

Article

Development and Verification of a Regional Residential Electricity Consumption Estimation Method

Yanghui Guo ¹, Andante Hadi Pandyaswargo ^{2,*}, Koki Matsumoto ¹ and Hiroshi Onoda ¹

¹ Graduate School of Environment and Energy Engineering, Waseda University, Tokyo 1620041, Japan; kaku18@akane.waseda.jp (Y.G.); kokimatsumoto@fuji.waseda.jp (K.M.); onoda@waseda.jp (H.O.)

² Environmental Research Institute, Waseda University, Tokyo 1620041, Japan

* Correspondence: andante.hadi@aoni.waseda.jp

Abstract: In pursuing Japan's target of net zero greenhouse gas (GHG) emissions by 2050, decarbonization strategies at the regional level have been taking place nationally. Some successes have been achieved in the residential sector in achieving decarbonization at the regional level due to improvements in the advancement of energy-saving technologies. An important prerequisite to achieving further decarbonization in the residential sector is understanding household electricity consumption of power demand objects. This study constructed a method for predicting residential electricity consumption in a case study region. First, we set up six models of household composition for scenario exercises. Then, we used the residential energy estimation based on daily activities (REEDA) method to calculate the hourly electricity consumption of each household composition in the four seasons based on the duration of daily life activity. Finally, we separately explore the impact of housing performance (insulation, airtightness), air-conditioning patterns (intermittent operation method in a habitable room/continuous operation method in a habitable room/continuous operation method in all rooms), and geographical location on residential air conditional electricity consumption. The output is a regional residential energy estimate method that can consider multiple key variables. We verified the developed model by (1) comparing the estimated output with the Japan Energy Database and (2) testing the method for various residential areas in Japan. The results showed an accuracy level greater than 75% and nationwide applicability.

Keywords: regional decarbonization; residential electricity consumption; electricity consumption estimate; household composition; air condition



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1. Introduction

In recent years, climate change due to global warming has progressed at an increased pace [1]. Many countries and regions have been committed to reducing greenhouse gas emissions in international agreements such as the Paris Agreement [2]. As a result, some countries and regions have begun to promote regional decarbonization. For example, the county of San Diego's Board of Supervisors directed staff on 27 January 2021 to develop a framework for a regional zero carbon sustainability strategy in partnership with the UC San Diego School of Global Policy and Strategy, which includes ways to achieve zero carbon emissions in the region. Energy, transportation, land use, buildings and industries, and other key sectors are considered [3]. In Japan, to realize a substantial zero of CO₂ emissions associated with the power consumption of the civilian sector (home sector, business, and other sectors), the Ministry of Environment Government of Japan (from hereafter, the country name will be omitted) proposed the concept of a “decarbonization leading region”, which collects decarbonization plans from various regions across the country. The proposed activity is a significant attempt towards realizing the 2050 carbon neutral goal that was declared in 2022 [4].

The share of CO₂ emitted by Japanese households in 2021 was 14.7%. It has been slightly reduced in 2023, unlike the other sectors, such as industry and transportation,

which have increased their emissions. Such success is influenced by the improvement in electricity emission intensity and the advancement in energy conservation [5]. Cities are attempting further reduction from the residential sector to achieve the zero-emission goal [6] for both the existing and the new residences that are scheduled for construction. Understanding the electricity needs in cities' residential areas is the first step toward decarbonization. For this purpose, a calculation method for residential electricity demand provided by the Ministry of Environment can be utilized [7]. However, the method involves the need to collect questionnaire surveys. Using a questionnaire survey method is not only prone to respondents' recall bias but is also cumbersome, time-consuming, and is not suitable for application if the target residential buildings have not yet been constructed.

The present study developed a method to accurately predict the hourly residential electricity consumption in a certain region on a single day during the four seasons using the available qualitative data to overcome those challenges. This method can be used to predict the electricity consumption of the residential sector in which districts are located, helping them to develop more implementable decarbonization plans.

The research objective of this study is to improve existing residential energy estimation methods. The first step is to extend the application scope of existing methods from "one residence" to "residential sectors within specific regions". To achieve this, our primary task involves redefining household compositions, calculating their time use, and estimating electricity consumption. Another aim of our research is to enhance the accuracy of existing methods. To accomplish this, we will delve into housing performance, air-conditioning patterns, and geographical location, conducting a detailed analysis of the electrical consumption of heating and cooling systems under different conditions.

In specific terms, to predict the electricity consumption of the residential sector in a district, it is necessary to know the estimated energy consumption for each type of household composition and the number of households in the district. The latter information can be obtained through government statistics. In calculating the estimated energy consumption for each household composition type, the electricity consumption for various activities can be determined using the existing methods. For the electricity consumption of heating and cooling, correction factors from this study are applied to adjust the estimated values based on actual conditions, such as housing performance, air conditioning patterns, and location. The framework of this research is shown in Figure 1.

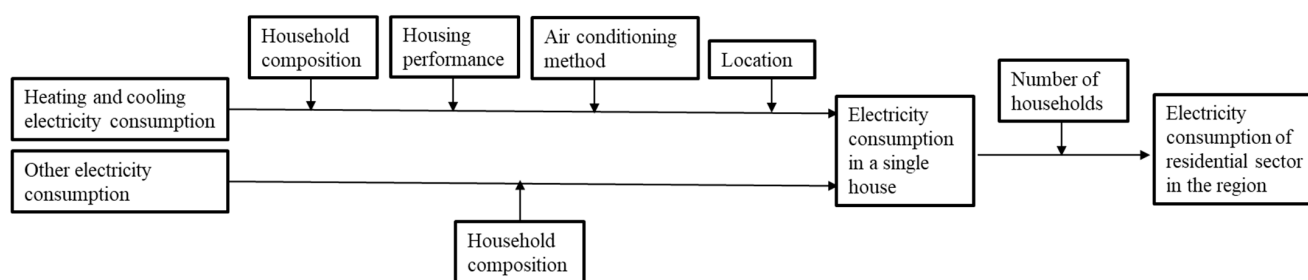


Figure 1. Research framework.

2. Previous Research

2.1. Overview of Energy Consumption in Residential Sector Modeling Techniques

Swan et al. [8] provided an up-to-date review of the various modeling techniques used for residential sector energy consumption. Two distinct approaches are identified: top-down and bottom-up. The top-down approach treats the residential sector as an energy sink and is not concerned with individual end-users. The bottom-up approach extrapolates the estimated energy consumption of a representative set of individual houses to regional and national levels.

