Energy expenditure and electrification progress by household heterogeneity in Japan*

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Overview

Electrification has been expected as one of the important solutions for energy conservation and decarbonization in the household sector. Japan's Sixth Basic Energy Plan, approved by the Cabinet in October 2022, also points out the importance of promoting electrification with decarbonized electricity. However, the current progress of electrification in the Japanese household sector is insufficient. In the previous studies, various factors, including cost factors, have been pointed out to promote or hinder energy conservation and electrification in the household sector (Klockner et al., Wilson et al.). We compiled a survey of nearly 40,000 data points on household energy demand in Japan, focusing on the diversity of households, including regional differences, housing type, income, household size, temperature, and electricity prices. Our study confirmed that more significant energy expenditure burden and less-advanced electrification in cold regions and low-income households. We used a logit model to find the barriers for promoting all-electric houses in the household sector. We confirmed that the increase in heating degree days and the rise in electricity prices are disincentives for all-electric, especially in cold regions.

1. Introduction

In Japan, there is an urgent need to reduce CO_2 emissions in the consumer sector in order to achieve carbon neutrality by 2050. As a measure to reduce CO_2 emissions in households, the importance of energy conservation through electrification and the decarbonization of electricity has been emphasized.

Pallonetto et al. analyzed the energy savings and CO_2 reductions achieved by retrofitting existing detached houses in Ireland to all-electric homes. They found that up to 45% of energy savings and approximately 29% of CO_2 emissions reduction could be achieved by combining solar power generation equipment, geothermal heat pumps, and electric vehicle chargers with building structural improvements.

Beauchampet et al. interviewed local government officials about efforts to de-gas in the household sector in the Netherlands. They pointed out that all-electrification is an important option along with heat supply networking, while all-electrification faces cost issues. According to the survey, the average payback period for energy conservation and all-electrification retrofits is more than 30 years.

Klockner et al. surveyed the decision-making factors for energy-saving investments such as home renovations in Norway. The results illustrated the importance of energy cost reduction in addition to comfortability and living environment.

Wilson et al. analyzed the energy savings potential and economic impact by region for single-family

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homes in the United States. They noted that the cost-effectiveness of electrification measures depends on factors such as fuel and electricity prices, climate, heating and cooling conditions of the home, and a durable year of equipment to be replaced.

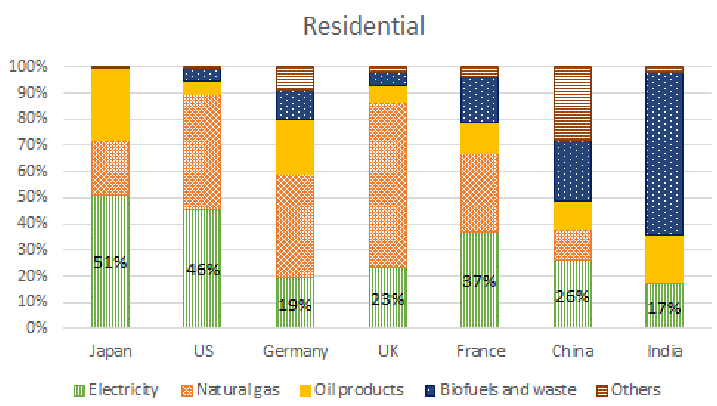
Khezri et al. compared the NPV(Net Present Values) of all-electric and combined gas-electric households in Australia, assuming each household with PV and storage batteries, with PV only, and without PV and storage batteries. The results showed that PV and storage battery systems are more economical for all-electric households. At the same time, it found that the NPV is higher for combined gas-electric households without PV and storage batteries.

Padovani et al. analyzed the potential of electrification for a typical house in a cold region of the U.S. Midwest where natural gas is not available. They confirmed that electrification can be beneficial for heating demand in cold climates by using heat pumps together with photovoltaic power generation.

Nishio et al. estimated the CO_2 reduction potential generated by electrification of household equipment, energy-using devices, and automobiles in the seven industrialized countries, including Japan. They pointed out that reducing CO_2 intensity of electricity is crucial not only for energy saving but also for CO_2 reduction.

