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Exploring Economies of Scale in Household Energy Consumption across Seasons and Uses

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ABSTRACT

The implementation of carbon pricing, without accounting for economies of scale in household energy consumption, may disproportionately impact smaller households. This study utilizes data from a survey of Japanese households to investigate variance in energy consumption patterns in response to household composition, energy source combinations, and weather conditions. First, we define the minimum energy requirement (MER) as the energy consumed during the month of lowest usage and analyze the influence of household consumption on the MER. Our findings indicate a notable economy of scale in household energy consumption; however, the extent of this effect varies across households utilizing different energy source combinations. Next, we examine how household composition impacts winter energy usage (WEU) by analyzing the energy consumption growth rate, expressed as the ratio of the WEU to MER. The results demonstrate a higher growth rate among lower-income households. Additionally, household composition and the choice of energy sources significantly influence the energy consumption growth rate. Households use energy for various purposes, and economies of scale are likely to differ across these uses. We classify the purposes of energy use into five categories, namely space heating, space cooling, hot water supply, cooking, and appliance use, and estimate the economies of scale for each. The results suggest that per capita energy consumption for space heating, cooking, and appliance use decreases significantly as the number of household members increases.

Keywords: Economies of Scale, Household Composition, Household Energy Consumption
JEL Classifications: Q4, D1

1. INTRODUCTION

Upon adoption of the United Nations Framework Convention on Climate Change at the 1992 United Nations General Assembly, the sectoral distribution of final energy consumption was as follows: Industry accounted for 51%, commercial and public services constituted 13%, households represented 12%, and transport comprised 24%. As of 2022, these figures shifted to 45%, 16%, 15%, and 24%, respectively, indicating that energy-saving measures have seen less advancement in the commercial and public services and household sectors compared to the industrial sector (International Energy Agency, 2023).

Nevertheless, some governments have formulated optimistic plans for energy conservation in the household sector in response to the Paris Agreement. For instance, the Japanese government has enacted a plan aimed at reducing carbon dioxide (CO_2) emissions from the household sector by 66% compared to 2013 levels by FY2030 (Ministry of Environment of Japan, 2024a). Government policies aimed at managing households must be implemented more gradually than those for the industrial sector because of the significant challenges associated with enforcing regulations that drive rapid changes in household behavior. Governments often recognize that behavioral change requires time and patience. This awareness is evidenced by the introduction of incentive programs to encourage individuals to adopt desirable practices. Household management limitations also apply to initiatives aimed at addressing global warming, such as the carbon pricing programs many countries are implementing to promote household energy conservation.

Carbon pricing is widely recognized as an effective strategy for mitigating global warming. However, the tax burden it imposes on households based on their CO_2 emissions can cause significant financial strain for some households (Reiss et al., 2005). This concern has prompted extensive debate regarding implementing an appropriate compensation system alongside carbon pricing. Numerous studies have addressed this issue by categorizing households according to income and evaluating the financial implications for each income group (Callan et al., 2009; Rausch et al., 2011; Farrell, 2017; Silva et al., 2017).

The characteristics of household energy consumption raise important questions regarding the suitability of a carbon pricing compensation scheme that relies solely on household income. First, energy services can be shared among family members, which creates economies of scale (Ironmonger et al., 1995; Schröder et al., 2015; Wu et al., 2021; Inoue et al., 2022). Consequently, smaller families may bear a heavier burden than larger ones due to carbon pricing, even when their incomes are similar. Second, households utilize energy for various purposes, and potential energy savings differ among these uses. Even among households with similar incomes, those who rely more heavily on energy for specific activities may face a disproportionately high financial impact due to carbon pricing. In light of these factors, a compensation scheme for CO_2 emissions based solely on income may not be the most effective approach. This necessitates a solution that considers differences in household composition, energy sources, and weather conditions. Our study leverages microdata to thoroughly examine how these factors influence household energy use.

The remainder of this paper is organized as follows. Given widespread knowledge of the reasons previously outlined, there has been a notable increase in studies analyzing household energy consumption using microdata. Section 2 summarizes these studies based on the results of a literature review and highlights the distinctive characteristics of our research, which uses Japanese Household Energy Survey data. In Section 3, we discuss the content of the survey and summarize the collected data.

Section 4 defines energy consumption during the month of June, the time of year when energy consumption in Japan is at its lowest, as the minimum energy requirement (MER) and reports the results of an investigation of how household income, floor area, energy source combinations, and family structure influence the MER. This MER analysis illustrates the functioning of economies of scale in household energy consumption under conditions where energy use for temperature regulation is minimal. The results of our analysis suggest that the economies of scale in household energy consumption exceed those typically assumed in the calculation of equivalent income. Therefore, if energy taxes are levied based on conventional equivalent income indicators, smaller households are likely to bear a disproportionately greater financial burden.