Top-down modeling needs widely available and only aggregate data, which is simple. For example, Nesbakken [9] developed such a model for Norway, testing sensitivity and stability across a range of income and pricing. Bentzen and Engsted [10] developed simple

residential energy consumption economic modeling. They tested three annual energy consumption regression models for Denmark. However, with top-down modeling, the details of energy consumption in individual end-uses are unavailable [8].

The bottom-up models can account for the energy consumption of individual end-uses, individual houses, or groups of houses and are then extrapolated to represent the region or nation based on the representative weight of the modeled sample. For example, Jaccard et al. [11] developed a model of Canadian provinces using the INSTRUM-R simulation tool. The inputs to the model include historical energy consumption, price, behavioral parameters, distribution levels of technologies, and quantification of appliance unit energy consumption, cost, and availability. Using a combination of distributions and microlevel data sources, Kadian et al. [12] developed an energy consumption model for Delhi's residential sector. The primary drawback caused by this level of detail is that the input data requirement is greater than that of the top-down models, and the calculation or simulation techniques of the bottom-up models can be complex. Furthermore, occupant behavior must be estimated, which is difficult, as behavior has been shown to vary widely and in unpredictable ways [8].

The method constructed in this study is based on a previous study by Ihara [13], Residential Energy Estimation based on Daily Activities (REEDA): A methodology to estimate household energy consumption. The REEDA method is a bottom-up modeling approach requiring detailed energy consumption data. However, the approach only requires inputting easily obtainable qualitative conditions such as household composition to estimate household energy consumption. The most apparent drawback of the existing REEDA is the assumption of occupant behavior. It is difficult to estimate occupant behavior, and the effect of occupant behavior can significantly affect energy consumption. Therefore, enhancing the REEDA method is necessary. In this study, we improve the REEDA method by utilizing Japan's official activities' time use statistics data. The household energy consumption estimation approach is developed around occupant behavior.

2.2. Residential Energy Estimation Based on Daily Activities (REEDA)

The components and flow of estimation in REEDA are presented in Figure 2. First, “energy consumption status” is estimated using data on residents' time-use reports on their daily activities obtained from a daily activities time survey [14]. Next, “energy equipment usage” is estimated using equipment data from household appliance manufacturers' published data [15]. This allows us to estimate how much energy each daily activity consumes and what equipment is used. Combining these data to evaluate energy consumption behavior makes it possible to comprehensively study effective improvement measures that lead to the transformation and improvement of daily life activities, in addition to conventional “equipment-oriented” energy conservation measures.

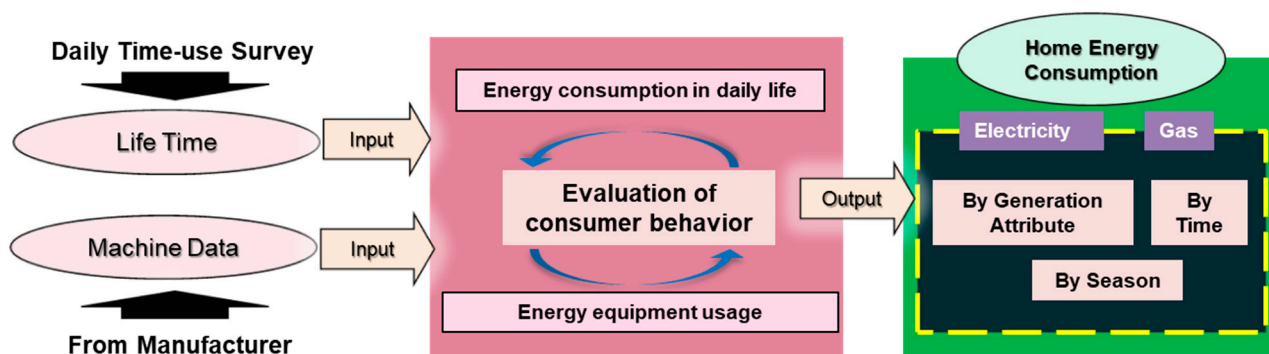


Figure 2. The development method of REEDA.

The data used during this research are as follows:

1. Data measured by the Home Energy Management System (HEMS) collected by the Ministry of the Environment: “Fiscal 2010 greenhouse gas emissions visualization consignment work” [16];
2. “Data collected in FY 2011 Family Ecological Diagnostic Effect Verification Actual Survey Project Outsourcing Business” [17];
3. “Survey Project for Improving the Value of HEMS Usage in 2012 Data collected in the commissioned work” [18].

The present study used 1037 households’ data from the above sources and “the daily time-use data” from the survey on time use. The details of the data are shown in Tables 1 and 2.

Table 1. Energy-use data that have been used in the existing REEDA.

Implementer	FY 2010 Green Gas Emissions Visualization Research Consignment Work (Ministry of the Environment)	FY 2011 Domestic Ecological Diagnosis Effect Verification Actual Survey Project Outsourcing Operation (Ministry of the Environment)	FY 2012 Survey Business Consignment Work to Improve the Value of HEMS Use (Ministry of the Environment)
District	The east of Japan	Japan	Japan
Measure target (scale)	General (196 Households) Air conditioner/TV/Refrigerator (360 Households)	General (341 Households)	General (500 Households) PV (228 Households)
Period	November 2010–February 2012	August 2011– February 2012	December 2011–December 2012
Household Attributes	District	Postcode	Postcode
	Dwelling	House/Mansion, Own/Lease	House/Mansion
	Equipment	All appliances	Air-conditioner/TV/Refrigerator PV
	Households/Individual	Households’ member Electric bill	Households’ member Household income Electricity contract information
	Consciousness/Behavior	Ecological diagnosis date Energy saving behavior date	Ecological diagnosis date Energy saving behavior date -

Table 2. Time use data to be used in the improved REEDA.

Investigation Matters	Period	Sample	Number of Samples
• Lifestyle behavior and home situation at different times (15 min) from 0:00 a.m. on the survey target data (2 days); • Individual attributes (sex, age, occupation).	14 October 2010–24 October 2012 (2 days per cycle, total of 4 times)	People older than 10 years old	4905

As a result, by analysing HEMS data of approximately 1000 households, this research developed a method that can easily estimate the average energy consumption of time series, including seasonal data on the day of the week in each life stage by applying time use data.

3. Materials and Methods

A number of tasks are solved in this study. First, we categorize the typical household compositions in Japan and calculate the lifetime of each type of household. Then, the REEDA method is used to estimate each household composition's total electricity consumption (heating and cooling and other uses) (Section 3.1).

The electricity consumption for heating and cooling is assumed to only occur in winter and summer. The difference between summer and autumn is considered as the annual cooling electricity consumption estimation, and the difference between winter and spring is considered as the annual heating electricity consumption estimation. Using this approach, the total electricity consumption of summer and winter can be separated into heating, cooling, and other uses (Section 3.2).

