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Field Study on Energy-Saving Behaviour and Patterns of Air-Conditioning Use in a Condominium

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Abstract: In the international movement to combat the threat of climate change, the timely implementation of residential energy-saving practises is becoming an urgent issue. Because the number of apartments is increasing, we analysed data from home energy management systems (HEMSs) and data from questionnaire surveys of 309 households in a condominium. We focused on the seasonal variation in air-conditioning (AC) use in living-dining rooms to determine the tendency of energy use for heating/cooling related to the characteristics of flats, the profiles of residents, and energy-saving behaviours. In winter, 80% of residents mainly used gas floor heating rather than AC and 24% did not use AC in winter. In households where someone stays home for long hours, they prefer gas floor heating rather than AC in winter. These households also tend to engage in energy-saving behaviours to adjust the indoor thermal environment. There are several types of energy-saving lifestyles; therefore, effective energy-saving measures should be considered for both energy efficiency and the thermal comfort of residents.

Keywords: condominium; air-conditioning; HEMS; electricity use; gas use; seasonal variation

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1. Introduction

1.1. International and National Policies against Global Warming

Global recognition of the requirement for an effective and progressive response to the urgent threat of climate change led to the enactment of the Paris Agreement [1]. This was unveiled at the Conference of Parties to the United Nations Framework Convention on Climate Change 21 (COP 21) held in 2015. From this agreement, the target of the global warming temperature limit was set at 2 °C. In light of this, the Japanese government, along with other countries, declared a nationally determined contribution (NDC) [2]. Consequently, the reduction target for greenhouse gas (GHG) emissions became 26% by 2030 compared to that of 2013. This NDC also included a reduction of 40% in the residential sector, which accounts for 14% of the energy consumed in Japan [3]. To realise this NDC, the Japanese government has designed global warming countermeasures [4]. The approach for the residential sector includes methods to achieve higher energy-saving performances in buildings, the introduction of energy-saving appliances, including fuel cell cogeneration systems (CGS) for residences, and home energy management systems (HEMS).

At COP 25 held in 2019, the necessity to shift the target of the global warming temperature limit to 1.5 °C was discussed; therefore, the Japanese and other governments plan to reduce greenhouse gas emissions to zero by 2050 [5]. To achieve this, the reduction target was increased to 46% in 2030 from the prior target of 26%; specifically, the target of the residential sector increased to 66%. Thus, the quick implementation of residential energy-saving measures is becoming an urgent issue.

1.2. The Need to Investigate the Energy Use in Condominiums Using Recent Data

Apartments make up more than 40% of the residences in Japan [6] and this proportion is growing, especially in urban areas. Therefore, to realise the national target of CO_2 emissions reduction, we cannot ignore the energy-saving measures for apartments. To achieve this target, the renovation of existing buildings is important for improving the energy-saving performance of the building envelope or appliances, as well as the new construction of high-performance buildings.

After 2012, air conditioners were installed in 90% of the households with more than two members [7]. In Japan, air conditioners are not only used for cooling, but are also for heating, which is more common than the use of stoves.

Japan experienced a shortage of electrical power after the Great East Japan earthquake in 2011, which led to excessive energy-saving measures in offices and residences. Several field studies after the earthquake indicated the possibility of the reduced productivity of occupants due to these measures [8,9]. Energy-saving strategies in residences should be based on the actual living situation, and suggestions that do not affect the comfort or health of residents are required.

1.3. Previous Studies Related to the Energy and Air-Conditioning (AC) Use in Residences

Many studies have been conducted to estimate the characteristics of energy and AC use in residences. Concerning European countries, Buttitta et al. [10] developed a new methodology to calculate the national heating energy demand by integrating different dwelling types in the UK. Ortiz & Bluyssen [11] conducted a field survey of home occupants in the Netherlands and France, and developed five types of occupants, according to their energy use and awareness, using cluster analysis. Calì et al. [12] conducted a field survey of residential buildings located in southern Germany and clarified that the key drivers of window operation were the time of the day, outdoor air temperature, and CO_2 concentration.