Figure 1. illustrates the composition of household sector energy demand as of 2019 in major countries. In Japan, electricity demand accounts for a large percentage of final energy consumption. It dominates 51% share of household final energy consumption, while those of Germany and UK are 19% and 23%, respectively. However, focusing on electricity consumption by regions in Japan, various characteristics are observed.

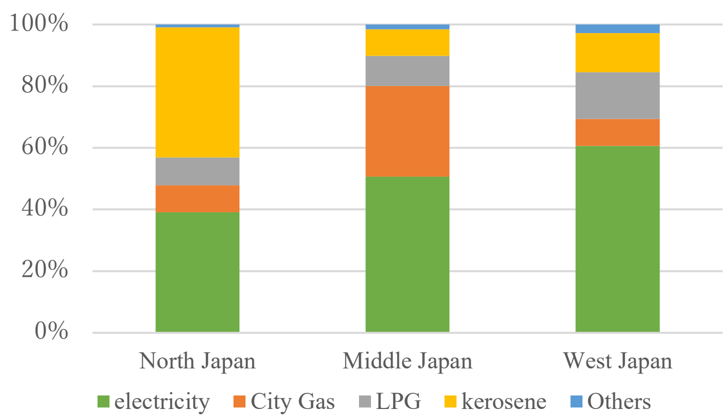
Figure 1. Residential final Energy Consumption in FY2019



Data source: IEA Energy Balance table, 2019

Figure 2 compares the composition of the household sector by energy source as of 2019 by region. The share of electricity is around 40% in northern Japan, 50% in middle Japan, and 60% in western Japan. There is a 20 percent point of difference on average across the regions. In addition, it is notable that the share of kerosene for heating purposes exceeds 40% in Northern Japan.

Figure 2. Residential Final Energy Consumption FY2019



Data source: “Energy Balance table in 2019”, Ministry of Economy, Trade and Industry
Note: See Figure 3 for regional classification.

Iwafune et al. estimated the electrification potential in the residential sector using survey data for the household sector by the Ministry of the Environment. They determined influencing factors on electrification by using a logit model analyzing with and without electrification cases of each residential appliance and private car.. It also estimated the maximum electrification potential when these influencing factors change. The results indicated that the factors influencing the promotion of electrification are household income, detached houses or not, and with/without PVs.

In the following section, we will focus on all-electric homes that meet all of their household energy needs with electricity. We will identify the determinants of adopting all-electric homes in the Japanese household sector by region and income.

2. Methodology

2.1 Model

In this paper, we estimated a binomial logit model in which each household chooses to be all-electric or not, based on survey data from the Ministry of the Environment's "Statistical Survey of CO_2 Emissions from the Household Sector" (Hereafter abbreviated as "Household CO_2 Emissions Statistics")[1].

$$P(y_i = j) = F_{ij}(\boldsymbol{x}'_{ij}\boldsymbol{\beta}), \quad i = 1,2, \ldots N, \ j = 1,2 \qquad , \ P(y_i = 1) + P(y_i = 0) = 1 \tag{1}$$

whare, $P(y_i = 1)$: Probability that household i is an all-electric home, $P(y_i = 0)$: Probability that household i is a non-all-electric home, $\boldsymbol{x}'_{ij}$is an explanatory variable vector, $\boldsymbol{\beta}$is a model parameter vector.

As for the explanatory variable that takes the value of one or zero, we use single-family detached house, own house, households with PV, and households for 65 years old or older. The other explanatory variables are year of construction, number of household members (in the form of square root), household income, heating degree days, electricity price/gas price (prefecture average), electricity price/LPG price (prefecture average), electricity price/heating oil price (prefecture average).