The estimation results for spring, autumn, summer (other uses), and winter (other uses) are directly output. In contrast, the estimation of electricity consumption for summer (cooling) and winter (heating) involves considerations of other impact factors. To obtain the coefficients, we analyzed the house performance, air conditioning patterns, and geographic locations' respective influences on heating and cooling electricity consumption (Sections 3.3–3.5).

With this method, we can calculate the hourly electricity consumption for various households in each season, and by multiplying this by the number of hours in each season and summing them up, we can obtain the annual electricity consumption of each household composition. Finally, by multiplying the number of each type of household composition in the target district, the electricity consumption of the household sector in the district can be estimated through this method.

3.1. Daily Activities and Household Composition

3.1.1. Daily Activities Survey

The NHK Broadcasting Culture Research Institute has carried out national activities and time investigations to clarify the actual condition of Japanese life from the viewpoint of time every five years since 1960 [14]. As shown in Figure 3. The content of the 2020 National Time Use Survey Report is as follows.

1. Basic data that reveal the actual living conditions of Japanese people from the perspective of time;
2. The survey data on the daily living department and home status are in 15-min increments on the survey days (2 days);
3. Personal social attributes are obtained as additional questions.

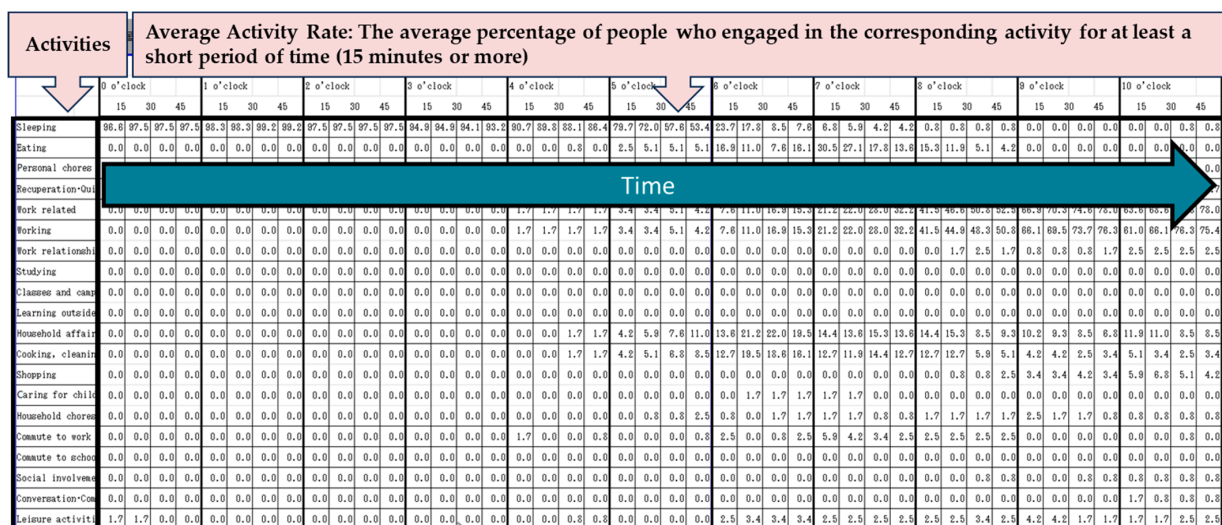


Figure 3. Contents of daily time use survey.

3.1.2. Daily Activities Time Synthetic Method

This study uses the time synthesis rule used in the existing REEDA approach. The average percentage of active participants in each activity was set according to the following conditions, focusing on whether the activity was performed by a single person or multiple people simultaneously.

1. If a single person performs the activity, the maximum activity rate of the entire household will be used;
2. If the activity is performed by multiple people simultaneously, the average activity rate of the entire household will be used.

The classification results according to the above conditions are shown in Table 3.

Table 3. Daily activities time synthetic method.

Categories	Activities
Activities performed by a single person. (Maximum actor rate)	Cooking, cleaning, laundry, hobbies, and entertainment
Activities performed by multiple people at the same time (Average activity rate)	Sleeping, eating, personal chores, conversation/socializing, newspapers, other/unknown, television

3.1.3. Household Composition

The Ministry of Health, Labor, and Welfare Government of Japan (in the following text, the country name will be omitted)'s 2021 Basic Survey on National Living lists the Japanese household composition into six types. Each type's prevalence nationally is stated in the report [19]. In this study, the composition of each household's type is set in Table 4.

Table 4. Settings and percentages by household composition.

Household Composition	Household Members	Composition Ratio [%] ¹
Single household	Worker	29.5%
Couple household	Worker, housewife	24.5%
Couple and children's household	Worker, housewife, student	27.5%
One-parent and children household	Worker, student	7.1%
Three generation household	Worker, housewife, student, Unemployed	4.9%
Other households	-	6.5%

¹ Ministry of Health, Labor, and Welfare (2021) [19].

3.2. Electricity Consumption Breakdown: Heating/Cooling vs. Other Uses

Figure 4 shows the results of a comparative analysis of seasonal activity usage using estimated and published values of air conditioner makers. The difference in energy consumption between summer and autumn, as well as between winter and spring, closely approximates the average energy consumption for air conditioning, cooling, and heating in Japanese residential buildings. As a result, the difference between seasons can be regarded as the amount consumed by air conditioners.