In Section 5, the focus will be on energy consumption associated with adaptation to weather conditions. While household energy consumption generally increases during the winter months, the magnitude of this increase is expected to vary according to household composition. This section compares winter energy use (WEU) with MER to examine how the rate of growth in winter energy consumption differs across household types. The analysis indicates that low-income households experience a higher rate of increase in winter energy consumption and consequently utilize more energy for weather adaptation.

Households utilize energy for a range of purposes, and the mechanisms through which economies of scale operate may vary according to the specific type of energy use. For instance, heating services can be shared among household members, whereas electricity consumption for devices such as computers is typically individual and non-shareable. In Section 6, energy consumption is categorized into five distinct types: space heating, cooling, water heating, cooking, and appliance use. The section examines how economies of scale manifest in each category of energy service. The results suggest that per capita energy consumption for space heating, cooking, and appliance use decreases significantly as the number of household members increases.

Finally, Chapter 7 summarizes the findings of this study on household energy consumption and discusses policy implications.

2. LITERATURE REVIEW

Economists have investigated household energy consumption and placed particular emphasis on the price and income elasticities of energy demand. Although extensive research has been conducted on the price elasticities of gasoline used for transportation, there has been less analysis of those of energies consumed in the home, with electricity being the notable exception. Labandeira et al. (2017) performed a meta-analysis of 428 studies published in academic journals between 1990 and 2016 to assess the price elasticity of demand for various types of energy in the short and long term. Those scholars' results indicate that the price elasticity of energy demand has declined since the oil shocks, rendering the promotion of energy conservation through price increases difficult. Elasticity varies by energy type, with heating energy exhibiting particularly low elasticity. Furthermore, the results of analyses based on aggregate data often differ from those based on microdata, with the latter typically yielding a higher estimate of short-term price elasticity.

A considerable amount of research has been dedicated to estimating income and expenditure elasticities. A value above one indicates that as individuals become wealthier, their energy consumption tends to rise. To investigate this relationship, studies have employed panel data from various countries to examine the correlation between income levels and energy consumption. These investigations have confirmed that income elasticity is below one, reinforcing the notion that energy is regarded as a necessity (Meier et al., 2013; Liddle and Huntington, 2020; Gao et al., 2021; Kostakis et al., 2021).

Conducting an analysis using aggregated data is effective for gaining a general understanding of energy consumption in the household sector. Analyzing microdata is also acknowledged as a valuable approach, given the critical roles of various factors such as household characteristics, housing attributes, and weather conditions in influencing energy consumption patterns (Harold et al. 2015). As Baker et al. (1989) and Baker and Blundell (1991), there has been an increasing trend of using microdata to study household energy consumption (Nesbakken, 1999, 2001). For example, researchers have analyzed microdata to assess the price or income elasticity of energy demand segmented by income group (Romero-Jordán, 2016; Harold, 2017; Schulte and Heindl, 2017; Galvin et al., 2024). The present study builds upon current trends in household energy consumption analysis using microdata and expands the analysis to incorporate additional methods.

Economies of scale are widely known to influence household energy consumption (Ironmonger et al., 1995; Schröder et al., 2015; Andor et al., 2020; Wu et al., 2021). However, researchers have examined the relationship between total and per capita energy consumption and the number of individuals comprising a household without formally defining this concept. The first objective of this study is to propose a model that explicitly describes the impact of economies of scale on household energy consumption.

Recent research has investigated the relationship between aging and energy consumption patterns, and the results indicate that the type and quantity of energy services individuals require evolve with age. Notably, the demand for space heating becomes increasingly significant as individuals age (Liao et al., 2002; Bardazzi and Pazienza, 2017; Inoue et al., 2021). However, due to data limitations, the analysis of energy demands beyond space heating and cooling has received insufficient attention. The second objective of this study is to explore how energy consumption, categorized into five uses (space heating, space cooling, hot water supply, cooking, and lighting), varies based on household composition.

Typical households utilize multiple energy sources that have a degree of substitutability among them. For example, electricity and kerosene can both be used to heat a room, but kerosene is not a practical alternative to electricity for operating a washing machine. Given that households rely on various combinations of energy sources, understanding their substitutability is essential. However, interest in this topic has been limited until now (Krauss, 2016; Matsumoto, 2023). The final objective of this research is to examine the differing energy consumption patterns among households that choose different combinations of energy sources.

3. DATA AND METHODS

3.1. Data Source

This study utilizes microdata obtained from the Japanese Ministry of the Environment's Survey on Carbon Dioxide Emissions in the Household Sector (SCDEH) in the years 2014, 2017, and 2018. The 2014 survey was administered from October to September, and the subsequent surveys were conducted from March to April of their respective years. The methodology combined face-to-face interviews and online approaches, and the survey encompassed households from all regions of Japan.

The survey data reflect socioeconomic characteristics, housing details, and monthly energy consumption for various types of households. The survey is cross-sectional, but energy consumption is asked about on a monthly basis. This study concentrates on the following aspects: total energy consumption for June (summer) and January (winter), estimated energy consumption by purpose, household income, living space, temperature, and household composition, specifically the number of working-age family members aged 20-64 years, the number of seniors aged 65 years and older, and the number of children under age 20 years. Although each respondent household was asked to indicate their income bracket, this study utilizes the median value in each bracket as the representative household income.