Table 1. Correlation Coefficients between Explanatory Variables

	all electric house	single-family ditached house	own house	year of construction	households with PV	number of household members	household income	households 65 years old or older	heating degree days	electricity rate / city gas price	electricity rate / LPG price	electricity rate / heating oil price	electricity rate / fuel price
all electric house	1.00	-	-	-	-	-	-	-	-	-	-	-	-
single-family ditached house	0.18	1.00	-	-	-	-	-	-	-	-	-	-	-
own house	0.16	0.70	1.00	-	-	-	-	-	-	-	-	-	-
year of construction	0.27	-0.09	-0.03	1.00	-	-	-	-	-	-	-	-	-
households with PV	0.30	0.22	0.18	0.20	1.00	-	-	-	-	-	-	-	-
number of household members	0.12	0.20	0.19	0.17	0.15	1.00	-	-	-	-	-	-	-
household income	0.11	0.08	0.15	0.25	0.12	0.39	1.00	-	-	-	-	-	-
households 65 years old or older	-0.06	0.12	0.12	-0.25	-0.05	-0.39	-0.29	1.00	-	-	-	-	-
heating degree days	-0.04	0.08	0.05	-0.03	-0.04	-0.03	0.00	0.01	1.00	-	-	-	-
electricity rate / city gas price	-0.14	-0.07	0.04	0.01	-0.04	-0.03	0.10	0.02	0.38	1.00	-	-	-
electricity rate / LPG price	-0.06	-0.06	0.02	0.01	0.01	0.00	0.08	0.01	-0.22	0.34	1.00	-	-
electricity rate / heating oil price	-0.11	-0.04	0.01	0.00	0.02	-0.04	0.04	0.01	0.52	0.75	0.17	1.00	-
electricity rate / fuel price	-0.11	-0.08	0.03	0.01	0.00	-0.01	0.12	0.01	-0.05	0.70	0.88	0.47	1.00

Data source: Household CO_2 Emissions Statistics, Ministry of the Environment

[1] The authors obtained permission to use the individual data of "Statistical Survey of CO_2 Emissions from the Household Sector" statistics from the Ministry of the Environment through the Japan Society of Energy and Resources.

Table 1 shows the correlation coefficients among the explanatory variables. From these results, the combinations of "heating degree days" and "relative price variable," "detached house or not" and "owner-occupied house or not," "number of household members" and "only 65 or older," and "number of household members" and "household income" are not used as explanatory variables simultaneously because they are highly correlated variables with each other. Next, to check for multicollinearity among these selected variables, the VIF (Variance Inflation Factor) was calculated for each explanatory variable. The calculated VIFs were 2 at most, acceptable enough for adopting them in our analysis.

2.2 Data

The analysis uses individual data from the Ministry of the Environment's "Household CO_2 Emissions Survey." This survey was initiated on a pilot basis in FY2016 and has been conducted annually since FY2017, with a sample of approximately 10,000 households nationwide obtained. Here we use information on the attributes of each household, consumption by energy source, and actual expenditures for the four-year period 2016-2019 from 40,794 surveyed data. Since data related to energy expenditures have been

Table 2. Data Characteristics
by Household Income and Region FY2017-FY2019

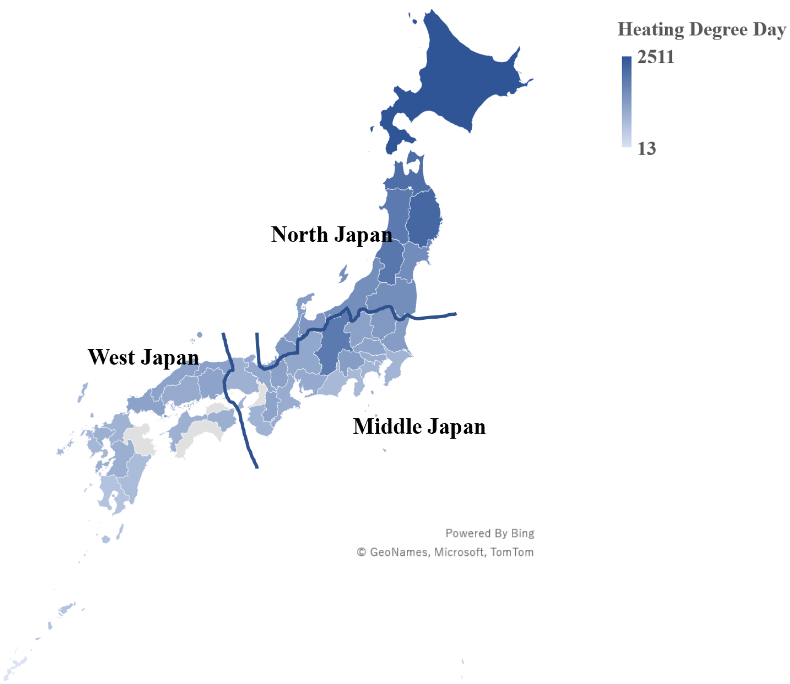
	Household Income (10,000 JPY)	share of all-electric house	share of households with PV	share of single-family detached house	number of households
North Japan	-250	5.0%	2.9%	63.8%	1,585
	250-500	7.6%	4.1%	68.5%	2,940
	500-750	14.2%	7.4%	73.0%	1,734
	750-1,000	18.1%	9.5%	77.4%	1,045
	1,000-1,500	20.0%	8.2%	81.2%	500
	1,500-2,000	25.0%	15.8%	86.8%	76
Middle Japan	-250	5.1%	2.9%	51.6%	1,794
	250-500	6.7%	5.9%	57.9%	3,740
	500-750	9.6%	10.8%	58.7%	2,510
	750-1,000	11.8%	11.3%	63.4%	1,736
	1,000-1,500	10.5%	12.6%	65.7%	1,077
	1,500-2,000	15.5%	13.5%	66.3%	193
West Japan	-250	9.8%	4.0%	58.1%	2,325
	250-500	13.4%	7.3%	61.0%	3,734
	500-750	22.5%	14.8%	65.0%	2,026
	750-1,000	27.1%	18.9%	72.0%	1,071
	1,000-1,500	26.9%	14.9%	71.4%	510
	1,500-2,000	25.8%	21.3%	68.5%	89