In the United States, Jain et al. [13] conducted a field survey in an urban residential building located in New York City and noted that eco-feedback, as an environmental externality, was more effective than the feedback in direct energy use values. Meinrenken et al. [14] introduced a case study using a multifamily residential electricity dataset (MFRED) in the US. In Canada, Stopps & Touchie [15] conducted a field survey of high-rise condominium buildings located in Toronto and reported that there was chronic over-conditioning across seasons that caused thermal discomfort in occupants. In Australia, James & Ambrose [16] analysed the results of a trial conducted in residences located in Victoria and noted that the behaviour change without the retrofit did not lead to a noticeable improvement.

In Asian countries, Chen et al. [17] conducted a field survey of households located on the east coast of China and reported that elderly residents tend to use less energy because of their frugal behaviour pattern. Ren et al. [18] analysed AC use in residential buildings in different climatic zones in China and developed an AC usage conditional probability model. Xia et al. [19] conducted a field survey of residential buildings located in South China and explained that occupant behaviour of AC use was classified into three patterns according to the operation time of the day. Indiraganti [20] conducted a field survey of households located in India and found that AC use was higher on the top floors. Zaki et al. [21], Aqilah et al. [22], and Sena et al. [23] analysed the electricity use in residences in Malaysia and noted that the AC was used more often in bedrooms than in living rooms.

In Japan, studies have either conducted country-wide questionnaire surveys [24–26], internet-based questionnaire surveys [27,28], or analysed statistical data [29]. They estimated living activities and energy consumption according to each use and analysed the influences that were affected by the characteristics of region, flats, or residents. However, most of these studies were conducted between the 1990s and the 2000s. Therefore, it is difficult to compare these results with the performance of recent buildings.

As for the recent data, the Ministry of Environment (MOE) of Japan is currently conducting 'CO_2 emission statistical surveys of the household sector' every year [30]. Using these statistics, Matoba et al. [31] analysed energy use according to the characteristics of households. However, they simulated the same AC use for all households.

Some studies have suggested a calculation model for energy use based on statistical data or questionnaire surveys [32–34]. However, they were under the condition of the standard family, which comprises four family members with a married woman who is a full-time housewife and two children. In Japan, the share of households with more than four family members decreased by 15% in the past 20 years (1994–2014), and the mean number of people in a household decreased to 2.5 persons because of low birth-rates and aging [35]. Furthermore, the share of married women working outside the home increased by 14% within 20 years (1997–2017), and is currently at two-thirds [36].

As for the studies on apartments, Hong [37] classified the influence of the floor space of the flats or the number of household members on the energy consumption of the residences in a suburb of Tokyo. Mae et al. [38] provided a pattern classification of living activities according to the return time or bedtime of residences in the central urban area of Tokyo. Hirose & Takaguchi [39] compared the secondary energy consumption of AC between buildings with no insulation and those with the highest level of thermal insulation in a suburb of Tokyo. However, these studies did not provide suggestions based on the differences in the characteristics of the residents.

Several studies have analysed energy consumption data. Hosoi et al. [40] estimated the individual usage of energy from the total electricity, gas, and water usage data in large-scale apartment housings in Tokyo. They reported that the heating energy consumption or the ratio of gas use was higher in the households with more members. Otsuka et al. [41–43] analysed HEMS data and the lifestyle factors or values of the residents obtained from a questionnaire survey in an all-electric apartment in Yokohama. They reported that not only the ways of living, but also people's values or energy cognition influenced electricity consumption. They also verified these relationships using an internet-based questionnaire survey targeting two-generation families in Tokyo. Abe et al. [44] suggested a method to detect households with heavy energy use based on an analysis of the relationship between the energy consumption data and questionnaire survey data. Moreover, Takase et al. [45] noted the increasing trend of electricity and water use in all-electric apartments in Tokyo after the COVID-19 expansion in 2020.

Regarding studies that focused on AC use, Habara et al. [46] measured AC and window operation in a living room and master bedroom and found that those operations depended on the occupants' preference for the indoor thermal environment. Yoshino et al. [47] measured the energy usage, including space heating/cooling, and reported that there were significant differences in energy use caused by the range of indoor temperatures in each household. Mae et al. [48] and Yano et al. [49] suggested that the differences in energy consumption between the flats were greatly influenced by the differences in AC use and noted that the rating ability of the air conditioner was too large considering the actual load. This conclusion was achieved by analysing the energy consumption data and questionnaire survey data from the residences, including five apartment flats in and around Tokyo. Ono et al. [50] found that residents kept using AC without noticing the change in outdoor temperature. Kindaichi et al. [51] measured AC use in detached houses located around Hiroshima, in western Japan, and noted that the time-reduction effect on energy saving efforts was large.