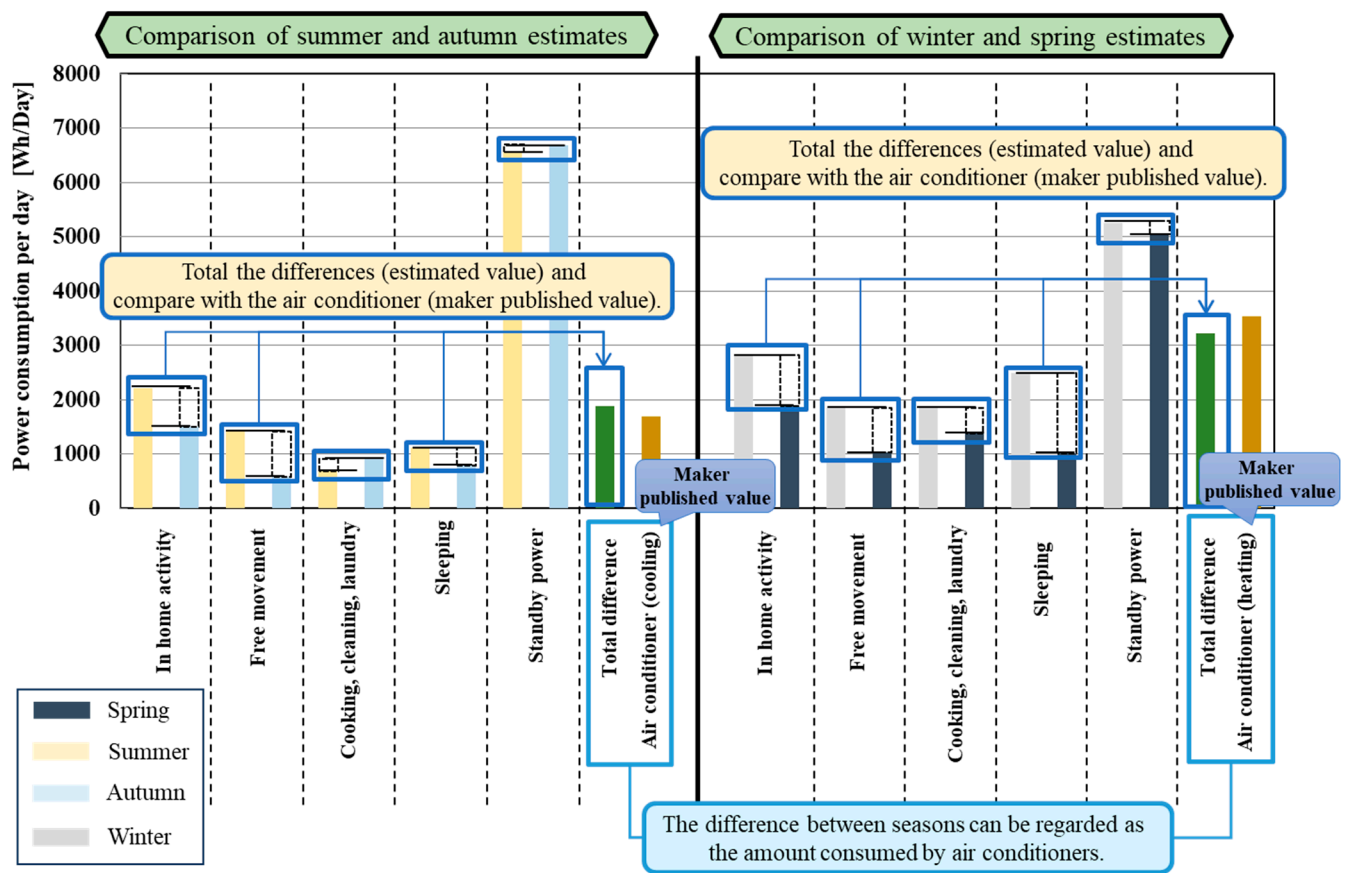


Figure 4. Analysis of activity usage by season.

3.3. Housing Performance

3.3.1. Insulation

Heat insulation is the ability to control the heat and cooling of the building from outside to escape and to keep the room temperature constant. In a building with high thermal insulation, the room temperature is stable against outside temperature changes, and the energy necessary for heating and cooling can be minimized. According to the Ministry of Land, Infrastructure, Transport and Tourism Government of Japan (in the following text, the country name will be omitted), the Zero Energy House (ZEH) standard of the regional division and the adiabaticity (U_a) value in the energy saving standard are prescribed [20].

To evaluate the energy-saving effect of improving thermal insulation performance on residential buildings, this study used the “Energy Consumption Performance Calculator” developed by the Ministry of Land, Infrastructure, Transport. and Tourism [21] (Figure 5). The calculator allows users to select and input the conditions for buildings and equipment to estimate the energy consumption and the house’s skin performance. In this study, we determined the energy consumption of air conditioning and heating by inputting various U_a into the calculator. We can determine the energy consumed by heating and cooling annually under specified conditions through program calculations.

Input housing envelope specifications

Envelope

3 Please enter the specifications of the exterior skin of the target house

Total skin area m² (2 decimal places) → Input the housing envelope area

Average heat transfer coefficient of envelope W/m²K (2 decimal places) → Input the Ua

Energy consumption performance calculation program

Residential Version

Simple Input Screen
Calculate by selecting basic equipment

Detailed Input Screen
Calculate by entering detailed specifications

Easy input mode

Detailed input mode

Difference between simple input screen and detailed input screen

Primary Energy Consumption

Breakdown item	Design primary energy	Reference primary energy
Heating Equipment	13,935 MJ	13,383 MJ
Cooling Equipment	6036 MJ	5634 MJ

Primary energy consumption of heating equipment

Primary energy consumption of cooling equipment

Home page of Energy Consumption Performance Calculation Program

Simulation results of primary energy consumption

Figure 5. Energy consumption performance calculation program [21].

3.3.2. Airtightness

Airtightness (C) influences the stabilization of the temperature inside a building. Good airtightness also minimizes the effect of wind and temperature changes outside the building. A building with high airtightness can prevent outside air from entering and control the indoor environment too easily. However, the standard of C for residential buildings is not clearly defined in Japan. In the energy-saving standard, the value of C was included in the item in 1999, which requested that the C should be lower than 5.0 cm²/m² (for cold regions, it should be 2.0 cm²/m² or lower) [22]. However, C was removed in the 2013 standard regulation [23]. Meanwhile, through our interviews with several construction companies and reviewing their official reports, we conclude that in the housing industry, high-airtight housing can be defined as where C is lower than 1.0 [24–26].

Due to the current lack of regulations on residential C in Japan, the calculation programs issued by the government and others did not consider the impact of C on residential energy consumption. Therefore, this study developed Equations (1) and (2) [27] to calculate the changes in Q_c in residential energy consumption caused by C.

$$Q_C = C_p * \rho * V(t_o - t_i) \quad (1)$$

Q_C : heat loss by C [W]; C_p : constant pressure specific heat of air [J/kgK]; t_i : inside temperature [K]; t_o : outside temperature [K]; V : outside air volume [m³/h]; ρ : air density [kg/m³].

$$V = 0.73C * S \sqrt{\frac{1}{4}(r_o - r_r)h + \frac{\{\frac{1}{2}(C_1 - C_2)(\frac{V_s}{4})^2\}^2}{(r_o - r_r)h}} \quad (2)$$

C: gap equivalent area [cm^2/m^2]; S: housing envelope area [m^2]; r_o : outside air density [kg/m^3]; V_s : outside air wind speed [m/s]; h: height of house [m]; r_i : inside air density [kg/m^3]; C_1 : windward wind force coefficient; C_2 : downwind wind force coefficient.

3.3.3. General Housing and High-Performance Housing

Using Equations (1) and (2) to estimate Ua and C, Japanese houses are classified into general and high-performance housing in this study. The specific definitions for each classification are shown in Table 5.

Table 5. Definition of general housing and high-performance housing.