Data source: Household CO_2 Emissions Statistics, Ministry of the Environment
Note: Households with annual household incomes of 20 million yen or more are not included.

available since FY2017, the analysis primarily uses data from FY2017-2019. Table 2 compares the percentage of households with all-electricity, PV installation, and detached houses by region and household income, as well as the number of households. The largest distribution of households is among those with annual incomes between 2.5 and 5 million yen. This distribution of household income is consistent with the trend in the distribution of the number of households by income level for Japan as a whole, according to the Basic Survey of National Living Standards conducted by the Ministry of Health and Welfare. The percentage of all-electric households is positively correlated with household income in all regions. In Hokkaido (included in "North Japan"), the proportion of detached households is higher than in other regions, while the proportion of households with PV is lower.

Iwafune et al., as seen earlier in the paper, used only FY2017 data to analyze the factors influencing the promotion of electrification. In addition, it did not include the impact analysis by different regions and energy prices. Therefore, this analysis will focus more on regional differences and energy prices by using three consecutive datasets from FY2016 to FY2019. In this paper, the heating degree days by region and heating fuel oil (kerosene) prices relative to electricity prices are analyzed in order to investigate the potential for electrification in heating applications where there are large differences by region.

Figure 3. Heating Degree Days by Prefectures



Data source: Japan Meteorological Agency, Heating degree days are determined by adding the difference between the daily average temperature and 14°C on days when the daily average temperature is below 14°C for the year

Figure 3 shows heating degree days by prefecture in 2017. It can be seen that heating degree days are higher in northern Japan than in middle and western part. For energy price data, we used each prefecture's average unit price of households[2] instead of the unit price by energy source by each household to address the issue of price endogeneity. For electricity prices, we used the average price of all-electric households in the prefecture of residence.

3. Results

Table 3. shows the percentage of household energy expenditures of each region by household income. From the survey data, we confirmed that energy expenditure burden and the electrification price are higher for households in cold regions and low-income households. This result is consistent to that of Hoshino and Ogawa (2021).

Table 3. Percentage of Household Energy Expenditures

		North Japan	Middle Japan	West Japan
Household Income	250-500	6.0%	4.5%	4.7%
	500-750	3.9%	2.9%	3.1%
	750-1,000	3.0%	2.2%	2.3%
	1,000-1,500	2.3%	1.7%	1.8%
	1,500-2,000	1.7%	1.3%	1.3%

Data source: Household CO_2 Emissions Statistics, Ministry of the Environment

Table 4. shows the estimation results for model (1). Since the data for FY 2016 does not provide information on unit energy payments, variables other than energy prices are used in our estimation with the data for FY 2016-2019 as the sample period. According to the estimation results, the number of household members and the number of households with only members aged 65 and older are not influential enough on the results. In addition, the estimated parameters do not change significantly when the variable for owner-occupied households is used instead of the variable for detached houses, and the coefficient of determination for the model with the variable for owner-occupied households is slightly lower. Therefore, owner-occupied households, number of household members, and households only aged 65 and older were excluded from the explanatory variables in the model with the estimation period of FY 2017-2019.