Over the course of the 3-year survey, a total of 31,133 households participated. However, we excluded 4,544 households due to insufficient data. Households were instructed to report their energy usage based on their payment statements, but some reported exceptionally high or low consumption. To ensure the reliability of our data, we excluded records from households whose per capita energy consumption fell within the top and bottom 1% ranges. Consequently, the number of households included in the analysis was 26,057.

3.2. Summary Statistics

Table 1 provides the descriptive statistics of the variables used in this study. Section 4 will report the results of an analysis of the relationship between the minimum energy requirement (MER) and household composition in June, a period when energy consumption tends to be at its lowest. Section 5 discusses how variations in household composition impact the rate of increase in energy consumption during the winter months based on the comparison

Table 1: Descriptive statistics

Variable	Unit	Sample	Mean or share	Standard error
Energy consumption (monthly)				
Minimum energy requirement in June (MER)	GJ	26,057	1.89	1.19
CO_2 emissions in June	kg	26,057	212.53	131.55
Winter energy usage in January (WEU)	GJ	26,057	5.44	3.70
Energy consumption by purpose (annual)				
Space heating	GJ	22,519	11.65	13.02
Space cooling	GJ	19,943	1.05	1.14
Water heating	GJ	24,566	12.21	9.33
Cooking	GJ	24,656	2.22	2.24
Appliance use	GJ	24,767	12.08	6.31
Housing characteristics				
Floor area	m^2	26,057	110.58	57.87
Age of house	Years	26,057	25.52	13.95
Detached house	Dummy	26,057	0.68	
Housing ownership	Dummy	26,057	0.77	
Weather and economic conditions				
Heating degree days	Unit	26,057	705.37	195.96
Income	JPY 10,000	26,057	570.71	376.54
Household composition				
Senior head	Dummy	26,057	0.33	
Working age	Persons	26,057	1.59	1.05
Senior	Persons	26,057	0.63	0.83
Child	Persons	26,057	0.52	0.90

between MER and WEU. Section 6 explores the relationship between energy usage by purpose and household composition. Furthermore, with reference to previous studies, as discussed in Section 2, we include housing characteristics, weather conditions, and income as control variables.

4. RESULTS AND DISCUSSION

4.1. Economies of Scale in the Minimum Energy Requirement

Household energy consumption in Japan is the lowest in June. We refer to energy consumption during June as the MER and analyze how it differs between households. The MER represents the energy a specific household requires for daily life in the month with the most favorable weather conditions. The solid line in Figure 1 illustrates the kernel density estimation of the logarithm of the MER.

Before exploring how household composition affects the MER, we first examine the variance of MER with household size. Columns 3 and 4 of Table 2 show the average MER per household and person, respectively, categorized by household size. The data reveal that the household MER increases with the number of household members, whereas the per person MER declines. This suggests the presence of economies of scale in household energy consumption.

Figure 1: Kernel density estimation (June, 2014, 2017, and 2018, N = 26,057)

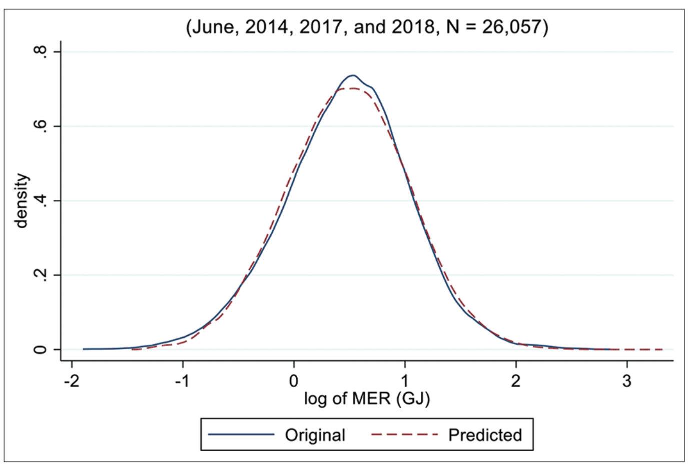

Table 2: Economies of scale in household energy consumption (June)

Number of family members	Frequency	Mean MER (GJ)	
		Per household	Per person
1	4,530	1.17	1.17
2	8,477	1.72	0.86
3	5,954	2.03	0.68
4	4,629	2.25	0.56
5	1,603	2.60	0.52
6	605	2.99	0.50
7	201	3.22	0.46
8	43	3.52	0.44
9	10	4.00	0.44
10	5	3.29	0.33
Total	26,057		

Numerous studies have utilized microdata to estimate the income elasticity of energy demand. Table 3 highlights how per household and per person MER increase with household income. The data reveal that although the MER rises with income, its increase is not proportional. For example, moving from the lowest to the highest income group results in a more than eightfold income increase, but the corresponding rise in the MER is less than double. This discrepancy can be attributed to the fact that energy is considered a necessity. Although the per household MER and per capita energy consumption grow as household income increases, the growth rate is less than that of overall household income.

