed direction, though this was only applicable to 1 of the 49 cities (Naha).
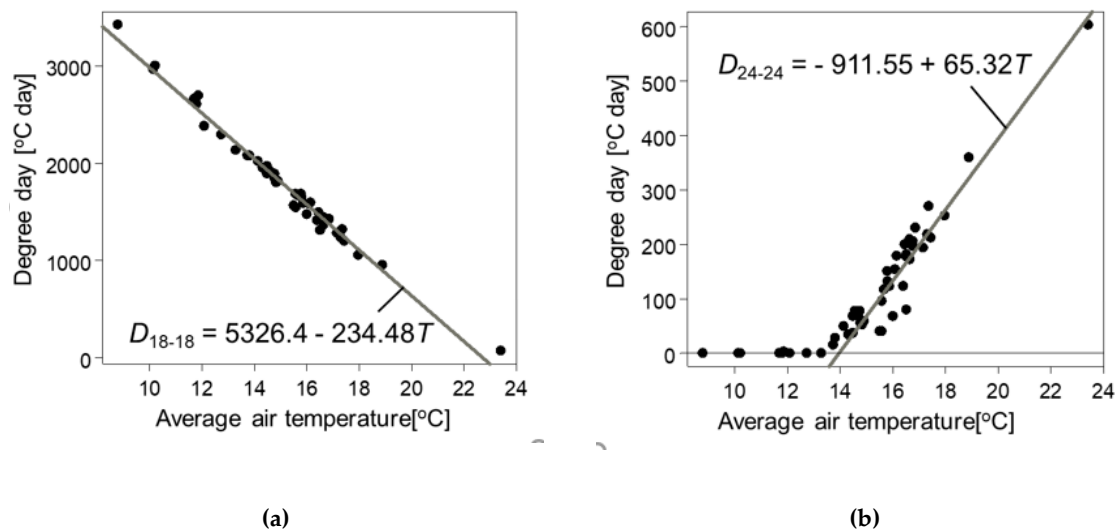
Figure 16. Relationship between average temperature and degree days for the 49 Japanese cities. (**a**) Heating degree days ($D_{18\text{-}18}$); (**b**) Cooling degree days ($D_{24\text{-}24}$).

In figure (a): $D_{18\text{-}18} = 5326.4 - 234.48T$

In figure (b): $D_{24\text{-}24} = -911.55 + 65.32T$

Figure 17. Isolines for total CO_2 emissions calculated from population density and average temperature based on the workflow shown in Figure 3.

We plotted similar results for heating, cooling, and hot water (Figure 18). The average temperature was the dominant factor for both heating and cooling, but population density also had a slight effect as this depends on the detached house to apartment ratio and city gas coverage ratio. For hot water, CO_2 emissions were greater than for cooling, however, the effect of air temperature was smaller than for heating and cooling. These results suggest that CO_2 emissions can be reduced by increasing urban density in cold regions. However, when creating new residential bases, relatively warm regions should be selected as moderate densification will likely lead to lower carbon emissions. Although there is a high possibility that CO_2 emissions can be reduced by appropriately increasing density in current low-density areas, significant reductions cannot be expected even with major increases in density. This result includes suggestive findings when considering location conditions.
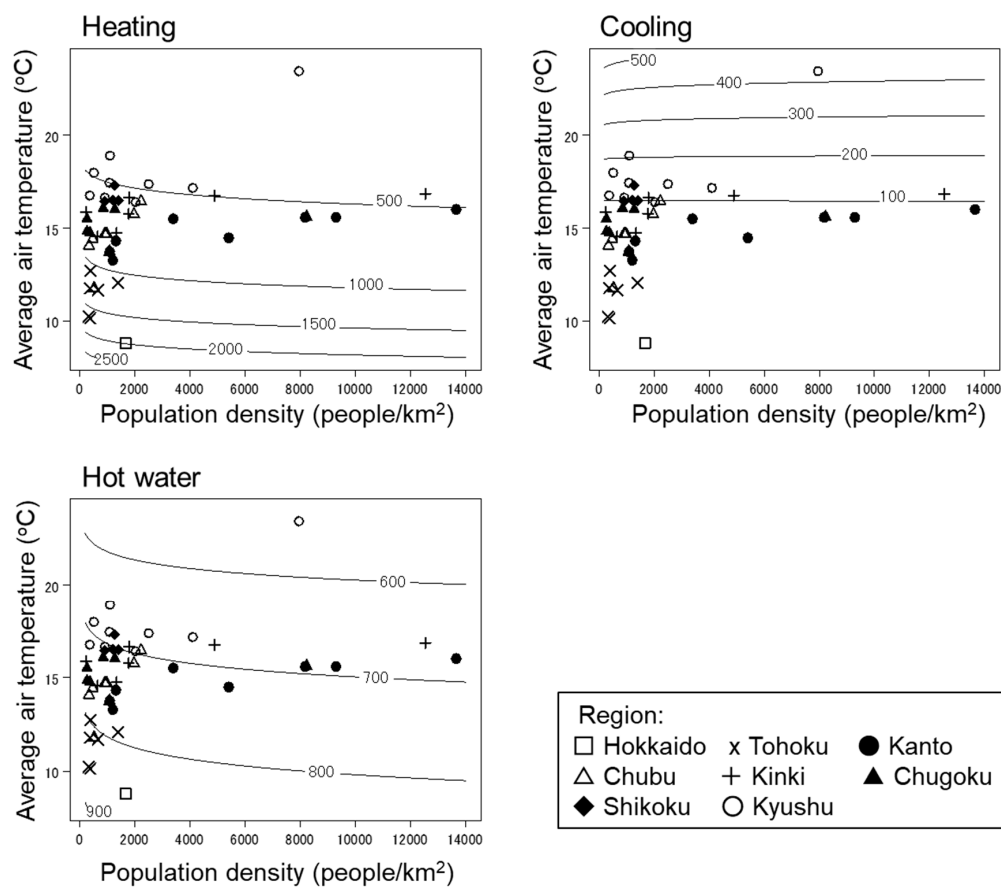
Figure 18. Isolines for CO_2 emissions related to residential heating, cooling, and hot water calculated from population density and average temperature based on the workflow shown in Figure 3.