Since 2010, the introduction of the HEMS has been promoted as a policy in condominiums. The main purpose of HEMSs is to visualise energy use for residents. Ueno et al. [52] showed that the introduction of HEMSs caused behavioural changes in residents and contributed to 9% of the energy-saving effect. However, residents tend to quickly lose interest in watching HEMSs; thus, the effect does not continue for a long time. Furthermore, the researcher could not use the accumulated data log in the analysis in most condominiums where HEMSs were installed. HEMSs only measure the total electricity use in most condominiums, so there are only a few cases in which the branch circuits, gas, and water usages were measured.

1.4. Objectives

The main objective of this study was to analyse the relationship between energy consumption, especially cooling or heating in living and dining rooms, and the lifestyles of various residents in a recently built condominium. We also aimed to suggest appropriate energy-saving behaviours or adaptive methods for a thermal environment that caters to the comfort and health of residents. The specific objectives of this study were as follows:

1. To analyse the characteristics of AC use in a living-dining room and clarify the relationship between AC use pattern and the energy-saving behaviours of residents.
2. To analyse the use of cooling or heating in flats and identify opportunities for improving the energy-saving performance of the building.
3. To analyse the use of cooling or heating in accordance with family size, age of residents, and the employment status of the married women of these households and to identify appropriate energy-saving practises for them.

2. Materials and Methods

2.1. The Residential Building under Investigation

The studied condominium is located in the south-eastern urban area of Tokyo and began housing occupants at the end of November 2015. It is an 18-storey building with 356 flats that are all facing the south side. There are two types of floor plans: three bedrooms with a living-dining room and kitchen (3LDK: 71.0–77.1 m^2), 272 flats; and four bedrooms with a living-dining room and kitchen (4LDK: 80.9–90.2 m^2), 84 flats (Figure 1a) [53–57].

(a) (**b**)

Figure 1. (**a**) The condominium under investigation; (**b**) the home energy management system (HEMS) that was installed.

The U value of the investigated building envelope is 0.69 W/m^2K, and the building is certified as a 'low-carbon building'. This value is 10% higher than the baseline level determined in the Japanese energy-saving act. Passive design has also been introduced in the building's architecture, including the consideration for natural ventilation with passive ducts at the entrance and hooks for green curtains to shade the flats located at storeys 2–6.

A polymer electrolyte fuel cell cogeneration system (PEFC-CGS), developed for apartments, was installed in every flat, which was a never-before-seen feature in buildings worldwide at the time. This system includes the backup gas boiler which provides the heat energy for the floor heating in the living-dining room and the heating in the bathroom as well as the supplement of the boiling water for the shortage of PEFC-CGS.

2.2. Measured Energy Consumption Data

A HEMS was installed in each flat of the building under investigation and was used to measure the energy consumption performance data, including electricity purchased, the branch circuit of AC in the living-dining room (LD), and gas use. Electricity usage data were measured by circuit transformer (CT) sensors (ratio error: 2% of full scale) installed on the distribution board, and gas use was measured by an installed gas meter (verification tolerance: 3%). Each piece of data was recorded at 30 min intervals and stored on a cloud server. Residents could visually confirm the energy use results in real time using a computer or smartphone (Figure 1b).

The use of the measured data for our study was attached to the purchase conditions of the condominium; therefore, we acquired the data logs of all flats from the HEMS servicer. The electricity use of each flat was calculated as the sum of the purchased electricity and that generated by the CGS. We analysed 1 year of energy performance data from April 2018 to March 2019 in 309 flats.

The conversion factors for primary energy consumption are listed in Table 1. Electricity was based on the Act on the Rational Use of Energy in Japan [58]. Gas was based on data from Tokyo Gas Co., Ltd. [59].

Table 1. Conversion factors for energy consumption.

Energy Source	Electricity (MWh)	Gas (m^3)
Primary Energy Consumption (GJ)	9.76 GJ/MWh	0.045 GJ/m^3

2.3. Questionnaire Survey and the Profile of Residents

We conducted a questionnaire survey among residents three times between February 2015 and November 2016 [57]. In this study, we analysed 162 responses that corresponded to 52% of the HEMS data that we analysed.