The number of people comprising a household typically changes as individuals age: Children become adults who leave their parent's home to live independently and may eventually partner and start a family, and when those children become independent adults, many couples return to a household comprising only two persons. Research has shown that energy consumption patterns also shift with age: Older individuals often spend more time at home, leading to increased energy usage for heating during the winter months. Considering these lifestyle changes, household energy consumption is influenced by the number of people in a household and their ages.

This study assumes that the MER of household *i* is characterized by Eq. (1):

$$MER_i = \begin{bmatrix} E_0 \left(Inc_i\right)^{\beta_I} \cdot \left(Floor_i\right)^{\beta_F} \cdot \left(Built_i\right)^{\beta_B} \\ \cdot \left(1+D_i^H\right)^{\beta_H} \cdot \left(1+D_i^O\right)^{\beta_O} \end{bmatrix} \left[\left(1+D_i^S\right)^{\beta_S} \cdot \prod_{g=1}^{3}\left(1+n_i^g\right)^{\beta_g}\right] \quad (1)$$

Where E_0 is constant term, *Inc* is income, *Floor* is floor area, and *Built* is the age of house. D^H is a dummy variable that takes a value of one if a residence is a detached house and zero if it is a collective house. D^O is another dummy variable that takes a value of one if an occupant of a house owns it and zero if they do not. The contents of the first square parentheses in Eq. (1) represent the primary determinant of household energy consumption.

The contents of the second square parentheses yield the impact of household composition on energy consumption, where D^S is a dummy variable that takes a value of one if the household head

Table 3: Income effect on household energy consumption (June)

Income class (JPY millions)	Frequency	Mean MER (GJ)	
		Per household	Per capita
<2.5	4,462	1.37	0.79
2.5-5.0	9,094	1.79	0.78
5.0-7.5	6,016	2.00	0.76
7.5-10.0	3,922	2.19	0.79
10.0-15.0	2,055	2.37	0.84
15.0-20.0	345	2.56	0.89
>2,000	163	2.60	0.99
Total	26,057		

is aged 65 years or over. Family members are classified into three age groups: Individuals aged 20-64 years are working age, those aged 65 years and over are seniors, and those under the age of 20 years are children. n^g represents the number of family members excluding the household head in age group g, that is, additional family members.

We use Eq. 2, the logarithm of Eq. 1, as the estimation model:

$$\ln MER_i = \beta_0 + \beta_I \ln Inc_i + \beta_F \ln Floor_i + \beta_B \ln Built_i + \beta_H \ln\left(1+D_i^H\right) + \beta_O \ln\left(1+D_i^O\right) + \beta_S \ln\left(1+D_i^S\right) + \sum_{g=1}^{3} \beta_g \ln\left(1+n_i^g\right) + \varepsilon_i \quad (2)$$

where $\beta_0 = \ln E_0$. Previous research has identified substantial variability in household energy consumption, as well as marked differences in the income and price elasticities of energy demand. In response to these findings, Romero-Jordán (2016) and Harold et al. (2017) advocated for the application of quantile regression as a methodological approach to more accurately capture these fluctuations. Consistent with their recommendations, the present study also employs quantile regression analysis. Detailed findings are provided in Appendix 1. Among these findings, the dotted line in Figure 1 represents the predicted kernel density obtained from the quantile regression, which closely mirrors the original kernel density.

An increase in income results in a rise in the MER, but the effect is relatively modest. Specifically, a 1% income increase corresponds to an MER rise of only 0.05-0.07%. Floor area also impacts the MER, with a 1% increase in floor area leading to a 0.07-0.11% increase in the MER. Thus, the influence of floor size on the MER is considerably more significant than that of income.

Table 4 presents the results of the quantile regression analysis based on Equation (2), illustrating the extent to which energy consumption varies across different household structures relative to single-person households. Therefore, a comparison of Rows 1 and 2 in Table 4 shows that the MER of a single senior is 2-6% higher than that of a single working-age person. This difference can be attributed to a pure aging effect (Inoue et al., 2021, 2024). Furthermore, the results presented in Table 4 reveal that adding one adult to a family results in an approximately 45% increase in the MER, whereas adding one child leads to only about a 20% increase. This highlights significant disparities in the increasing effect on the MER between adults and children.

Table 4: Economies of scale in household energy consumption: Equivalent scale[1] (June)

Quantile	10th	30th	50th	70th	90th
1. Single working age	1	1	1	1	1
2. Single senior	1.06	1.05	1.04	1.03	1.02
3. Working age couple	1.47	1.46	1.45	1.43	1.40
4. Senior couple	1.50	1.48	1.43	1.39	1.38
5. Single parent+one child	1.21	1.21	1.20	1.20	1.19
6. Working age couple+one child	1.78	1.77	1.74	1.71	1.66
7. Working age couple+two children	1.99	1.97	1.94	1.90	1.84

The superscript 1 indicates the number of times the energy consumption of the corresponding household is compared to that of a single-person household. Income and floor area are assumed to remain constant

These estimation results underscore two key points. First, the MER derived from these estimates is lower than the equivalent income calculated for total household consumption (Chanfreau and Burchardt, 2008).[1] This discrepancy arises because family members can share energy services, unlike food and clothing. Second, economies of scale in household energy consumption are more evident among seniors, suggesting that older individuals tend to consume energy more independently.