	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8
General Housing								
Ua [$\text{m}^2 \cdot \text{K}/\text{W}$] ¹	0.46	0.46	0.56	0.75	0.87	0.87	0.87	0.87
C [cm^2/m^2] ²	2	2	2	2	5	5	5	5
High-Performance Housing								
Ua [$\text{m}^2 \cdot \text{K}/\text{W}$] ³	0.4	0.4	0.5	0.6	0.6	0.6	0.6	0.6
C [cm^2/m^2] ⁴	1	1	1	1	1	1	1	1

¹ MLIT, Energy conservation standards for houses, adiabatic performance grade 4. ² MLIT, Energy conservation standards for houses, 1999. ³ MLIT, Energy conservation standards for houses, adiabatic performance grade 5 (ZEH standard). ⁴ Joint recognition of the housing industry in Japan.

3.4. Air Conditioning Patterns

According to the research results of the building standards maintenance promotion project (2021), the common air conditioning patterns in Japanese residences can be divided into intermittent operation methods in a habitable room (IH), continuous operation methods in a habitable room (CH), and continuous operation methods in all rooms (CA) [28].

CA is an air conditioning pattern that centrally manages all spaces within a building and maintains appropriate temperature and humidity. It is mainly installed in commercial facilities and is characterized by creating a consistent and comfortable space. Unlike CA, both IH and CH balance comfort and energy efficiency by only maintaining the temperature and humidity of a partial space (living room) in the entire room. When comparing partially intermittent and partially continuous operations, IH is considered more energy efficient. However, when considering the dehumidification effect in summer, many lifestyles choose CH.

The air-conditioned spaces, operating times, and equipment examples of these three air-conditioning pattern modes are shown in Figure 6.

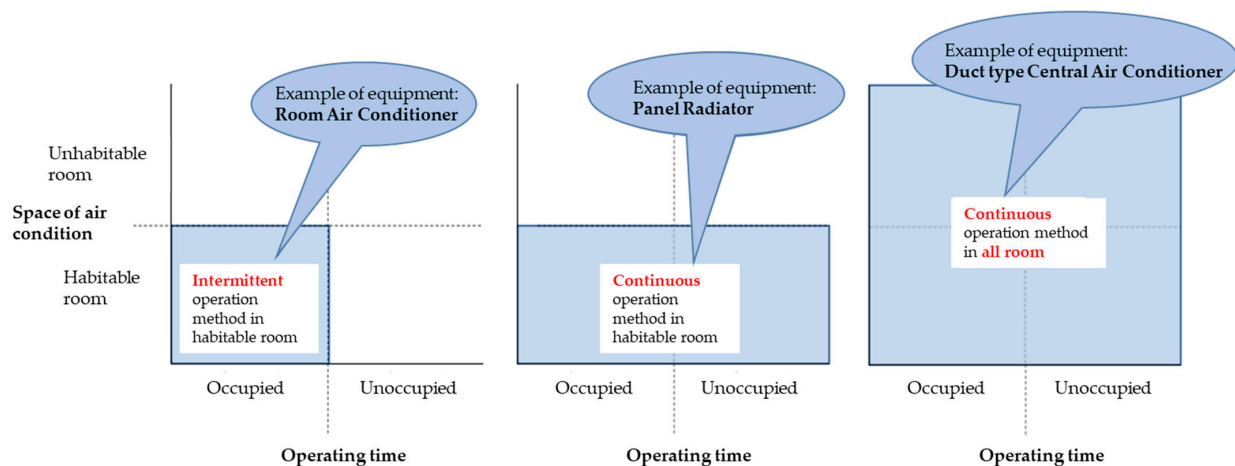


Figure 6. Three air-conditioning operation modes in Japan.

Additionally, based on the above research, the annual heat load of houses under different insulation performance standards is shown in Section 4.3. The research object in REEDA uses the “IH” pattern of air conditioners. In this study, the corresponding coefficients can be estimated when the power consumption of other air conditioner types needs to be estimated.

3.5. Geographic Location

3.5.1. Energy Conservation Standards Division

The Ministry of Land, Infrastructure, Transport, and Tourism has divided Japan into eight regions [29]. The division implies that the needed insulation performance and the standard values to be achieved will vary depending on which region category the proposed site for notification is in (Figure 7). For example, Hokkaido is the coldest region in Japan, designated region 1 or 2. The region’s number increases as one moves southwards, with major urban areas such as Tokyo and Osaka being designated as almost region 5 or 6. Okinawa, the southernmost region, is region 8 [29].

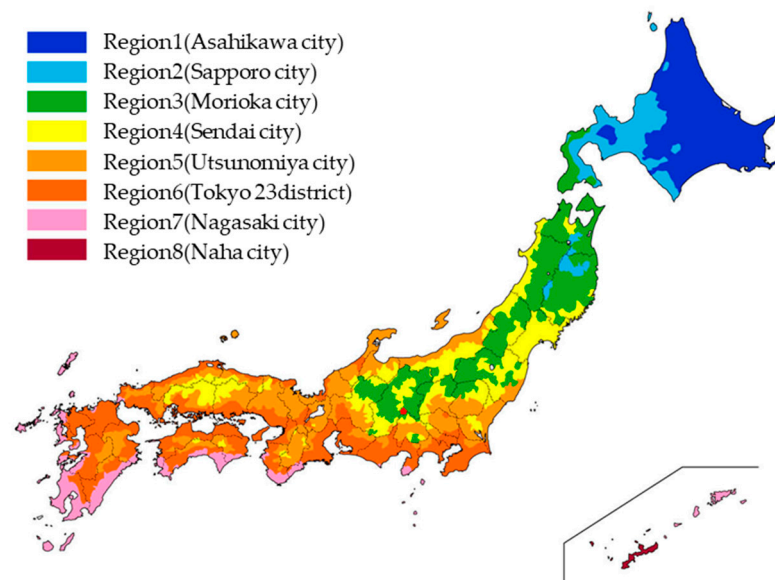


Figure 7. Energy conservation standards division [29].

3.5.2. Heating and Cooling Coefficient by Region

Through the research of Akabayashi (2012) [30], we calculated the values for electricity consumption for heating and air conditioning in all eight regions. The main research object of this study is region 6. Therefore, region 6 is used as the standard in the REEDA calculation. For the other regions, we derived the power consumption of heating and cooling air conditioning from each region’s heating and cooling coefficients.

4. Results

4.1. Daily Activities and Household Composition

Following the Daily Activities Time Synthetic Method in Table 3, we calculated the occurrence probabilities of various activities per hour for the six household compositions in Table 4 using data from the NHK Daily Time Use survey, as shown in Figure 3. The result for single households’ lifetime is presented in Table 6.