Households of three members occupied the largest share (39%), which was higher than the Japanese average (20%). This was followed by households with two members (30%). The mean number of household members was 2.7, which was higher than the average number in Japan (2.5) [35].

Two-thirds of the married women worked outside of the home, which is approximately the same level as that of Japan as a whole [36]. As for the tendency of the flat plan, there was no significant difference in any profiles between the residents of 3LDKs and 4LDKs.

2.4. Process of Analysis

We analysed the relationship between the HEMS data and the building information, or the results of the questionnaire survey, by the process shown in Figure 2. We clarified the influence of the characteristics of flats or residents on the use of air conditioners in living-dining rooms. IBM SPSS Statistics 26 was used for the analysis.

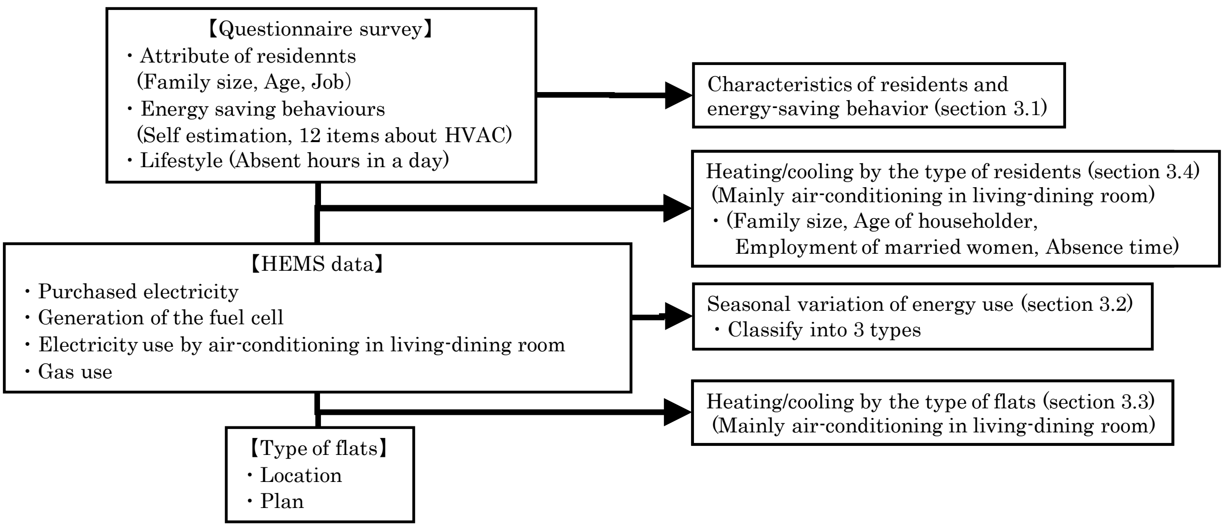
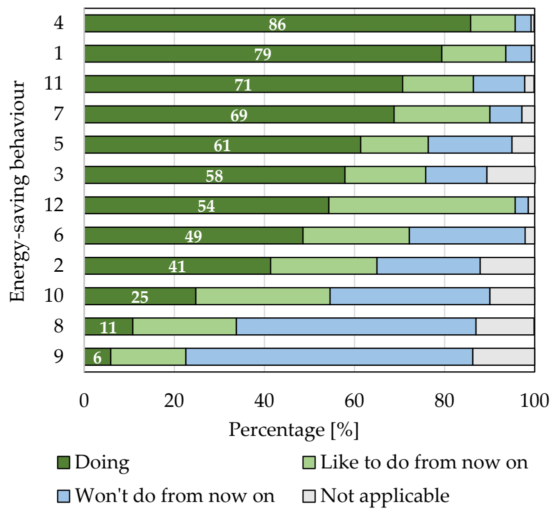


Figure 2. Scheme of the study.