The detached house variable has significantly positive explanatory power in both regions. By

[2] Since city gas and LPG prices are based on metered and decreasing rates, the unit price is higher for households with extremely low usage. Strictly speaking, such households should be excluded from the model estimation, but the analysis here includes them.

region, larger parameters are estimated in West Japan. The household income variable has significantly positive explanatory power in Japan as a whole, except Middle Japan. By region, the household income parameter is estimated to be largest in North Japan followed by West Japan. Regarding the timing of housing construction, all regions have significantly positive explanatory power. By region, the construction timing parameter is particularly large in North Japan. The with/without of photovoltaic power generation equipment has positive explanatory power in all regions. The largest parameter is estimated for Middle Japan. In summary, in all regions, the probability of all-electrification increases for detached houses with PV. By region, in West Japan, being a detached house has a significant impact on the probability of adopting all-electric, while in Middle Japan, being a house with PV has a particularly significant impact on the probability of adopting all-electric. In contrast, in North Japan, higher household income and newer houses increase the probability of all-electrification.

As for the energy price variable, the prefectural average electricity unit price for all-electricity households relative to each of the prefectural average unit prices for city gas, LPG, and kerosene were used. For Japan as a whole, all relative prices have significantly negative explanatory power. This implies the relative lower unit price of electricity relative to competing energy sources can increase the probability of converting to all-electric homes in Japan.

However, the results differ by region. The parameters for the relative electricity price with

Table 4.　Estimation Results of Binary Logit Model

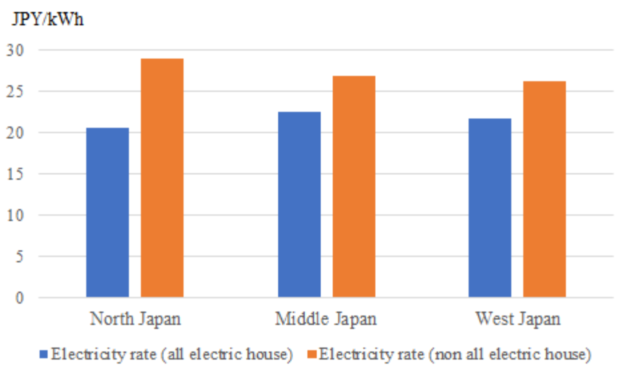
	number of observations (positive)	Costant	single-family detached house	own house	year of construction	households with PV	number of household members (SQRT)	household income	households 65 years old or older	heating degree days	electricity rate/gas price (prefecture average)	electricity rate/LPG price (prefecture average)	electricity rate/heating oil price (prefecture average)	R^2
2016-2019	Japan	-4.8661	1.2158		0.2720	1.2888		0.3567	0.0782**	-0.2320				0.111
		-4.8347	1.2211		0.2694	1.2869		0.3413		-0.2323				0.111
	40793	-4.6917	1.2440		0.2807	1.3095	-0.0162**			-0.2294				0.109
	(3492)	-4.8453		1.1230	0.2616	1.4257		0.2922	0.0626**	-0.1890				0.105
		-4.8157		1.1564	0.2665	1.4306	0.0582**			-0.1874				0.104
2017-2019	Japan	-4.9371	1.4114		0.3628	1.2548		0.1917		-0.2329				0.179
		-4.9073	1.3882		0.3714	1.2617		0.3187			-1.4966			0.203
	29161	-5.3024	1.3693		0.3669	1.2959		0.2404				-0.5740		0.185
	(3492)	-3.8906	1.3827		0.3648	1.2869		0.2080					-1.4275	0.181
	North japan	-6.5472	1.1644		0.5707	1.1683		0.6027						0.234
		-6.1986	1.1076		0.5858	1.1702		0.5629			-1.3247			0.255
	7970	-6.9173	1.1936		0.5769	1.2196		0.6269				-0.7900		0.239
	(866)	-3.1741	1.1234		0.5805	1.2061		0.5762					-3.8293	0.244
	Middle Japan	-4.9212	1.0672		0.2830	1.4571		0.1189**						0.128
		-4.1277	1.0350		0.2836	1.4112		0.1576*			-1.5072			0.134
	11280	-4.8934	1.0561		0.2845	1.4451		0.1371**				-0.3543		0.129
	(959)	-6.0179	1.0677		0.2822	1.4600		0.1148**					1.1441*	0.129
	West Japan	-5.0000	1.7769		0.3392	1.1519		0.4103						0.223
		-5.0160	1.7677		0.3409	1.1422		0.3963			0.5678			0.223
	9911	-4.9013	1.7662		0.3405	1.1526		0.4031				0.5307		0.223
	(1667)	-7.4830	1.7276		0.3440	1.1473		0.3879					2.7639	0.224