Table 6. Single households' lifetime.

Time	Sleeping	Cooking, Cleaning, Laundry	Hobbies and Entertainment	Television (at Home)
0	81.65	0.325	2.725	3.425
1	90.2	0.05	1.425	1.375
2	93.95	0.025	0.85	0.6
3	94.675	0.05	0.325	0.525
4	92.825	0.525	0.2	0.95
5	78.025	3.825	0.2	3.5
6	38.875	11.9	0.325	13.725
7	11.875	10.275	0.575	17.6
8	5.725	5.125	0.35	8.8
9	3.7	2.625	0.7	4.425
10	2.775	1.625	0.8	3.375
11	2.175	1.5	0.725	3.225
12	2.1	1.575	1.275	5.15
13	2.275	1.5	1.05	3.95
14	2.1	1	0.775	3.875
15	1.9	1.95	0.85	3.8
16	1.375	2.575	1.175	4.425
17	1.1	6.875	1.05	5.275
18	0.825	12.625	1.525	11.3
19	1	9.625	1.6	25.8
20	1.625	5.725	3.25	35.325
21	6.425	3.425	4.925	39.875
22	19.45	1.975	6.05	34.4
23	47.6	0.975	6.1	16.925

Next, by multiplying the time use with the average electricity consumption for various activities from a previous study [13], we can estimate the electricity consumption for each activity per hour for each household composition in each season. The results are illustrated in Table 7, which shows the electricity consumption estimation of single households.

Table 7. Single households' electricity consumption for activities in spring.

Time	Constant [Wh]	Sleeping [Wh]	Cooking, Cleaning, Laundry [Wh]	Hobbies and Entertainment [Wh]	Television [Wh]	Estimated Power Consumption [Wh]
0	97.68	52.49	1.68	34.91	9.08	195.83
1	97.68	57.99	0.26	18.25	3.64	177.82
2	97.68	60.40	0.13	10.89	1.59	170.68
3	97.68	60.86	0.26	4.16	1.39	164.35
4	97.68	59.67	2.72	2.56	2.52	165.15
5	97.68	50.16	19.81	2.56	9.28	179.48
6	97.68	24.99	61.63	4.16	36.37	224.84
7	97.68	7.63	53.22	7.37	46.64	212.54
8	97.68	3.68	26.54	4.48	23.32	155.71
9	97.68	2.38	13.60	8.97	11.73	134.35
10	97.68	1.78	8.42	10.25	8.94	127.07
11	97.68	1.40	7.77	9.29	8.55	124.68
12	97.68	1.35	8.16	16.33	13.65	137.17
13	97.68	1.46	7.77	13.45	10.47	130.83
14	97.68	1.35	5.18	9.93	10.27	124.40
15	97.68	1.22	10.10	10.89	10.07	129.96
16	97.68	0.88	13.34	15.05	11.73	138.68
17	97.68	0.71	35.61	13.45	13.98	161.42
18	97.68	0.53	65.39	19.54	29.95	213.08
19	97.68	0.64	49.85	20.50	68.37	237.04
20	97.68	1.04	29.65	41.63	93.62	263.62
21	97.68	4.13	17.74	63.09	105.67	288.31
22	97.68	12.50	10.23	77.50	91.16	289.08
23	97.68	30.60	5.05	78.14	44.85	256.32
Total	2344.26	439.85	454.10	497.36	666.84	4402.42

4.2. Housing Performance

We input the basic information of a standard Japanese residence model [31] into the program of Figure 5, including floor area, envelope area, heating and cooling equipment,

ventilation system type, and frequency. Additionally, for regional classification and U_a , we use the data corresponding to general and high-performance residences in each region from Table 5. Subsequently, we can obtain the energy variation resulting from improved thermal insulation. The results are shown in Table 8.

Table 8. The influence of housing performance on heating and cooling energy consumption.

Cooling					
	General Housing [MJ/Year]	High-Performance U_a		High-Performance C	
		ΔQ_{ua} [MJ/Year]	Reduction Rate of Q_{ua}	ΔQ_c [MJ/Year]	Reduction Rate of Q_c
Region 1	1095	−80	−7%	0.36	0%
Region 2	1048	−77	−7%	0.72	0%
Region 3	1628	−88	−5%	4.63	0%
Region 4	2271	−241	−11%	0.76	0%
Region 5	2139	−289	−14%	58.54	3%
Region 6	6036	−685	−11%	299.40	5%
Region 7	7347	−1004	−14%	180.66	2%
Region 8	13,377	−1219	−9%	480.59	4%

Heating					
	General Housing [MJ]	High-Performance U_a		High-Performance C	
		ΔQ_{ua} [MJ]	Reduction Rate of Q_{ua}	ΔQ_c [MJ]	Reduction Rate of Q_c
Region 1	34,026	4593	13%	959.50	3%
Region 2	26,503	3659	14%	572.83	2%
Region 3	20,528	2254	11%	560.84	3%
Region 4	25,021	4672	19%	507.64	2%
Region 5	19,922	6026	30%	1687.31	8%
Region 6	13,935	4237	30%	1428.63	10%
Region 7	7281	2428	33%	655.82	9%
Region 8	0	0	−	−	−

To calculate the change in energy loss due to variations in airtightness, as expressed in Equations (1) and (2), we need to determine the average temperature during heat exchange between indoor and outdoor environments (summer: outdoor temperature higher than indoor; winter: outdoor temperature lower than indoor) for each region. In this case, we utilize data from the Japan Meteorological Agency [32] to filter temperatures based on the specified conditions for each region, calculate the averages, and then substitute them into Equations (1) and (2). The results are shown in Table 8.

4.3. Air Conditioning Patterns

The existing study [28] provides experimental data on heating and cooling loads for general housing and high-performance housing under three air conditioning patterns. According to the calculations, when considering general housing, the CH mode consumes 92% more energy than the IH mode, and the CA mode consumes 178% more energy than the IH mode. When considering high-performance residences, the CH mode consumes 82% more energy than the IH mode, and the CA mode consumes 166% more energy than the IH mode. The results are shown in Table 9.

Table 9. Effect of air conditioning patterns on heat load.

	IH Pattern [GJ]	CH Pattern [GJ]	CH's Increase Rate (Compare with IH Pattern)	CA Pattern [GJ]	CA's Increase Rate (Compare with IH Pattern)
General housing	12.8	24.6	92%	35.6	178%
High-performance housing	9.9	18	82%	26.3	166%

4.4. Geographic Location

An existing study [30] estimated the heating and cooling consumption for eight regions in Japan. Based on these data, we calculated the heating and cooling region coefficients when we set region 5 as the standard region. The results are shown in Table 10.