3. Results and Discussion

3.1. The Energy-Saving Behaviours of Residents

We analysed the practising rates of energy-saving behaviours concerning the thermal environment. Figure 3 shows the practising rates for the 12 items concerning the thermal environment arranged in the order of highest to lowest. Behaviours with high practising rates are '4. Shut the door during cooling/heating use', '1. Setting AC temperature to a moderate level', '11. Opening the windows for ventilation positively', and '7. Shutting the curtain/blind during cooling/heating use'. These four behaviours are possible through simple actions. In contrast, the behaviours with low practising rates are '9. Using the green curtain (curtain made of plants for shading) in summer', '8. Hanging the bamboo blind at the window in summer', and '10. Staying at places cooler/warmer than in the house'. These three behaviours take more time or effort. As for items 2 and 3, a stand electric fan is used in summer.



12 items for energy-saving behaviour

1. Setting AC temperature to a moderate level
2. Using the fan instead of AC in summer
3. Using the fan with AC in summer
4. Shutting the door during cooling/heating use
5. Saving cooling/heating use at day
6. Saving cooling/heating use at night
7. Shutting the curtain/blind during cooling/heating use
8. Hanging the bamboo blind at the window in summer
9. Using the green curtain in summer
10. Staying at places cooler/warmer than in the house
11. Opening the windows for ventilation positively
12. Cleaning the AC filter regularly

* AC: Air conditioner

Figure 3. Percentage of energy-saving behaviours.

Figure 4 shows the distribution of the number of energy-saving behaviours practised in each household. The practising numbers indicate a nearly normal distribution with an average of six items. There were no households who conducted all the 12 items. However, they vary over a wide range; therefore, energy use might be influenced by energy-saving behaviours.

3.2. The Seasonal Variation in AC Use in the LD

We analysed several energy-use factors, including the use of AC in the LD. We classified the flats by type based on the seasonal variation in AC use and considered the relationship of AC use in each flat with the energy-saving behaviours of residents.

3.2.1. The Seasonal Characteristics of Energy Use

Figure 5 shows the monthly electricity use for AC in LDs per day for each flat. We found that the AC use in the LD is mainly for 4 months from June to November with a peak in July and August in summer, and for 4 months from December to March with a peak in January and February in winter. Therefore, in this study, we used 'summer' as the cooling period of June to September and 'winter' as the heating period from December to March.

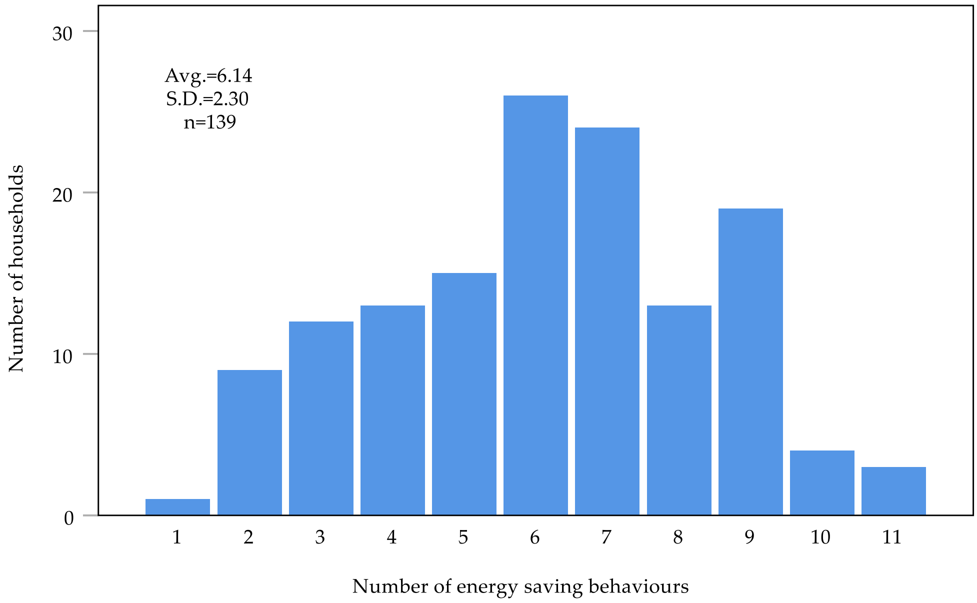


Figure 4. Number of energy-saving behaviours practised in households.