note: * denotes p-value is grater than 0.05, ** denotes p-value is grater than 0.1

kerosene in Middle Japan and electricity relative prices with all other energy in West Japan are estimated to be positive, not satisfy the theoretically expected sign condition. This implies that a reduction in the unit price of electricity or an increase in the unit price of competing energy sources is not expected to be effective in encouraging a shift to all-electricity in these energies and regions. In contrast, relative electricity prices have significantly negative explanatory power for city gas, LP gas, and kerosene in North Japan and city gas and LP gas in Middle Japan. This indicates that reducing the unit price of electricity or increasing the unit price of competing energy sources can higher the probability of conversion to all electrification.

Among the price variables, the parameter of relative electricity price to kerosene price in North Japan stands out as particularly large. Given the large demand for heating purposes in North Japan, the potential for converting to all-electric homes is expected to be found in the heating demand. This makes it more sensitive to changes in the relative electricity price of kerosene for heating purposes.

Figure 4. Comparison of Electricity Prices between All-electrified Household and Others



Data source: Household CO_2 Emissions Statistics, Ministry of the Environment

Figure 4 shows the comparison of electricity Prices between all-electrified households and others. In North Japan, where all-electrification has not been widely adopted, the difference between electricity price for all-electrified and non-electrified households is larger than in Middle Japan and West Japan. This suggests that greater price incentives will be needed to promote all-electrification in North Japan.

In North Japan, the lower unit price of electricity for all-electric households relative to competing energy prices is expected to encourage conversion to all-electricity, especially for heating purposes. It should be noted, however, that the unit price of electricity for all-electric households is already lower in North Japan than in other regions. More importantly, as the household income parameter was observed as the most crucial parameter in North Japan, the probability of conversion to all-electric homes will be affected by not only prices but also income level and other factors.

4. Conclusion

While progress in electrification in the household sector will be important for achieving carbon neutral goals, it will be important to take into account the different level of energy cost burden by the household characteristics. This analysis, based on the survey data of approximately 40,000 Japanese households by region and household demographics from FY2016 to FY2019, identifies factors driving the conversion to all-electrified homes. In North Japan, the percentage of all-electrified homes is currently lower than in other regions of Japan due to the large energy demand for heating purposes.

In addition, since income effects play a larger role in the conversion to all-electrified homes in North Japan, differences in household income level will have a greater impact on the degree of conversion to all-electrified homes. In North Japan, where the energy expenditure burden is higher than in other regions, the hurdle for low-income households to obtain the energy-saving benefits of all-electrification is even higher.

This analysis also confirmed the relative prices of electricity with competing energy prices would affect the conversion to all-electric homes. This suggests that stable electricity prices are essential factors for electrification progress in the household sector in all regions throughout Japan.

Finally, as a perspective for future analysis, it should be noted that factors other than climate change also affect energy choices in the household sector. Resilience, especially in Japan, is another important issue, which is prone to natural disasters, and having a variety of energy sources in the household sector may work effectively in an emergency. Promoting electrification in the household sector is the centerpiece of decarbonizing policy, it is also essential to consider policies based on such characteristics of Japan, in addition to the cost burden analyzed in this paper.

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