In Japan, households rely on a diverse range of energy sources, such as electricity, city gas, liquefied petroleum gas (LPG), and kerosene, and frequently employ a combination of these options. Our analysis investigates whether the impact of household composition differs among households that utilize various combinations of these energy sources. Households typically do not use city gas and LPG simultaneously; therefore, we categorize households into six types based on their energy source combinations: (1) electricity only, (2) electricity and city gas, (3) electricity and LPG, (4) electricity and kerosene, (5) electricity, city gas, and kerosene, and (6) electricity, LPG, and kerosene[2].

Table 5 illustrates the impact of increased household members across various energy source combinations. In addition to the findings for the MER, the results for CO_2 emissions (measured in kilograms) are presented in italics.

Among the surveyed households, 13% are classified as Type 1, comprising those that use only electricity. Among households comprising a single person of working age, Type 1 households demonstrate higher energy consumption than those of other types. Contrastingly, 12% of the households are identified as Type 3, that is, utilizing both electricity and LPG. Notably, single-person Type 3 households exhibit the lowest energy consumption across all categories.

The results based on CO_2 emissions differ from those derived from comparisons of the MER. Type 4 households that use both electricity and kerosene record the highest CO_2 emissions. Type 5 households that rely on electricity, city gas, and kerosene produce the least emissions.

In all groups, the MER and CO_2 emissions rise with an increase in household size. However, the extent of this impact varies among groups. The results reported in Table 5 indicate a particularly significant effect of an increase in the number of household members among Type 2 and 3 households that use electricity and

1 The equivalent income of an adult is 1.7 on the original Organisation for Economic Co-operation and Development (OECD) scale and 1.5 based on the revised OECD scale. These values exceed our estimate of 1.45. Research based on the Poverty Exclusion Survey (PES) has shown more pronounced economies of scale among couples, with an equivalent income for couples estimated at approximately 1.43. This scale value aligns closely with our estimate of 1.45 for working-age couples. However, the PES scale value for couples with one child is 1.93, which exceeds our estimate of 1.74.

2 Households were classified into six groups based on the type of energy consumed and characteristics of their residential area.

Table 5: Economies of scale by energy source combinations (June)

Energy combination	Number of households		Single working-age household Adult	Equivalent scale (q50)[1]		
				Senior	Child	
1. Electricity only	3,294	13%	1.27 GJ	1.29	1.29	1.09
(CO_2)			185.97 kg	1.25	1.30	1.08
2. Electricity and city gas	6,558	25%	1.12 GJ	1.51	1.41	1.23
(CO_2)			107.77 kg	1.42	1.45	1.20
3. Electricity and LPG	3,127	12%	0.93 GJ	1.57	1.44	1.24
(CO_2)			114.81 kg	1.55	1.53	1.24
4. Electricity and kerosene	3,064	12%	1.28 GJ	1.31	1.34	1.19
(CO_2)			186.53 kg	1.30	1.34	1.16
5. Electricity, city gas, and kerosene	4,070	16%	1.26 GJ	1.46	1.38	1.23
(CO_2)			126.22 kg	1.40	1.35	1.19
6. Electricity, LPG, and kerosene	5,944	23%	1.20 GJ	1.45	1.37	1.26
(CO_2)			139.50 kg	1.41	1.37	1.20
	26,057					

The superscript 1 indicates the number of times the energy consumption of the corresponding household is compared to that of a single-person household. Values are in the 50th quantile

gas. When the size of a Type 2 or 3 household increases from comprising one individual to two persons, the MER increases by over 50%; however, Type 1 and 4 households, which primarily rely on electricity and kerosene, experience a modest rise in the MER under the same circumstances. This is primarily because the MER of Type 1 and 4 households is more strongly influenced by factors other than household size.

4.2. Growth in Winter Energy Usage

Winter energy consumption is widely known to represent a substantial share of a household's annual energy use. Hence, we compare the WEU in January, the month when energy consumption usually peaks, with the MER. Additionally, we explore the relationship between household composition and increased WEU owing to lower temperatures.