5. Conclusions

In this study, we calculated CO_2 emissions from the consumption behavior of multi-person households in 49 Japanese cities in order to estimate both direct and indirect CO_2 emissions from product and service consumption in a comparable way. The major difference between regions was CO_2 emissions from direct energy consumption, which were influenced by climatic conditions and urbanization. In addition, indirect CO_2 emissions from product and service consumption were almost as large as CO_2 emissions from direct energy consumption, suggesting the potential to reduce CO_2 emissions through lifestyle changes. The categories of utilities (i.e., energy and water) had the largest emissions, making reductions in direct CO_2 emissions by energy-saving measures an important focus for future policymaking. As differences in regional conditions caused large differences in CO_2 emissions from direct energy consumption, we further analyzed the effects of regional conditions on CO_2 emissions per household as calculated from the sub-model used for estimating CO_2 emissions from households. Regional conditions were approximated using two variables (temperature and population density), and CO_2 emissions were then calculated by energy use associated with daily life. In addition, CO_2 emissions tended to be higher in colder regions and lower in large cities. High CO_2 emissions in cold regions were mainly caused by energy consumption for heating. This indicates that better insulation, higher efficiencies of heat source equipment, and lower heating temperature settings by adjusting clothes may be effective measures for reducing CO_2 emissions. One of the most influential factors underpinning lower CO_2 emissions in large cities was the low CO_2 emissions from transportation. This suggests that promoting the use of public transportation and improving the fuel efficiency of automobiles may also be effective CO_2 reduction measures. These results suggest the

necessity for more detailed measures to reduce CO_2 emissions, taking into account the substitutability of consumption behavior across the building, industrial, and transportation sectors.

Our next research topic would be the improvement of the method for data update and future prediction. At present, the efficiency of lighting, air conditioning, and automobiles is improving, and CO_2 emissions may decrease with the spread of these new technologies. Therefore, the estimation equations of this study need to be updated continuously in the future. Since the method of this research is mainly based on the statistical information that is continuously surveyed in Japan, such as the Family Income and Expenditure Survey and input–output tables, it is considered possible to continuously update it in the future. Therefore, this study is meaningful as it presented the framework of the evaluation. However, in the sub-model for estimating direct energy consumption shown in Figure 3, since the heating and cooling estimation equations using degree days are based on existing research [9], it is difficult to update it using only statistical information. Therefore, we are developing a method of estimating energy consumption by heating and cooling from monthly energy consumption and temperature variation pattern. We have already proposed a method in the commercial sector to extract the variation components due to temperature from seasonal change information [52]. It is considered that our method is also applicable in the residential sector by using monthly data from the Family Income and Expenditure Survey. After continuous data acquisition becomes possible, we aim to contribute to environmental policies by forecasting and planning CO_2 reductions due to the introduction of low-carbon technologies.

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