Table 10. Heating and cooling region coefficients by eight regions.

	Cooling Electricity Consumption [kWh]	Heating Electricity Consumption [kWh]	Cooling Region Coefficients	Heating Region Coefficients
Region 1	54.79	3472.60	0.10	2.52
Region 2	23.97	2955.47	0.05	2.15
Region 3	95.89	2126.71	0.18	1.54
Region 4	236.30	1815.06	0.45	1.32
Region 5	253.42	1876.71	0.48	1.36
Region 6	527.39	1376.71	1.00	1.00
Region 7	547.94	821.91	1.04	0.60
Region 8	883.56	0	1.68	0.00

4.5. Verification

4.5.1. Verification Procedure

To verify the accuracy of the developed method in this study, we performed a verification by implementing it in multiple regions of Japan.

First, among the 1–8 regions, the districts with the largest/medium/least number of households in each region were selected for verification. In setting the housing performance, the air conditioning model, we chose the models currently the majority of choices in Japan: general housing of housing performance; IH in air conditioning method. The specific conditions set in this validation can be seen in Table 11.

Table 11. Variable and selection conditions for verification.

Variable	Selection Conditions for Verification
Households Composition	National Average (Table 4)
housing performance	General housing in each region (Table 5)
Air Conditioning Method	Intermittent operation method in habitable room
Regions	1–8

Next, the values of annual household energy consumption in the relevant region are obtained from the regional energy supply and demand database, and the obtained values are used as the data for verification. The Regional Energy Supply-Demand Database provides energy supply-demand data (data on energy resources and demand) for 1741 cities, wards, towns, and villages in Japan to contribute to formulating regional energy plans by local governments and promoting understanding of regional energy systems. The data are available to the public [33] and are shown in Figure 8. The energy consumption statistics table summarizes the annual energy consumption by energy type and demand sector. It provides an overview of which energy types were consumed, in which demand sectors, and how much would be used over a year. The energy usage recorded in the residential sector includes city gas, new renewable energy, nuclear energy, heat, and electricity.

4.5.2. Verification Results

Using the methodology developed in this study, electricity consumption in the residential sector of 40 target areas, five districts for each region, was calculated (estimated values). The results were compared with the Japan energy database (actual values). Specifically, we labelled the targeted 40 districts of a scatter plot in the coordinate system using the horizontal axis as the actual values and the vertical axis as the estimated values in Figure 9.

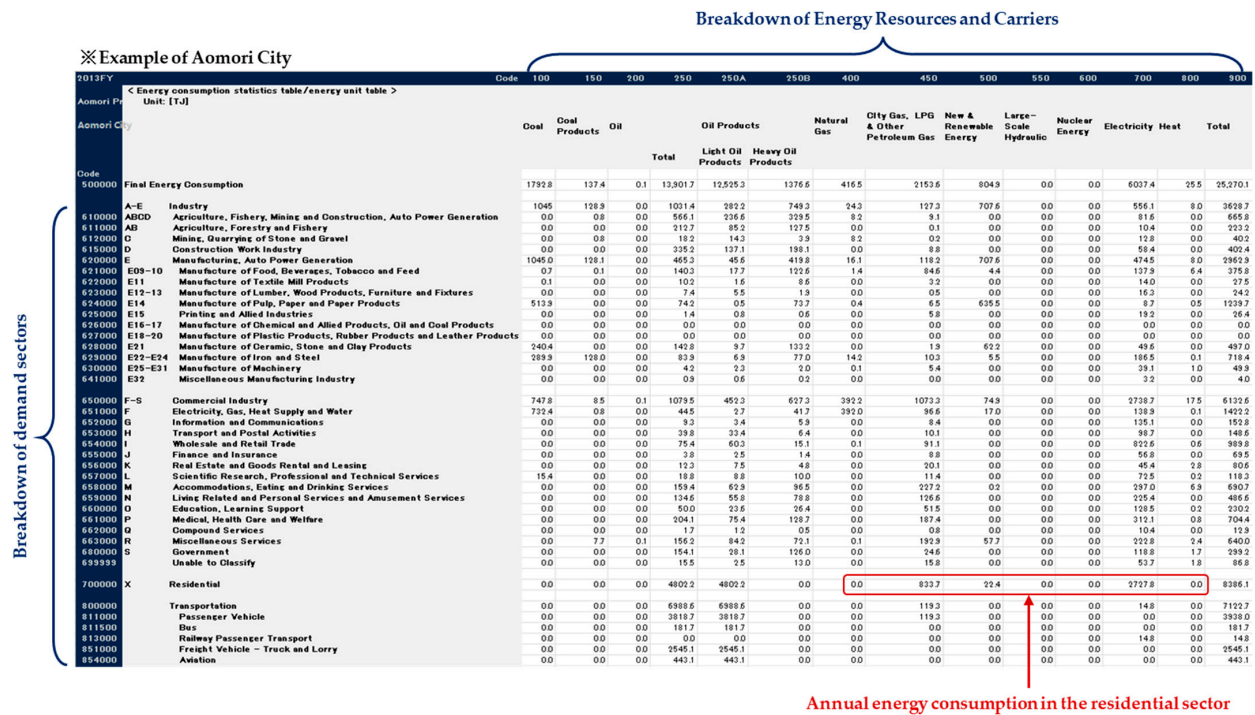


Figure 8. Energy consumption statistics.