We assume that WEU can be characterized by the following equation:

$$WEU_i = MER_i \begin{bmatrix} \left(HDD_i\right)^{\gamma_H} \cdot \left(Inc_i\right)^{\gamma_I} \cdot \left(Floor_i\right)^{\gamma_F} \\ \cdot\left(1+D_i^H\right)^{\gamma_H} \cdot \left(1+D_i^O\right)^{\gamma_O} \end{bmatrix}$$
$$\left[\left(1+D_i^S\right)^{\gamma_S} \cdot \prod_{g=1}^{3}\left(1+n_i^g\right)^{\gamma_g}\right] \quad (3)$$

Where *HDD* represents the heating degree days of household *i*. We analyze how factors such as income, living space, and family structure contribute to increasing the MER. To execute the empirical estimation, we estimate Eq. 4, which is a modification of Eq. 3[3]:

$$\ln\left(\frac{WEU_i}{MER_i}\right) = \gamma_S \ln HDD_i + \gamma_I \ln Inc_i + \gamma_F$$
$$\ln Floor_i + \gamma_H \ln\left(1+D_i^H\right) + \gamma_O \ln\left(1+D_i^O\right)$$
$$+\gamma_S \ln(1+D_i^S) + \sum_{g=1}^{3}\gamma_g \ln(1+n_i^g) + \omega_i. \quad (4)$$

3 In Equation (3), it is assumed that MER is affected by changes in weather conditions. Since Equation (4) aims to evaluate this rate of change, the analysis is performed without including constant terms.

Table 6 summarizes the estimation results. Heating degree days (HDD) are positive and statistically significant at the 1% level across all models, indicating that households in colder regions experience a more substantial increase in WEU. Specifically, the estimates reveal that an average 1% rise in HDD is associated with a 0.6% increase in winter energy consumption.

However, the growth rate varies among households that rely on different energy sources. For example, a comparison of Type 1 and 4 households with those classified as Types 2 and 5 and Types 3 and 6 shows a lower growth rate among households that use gas and a higher growth rate among those that use kerosene. Additionally, a comparison of Type 2 and 3 or Type 3 and 6 households shows a lower growth rate among those that use city gas compared to those that use LPG.

Income exerts a negative and statistically significant impact at the 1% level across all models. This negative effect can be elucidated as follows: The MER of high-income households exceeds that for low-income households; consequently, even if energy consumption increases equivalently with temperature decreases, high-income households will show a lower growth rate than low-income households. Moreover, if the energy consumption of high- and low-income households increases by the same amount during winter, the difference between the WEU and MER, according to Eq. 4, will be identical for both types of households. However, as the MER of high-income households is higher, their growth rate will be lower. Moreover, high-income households are more inclined than their low-income counterparts to invest in energy-efficient technologies (Ameli and Brandt 2015). Therefore, even when both household types escalate their energy service usage uniformly as temperatures decline, high-income households will exhibit a greater capacity to limit their overall energy consumption. Despite the notable negative impact of income, its magnitude remains relatively minor. Specifically, a 10% increase in income is associated with only about a 1% reduction in the growth rate of winter heating usage.

The overall relationship between floor area and energy consumption is negative, indicating that increased energy consumption is less pronounced in households with larger living spaces. This phenomenon is likely observable because central

Table 6: January-June comparative winter energy use intensity

Variable	Unit	All	Combination of energy sources					
			1.	2.	3.	4.	5.	6.
Households		26,057	3,294	6,558	3,127	3,064	4,070	5,944
Heating degree days	1%	0.29**	0.2**	0.18**	0.22**	0.28**	0.24**	0.38**
Income	1%	−0.09**	−0.08**	−0.03**	−0.06**	−0.06**	−0.06**	−0.10**
Floor area	1%	−0.10**	−0.11	−0.05**	−0.08**	−0.08*	−0.01	−0.15**
Age of house	1%	−0.04**	−0.06**	−0.02**	−0.07**	−0.05**	−0.02	−0.09**
Detached house	Dummy	39.97**	29.33**	27.48**	18.07**	33.08**	31.17**	27.38**
Housing ownership	Dummy	9.03**	18.48**	7.47**	6.88**	10.67*	1.81	9.26*
Senior head	Dummy	1.67**	−3.60*	4.95**	2.98*	0.17	2.59	0.86
Working age	1 person	0.15	3.77*	−0.58	2.06	−2.32	−6.45**	−3.38*
Senior	1 person	0.91	5.38*	−1.98	4.63*	−0.76	−6.44**	−2.52
Child	1 person	−4.29**	−1.15	−1.30	1.95	−6.45**	−7.11**	−8.70**
Adjusted R^2		0.79	0.85	0.83	0.74	0.83	0.85	0.76

The values represent the expected percentage changes. ** and * indicate statistical significance at 1% and 5%, respectively

heating systems are not widely utilized in Japanese homes except in certain cold regions; only rooms that are actively used are heated. Consequently, as the number of rooms (and thus the floor area) increases, the number of unused rooms also increases, resulting in a reduced energy consumption growth rate during the winter months.

The age of a house is indicated by a negative value. This result initially seems to contradict expectations as older homes generally exhibit lower airtightness and, therefore, greater energy loss. However, as shown in Appendix 1, residents of older houses tend to consume more energy during the summer than those in newer homes. This observation implies that the rate of increase in WEU may not be as significant.

The dummy variable for detached houses is statistically significant at the 1% level. The coefficients reveal that the winter energy consumption growth rate in detached houses is 30-40% higher than that in apartment buildings, demonstrating a notable difference between the two.

Furthermore, the estimation results of our analysis of the energy consumption patterns of owner-occupied households compared to rented households show an approximately 9% higher winter energy consumption growth rate among owner-occupied households. This may seem counterintuitive, given that renters typically invest less in energy-saving measures. However, the discrepancy is likely attributable to the fact that the residents of owner-occupied households tend to spend more time at home than their renter counterparts.

The dummy variable for households headed by seniors shows a positive effect across all models except those analyzing all-electric homes. The presence of a senior household head correlates with an average increase of 1.67% in the MER. This outcome can be explained by older individuals' tendency to spend more time at home, during which they frequently endeavor to maintain a warmer living environment, resulting in higher energy consumption during the winter months.

The impact of an increased number of family members on the growth of winter energy consumption is somewhat complex. If we denote the MER for households with one or two individuals as MER_1 and MER_2, respectively, and if the additional energy each household consumes in winter is represented as ΔE_1 and ΔE_2, the sign of the variable is determined by comparing MER_2/MER_1 and $\Delta E_2/\Delta E_1$. In essence, if the economies of scale related to energy use during winter surpass those in summer, the sign will be positive. This relationship depends on the intended purpose and method of energy consumption.

The data on working age, senior, and child demographics in Table 6 elucidate the extent to which the WEU growth rate is affected when the number of individuals in each age category increases by one. For example, an additional child leads to an average growth rate decrease of 4.29%; contrastingly, the growth rate is unaffected by an increase in the number of working-age or elderly individuals. Such variance in the effects of age is likely attributable to differences in time spent at home and variations in heating practices. Furthermore, numerous negative correlations are evident in Type 4-6 households that use kerosene, indicating that, for these households, the economies of scale associated with winter usage are more prominent than those associated with summer usage.

4.3. Energy Consumption by Purpose

Ascertaining the amount of energy used in a home by purpose is inherently difficult. For this reason, estimated values based on certain assumptions are necessary for analysis. In this study, we rely on the estimates published by the SCDEH, which classifies energy consumption into five distinct categories, namely space heating, space cooling, water heating, cooking, and lighting and appliance use, and calculates the total energy consumed in each category (Appendix 2).

Table 7 presents the findings of a quantile regression analysis investigating the effects of family structure, weather conditions, income, and floor area on energy use for various purposes. As anticipated, HDD positively influences energy consumption related to space and water heating, indicating that colder regions exhibit higher energy use for heating. Conversely, HDD negatively impacts space cooling, suggesting that areas with cooler temperatures typically have lower cooling demands.

Table 7: Economies of scale in annual energy use by purpose: Quantile regression q50

Number of households	Unit of increase	Space heating	Space cooling	Water heating	Cooking	Appliance use
		20,188	17,784	21,994	22,067	22,163
Heating degree days	1%	2.66**	−0.92**	0.51**	−0.08*	−0.08**
Income	1%	0.04**	0.03*	0.07**	0.01	0.05**
Floor area	1%	0.27**	−0.06*	0.05**	0.01	0.14**
Age of house	1%	0.17**	−0.02	0.07**	0.18**	−0.02**
Detached house	Dummy	2.23**	1.09**	0.94**	0.82**	1.23**
Housing ownership	Dummy	0.89**	1.00	1.01	0.99	1.03**
Senior head	Dummy	1.12**	0.98	1.05**	1.07**	1.02**
Adult	1 person	1.30**	1.45**	1.62**	1.32**	1.31**
Senior	1 person	1.28**	1.40**	1.42**	1.34**	1.30**
Child	1 person	1.07**	1.18**	1.27**	1.18**	1.11**
Pseudo R^2		0.24	0.08	0.14	0.10	0.22

The values are the expected percentage changes. ** and * indicate statistical significance at 1% and 5%, respectively

The variable representing senior-led households shows a negative and statistically significant impact at the 1% level across all energy uses except space cooling. This pattern is likely a result of seniors spending more time at home and their specific biological needs. Senior-headed households consume 12% more energy for space heating than those headed by working-age individuals.

Household income positively affects energy consumption across all categories; however, the effect is somewhat modest. Energy consumption related to heating, hot water, and electrical appliances rises with increased floor area, with heating showing the most significant increase. As demonstrated in Table 6, households with larger floor areas experience a lower energy consumption increase rate from summer to winter, but their total energy usage rises more substantially. Similarly, households residing in older homes tend to exhibit a lower energy consumption increase rate compared to those in newer residences, but the former face a greater overall increase. Additionally, households living in detached houses consume notably more energy for heating than those in apartment buildings. Conversely, households in owner-occupied residences typically use less energy for heating than rental property tenants. The results are consistent with those of previous studies, such as those of Rehdanz (2007) and Meier and Rehdanz (2010).