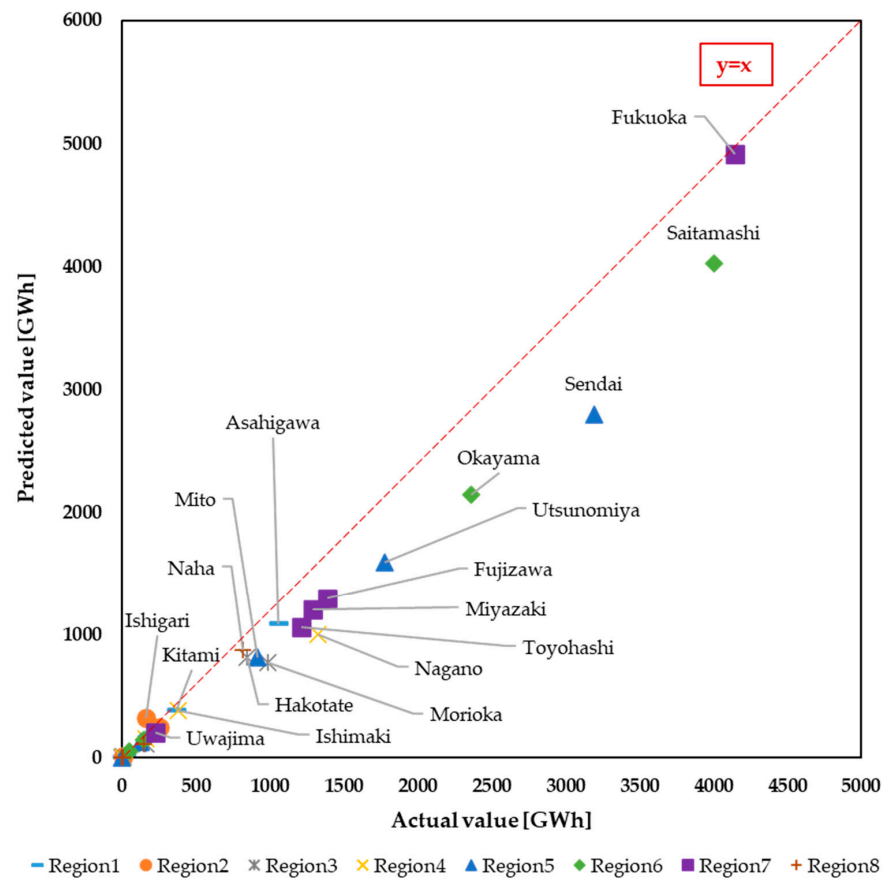


Figure 9. Distribution plot of actual and predicted values.

It is known from the calculation results that the average relative error of the predicted and actual values is 14.4%, which means that the average error when using the method of this study for estimating will be, at most, 14.4%.

In addition, this study also used the root mean square error (RMSE) for validation. The RMSE is often used to measure a model's goodness for numerical estimation. Using Equation (3), the RMSE is 167.06 GWh in this verification. When normalizing by the mean value of the measurements, the term coefficient of variation of the RMSD, $CV(RMSE)$, may be used to avoid ambiguity. The $CV(RMSE)$ calculated with Equation (4) is 0.19.

$$RMSE = \sqrt{\frac{1}{T} \sum_{t=1}^T (\hat{y}_t - y_t)^2} \quad (3)$$

$RMSE$: root mean squared error; T : times of estimation; $\hat{y}_t$: estimated value [GWh/Y]; y_t : actual value [GWh/Y].

$$CV(RMSE) = \frac{RMSE}{\bar{y}} \quad (4)$$

CV : coefficient of variation; $\bar{y}$: the average of actual value [GWh/Y].

5. Discussion and Conclusions

The residential sector in Japan has shown a positive contribution to decreasing GHG emissions due to an improved advancement of energy preservation technologies. However, to achieve the net zero GHG emission target by 2050, further efforts must be made in the sector. This study suggested that the electrical consumption of cooling and heating in houses should incorporate various key building characteristics that have been neglected in the existing methodologies. These characteristics are airtightness, air conditioning patterns, and geographical location. By incorporating those factors, the energy consumption estimation in the sector may be improved.

In this study, we demonstrated the development of a methodology that incorporates those key characteristics. The methodology also uses information such as the households' composition and time use of activities occurring in the household in all four seasons. The conclusions that can be drawn from this study for the respective attributes are as follows.

- (1) We grouped the households by their composition types and used the improved REEDA method that utilizes the NHK Daily Time Use survey to predict the electricity consumption of each living activity every hour of the day in each season for various household compositions.
- (2) We simulated the energy-saving effects of improved residential performance in regions 1–8 in Japan and came to the following conclusions:
 - (a) Regarding heating performance after improving thermal insulation, the colder region has a greater reduction in heating energy. The largest reduction is in region 1, where the annual heating energy consumption will be reduced by 4593 MJ. However, when we discuss the reduction rate, since the heating usage in warm areas is less, although the energy reduction in warm regions is not much, the energy reduction rate is higher than that in cold regions. The largest reduction rate is in region 7, where annual heating energy consumption will be reduced by 33%.
 - (b) Regarding cooling performance after improving thermal insulation, the warmer region has a greater reduction in cooling energy. The largest reduction is in region 8, where the annual heating energy consumption will be reduced by 1219 MJ. The largest reduction rate is in region 5, where annual heating energy consumption will be reduced by 14%.
 - (c) Regarding heating performance after improving airtightness, the colder region has a greater reduction in heating energy. However, for regions 1–4, when upgrading from general housing to high-performance housing, the improve-

ment in airtightness is small (C changes from 2 to 1); for regions 5, 6, 7, and 8, when upgrading from general housing to high-performance housing, the airtightness is greatly improved (C changes from 5 to 1). The largest reduction is in region 5, where the annual heating energy consumption will be reduced by 1687.31 MJ. The largest reduction rate is in region 6, where annual heating energy consumption will be reduced by 10%.

- (d) Regarding cooling performance after improving airtightness, the warmer region has a greater reduction in cooling energy. The largest reduction is in region 8, where the annual heating energy consumption will be reduced by 481 MJ. The largest reduction rate is in region 6, where annual heating energy consumption will be reduced by 5%.
- (3) We found that when considering general housing, the CH mode consumes 92% more energy than the IH mode, and the CA mode consumes 178% more energy than the IH mode. When considering high-performance residences, the CH mode consumes 82% more energy than the IH mode, and the CA mode consumes 166% more energy than the IH mode.
- (4) We obtained conversion factors for heating and cooling electricity consumption among different regions.
- (5) By comparison with the database, it was confirmed that the average relative error of the method developed in this study is approximately 14.4%. The RMSE is 167.06 GWh, and the CV (RMSE) is 19%.

This study has developed a comprehensive yet simple method for electricity estimation compared to the existing survey-based method. The accuracy of the developed method was also verified. It was confirmed that the developed method has a relative error of 14.4% when compared with the Japan Energy Database.

The Japanese government plans to designate 100 districts as carbon-neutral pilot areas, with the primary goal of achieving carbon neutrality in the civil sector. As a significant component of the civil sector, estimating the electricity demand for households is crucial when formulating carbon-neutral plans. Unlike many existing methods that focus on estimating individual residences, the method developed in this study requires minimal qualitative information, which is also easy to obtain but can accurately estimate energy consumption for the entire residential sector of a district. It can even be used for future predictions, such as the widespread adoption of high-performance residences. We believe this method can be applied by municipalities dedicated to carbon neutrality and research teams providing carbon-neutral solutions for local governments. As the demand for carbon neutrality expands, such a convenient model is also suitable for use by nonprofessionals.

However, this study has limitations in terms of its research horizon. The research methodology of this study is based on the all-electric residential detached house; however, the apartment and mansion, as well as the energy consumption of gas and heat, should not be ignored. Future research will further discuss the estimation method of energy sources other than electricity in the residential sector and attempt to model the energy consumption of apartments and mansions.

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