Moreover, the results reported in Table 6 illustrate a varied effect of economies of scale depending on the intended energy use. Regarding hot water supply, economies of scale are less effective compared to other applications, primarily due to the challenges associated with sharing hot water, whereas energy used for space heating, cooking, and appliance usage can be shared among family members, resulting in a more pronounced effect of economies of scale.

5. CONCLUSION

A larger household size typically results in lower energy consumption due to the benefits of economies of scale; however, the specific mechanisms driving this phenomenon are not well understood. This study used microdata to examine the influence of economies of scale on the MER, energy consumption growth rate from summer to winter, and energy consumption by purpose. The analytical results indicate that economies of scale are more pronounced for the MER than is often assumed in discussions regarding equivalent income. Many developed countries anticipate rapid population aging, leading to a significant increase in single-person households. This shift will diminish the economies of scale associated with household energy consumption, creating a greater need for support targeting smaller households.

Moreover, our study has identified considerable variations in energy use based on residents' age. Whereas the presence of children minimally impacts energy consumption, the presence of seniors significantly affects it. Notably, compared to working-age individuals, elderly residents require more energy to heat their homes during winter. These findings suggest that enhancing the airtightness of elderly residents' homes could be an effective energy conservation strategy.

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APPENDIX

Appendix 1: Minimum energy requirement estimation results

The MER is estimated by Eq. 2, a logarithm of Eq. 1, used as the estimation model:

$$\ln MER_i = \beta_0 + \beta_I \ln Inc_i + \beta_F \ln Floor_i + \beta_B \ln Built_i + \beta_H \ln\left(1+D_i^H\right) + \beta_O \ln\left(1+D_i^O\right) + \beta_S \ln\left(1+D_i^S\right) + \sum_{g=1}^{3} \beta_g \ln\left(1+n_i^g\right) + \varepsilon_i \quad (2)$$

where β_I and β_F measure elasticities and show the percentage change in the MER caused by a 1% increase in income and floor space. β_S and β_g evaluate the impacts of family structure changes. Specifically, β_S represents the MER change when the household head becomes a senior, and β_g represents the same when the number of family members increases. If $\beta_S > 0$, then the energy consumption of the senior-headed household exceeds that of the working-age adult-headed household. If $\beta_S < 1$, an economy of scale in household energy consumption is indicated.

Quantile regression analyses yielded statistically significant results for all variables except home ownership type (Table A1). The marginal effects of the variables differ across the quantiles. Specifically, the impact of an increase in household size is more substantial in the lower quantiles, where energy consumption is low. This indicates that in households with minimal initial energy use, an increase in the number of occupants leads to a significant rise in energy consumption.

Appendix 2: Estimation of energy consumption by use

The SCDEH categorizes energy consumption into five primary areas: space heating, space cooling, water heating, cooking, and lighting and appliance usage. The methodology for calculating energy consumption in each category is outlined as follows.

Electricity is applicable for all five purposes. Gas is conventionally utilized for space and water heating as well as cooking, whereas kerosene is employed for space and water heating. The specific combination of the energy sources a household uses provides a reference point to ascertain the allocation of energy for each purpose. The total amount of energy consumed is apportioned to the five categories according to a defined procedure.

Regarding the energy quantity used for cooking derives from the findings of metering surveys. The estimation of energy used for water heating is based on the assumption that a stable volume of hot water is utilized throughout the year. Given that the survey spans 12 consecutive months, monthly variations are integrated into the estimations of heating and cooling energy consumption.

To determine the electricity allocated to lighting and appliances, the total energy consumed is adjusted by deducting the energy utilized for space and water heating, cooking, and space cooling. Regarding gas, the survey collects data regarding cooking frequency to assess the quantity of gas used for cooking and any residual gas is assumed to be designated for space and water heating. The quantities of gas utilized for space and water heating are calculated under the premise that the daily demand for hot water remains constant. Kerosene is assumed to serve both hot water supply and heating functions, thereby facilitating the calculation of quantities used for these purposes. Please refer to the Ministry of Environment of Japan (2024b) for more detailed assumptions.

Table A1: Quantile regression estimation results

Variables	Parameters	Quantile				
		q10	q30	q50	q70	q90
Income	β_I	0.07**	0.07**	0.07**	0.06**	0.05**
Floor area	β_F	0.09**	0.07**	0.08**	0.09**	0.11**
Age of house	β_B	−0.16**	−0.09**	−0.01	0.05**	0.14**
Detached house	β_H	0.01	0.03**	0.03**	0.04**	0.04**
Housing ownership	β_O	0.05	0.04	0.01	0.00	0.01
Senior head	β_S	0.08**	0.07**	0.06**	0.04*	0.03**
Adult	β_g	0.55**	0.55**	0.54**	0.52**	0.48**
Senior	β_g	0.50**	0.49**	0.46**	0.43**	0.43**
Child	β_g	0.28**	0.27**	0.26**	0.26**	0.25**
Constant	β_0	0.08**	0.07**	0.06**	0.04*	0.03**

One hundred bootstrap replicates were performed. The values are the expected percentage changes. ** and * indicate statistical significance at 1% and 5%, respectively