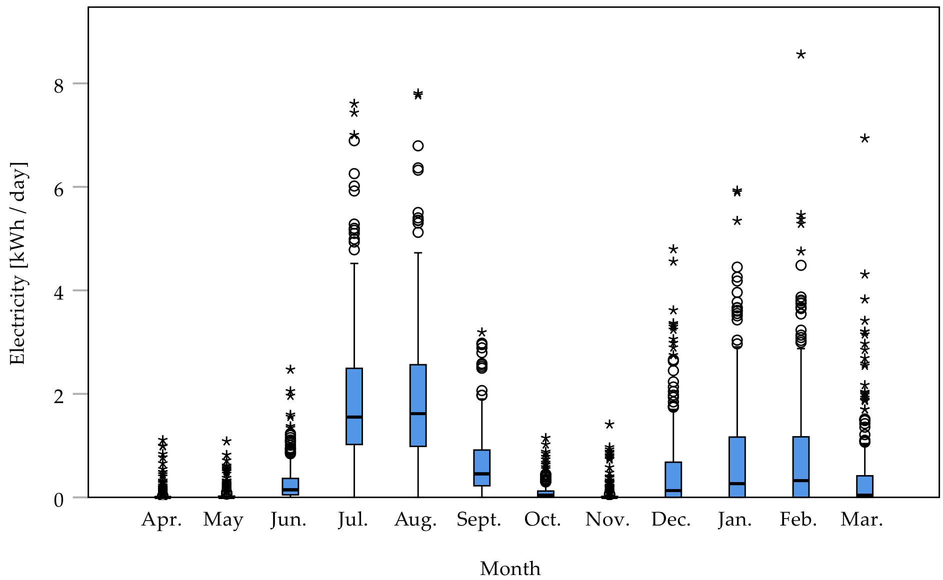


Figure 5. Monthly mean electricity use of each household per day for the air conditioner (AC) in the living-dining room (LD).

From the results of the questionnaire survey conducted in 2002–2003 by Mizutani et al. [28], the national average heating period in the apartments was 3.9–4.1 months and the cooling period was 1.8–2.4 months—approximately half of the heating period. In our study, AC use in LDs occurs as cooling in 78–99% of the flats in the 5 months from June to October, occurs as heating in 58–68% of the flats in the 4 months from December to March, and occurs in 37–43% of the flats in the other 3 months. The difference in the previous study might be the high thermal insulation of the building envelope, the high efficiency of cooling/heating appliances, the change in the lifestyle of residents over approximately 15 years, and the increasing impact of the urban heat island effect.

Table 2 shows the electricity use for ACs in the LD. AC use in LDs in summer (146 kWh) was approximately double that in winter (73 kWh).

Table 2. Air conditioner (AC) use in the living-dining room (LD).

Variable	Average	S.D.	Variable	Average	S.D.
Annual AC use in LD (kWh/household)	227	172	AC use in LD in summer (kWh/household)	146	103
Number of months when AC was used	8.4	2.8	AC use in LD in winter (kWh/household)	73	111

In recent studies, Hosoi et al. [40] showed that the secondary energy consumption for cooling was approximately 10 MJ/day in July and August, and 5 MJ/day in June and September, in condominiums using both electricity and gas. Notably, the secondary energy consumption for heating was larger than that for cooling: 20 MJ/day in February and 15–20 MJ/day in December, January, and March. Otsuka et al. [42] showed that the electricity use for cooling was 2.0 kWh/day in July and that for heating was 3.1 kWh/day in February.

The electricity use for heating in this study was lower than that for cooling as reported in other studies. This might be because the building under investigation was certified as a 'low-carbon building' and heat loss might be lower in winter than in the buildings of the previous studies. However, gas for the fuel cell, boiling water using the backup boiler, floor heating, heating or mist sauna in the bathroom, and cooking were not measured in this study; therefore, further studies are needed to clarify this aspect.

3.2.2. Type Classification by the Seasonal Variation in AC Use

As shown in Figure 5, there are wide variations in AC use in the LD, especially during summer and winter. Furthermore, the values of AC use in LD in winter were widely distributed from 0 kWh (74 households) to 780 kWh. One household did not use AC throughout the year.

As each flat indicated the different tendencies in these two seasons, we classified each flat in three types as shown in Table 3. Type S is the flat that uses AC in summer but not in winter; Type Sw is the flat where the monthly mean peak use of AC per day in the LD occurs in summer, and it is also used in winter; and Type Ws is the flat where the monthly mean peak use of AC per day in the LD occurs in winter, and it is also used in summer. The shares of Sw, S, and Ws were 57, 24, and 19%, respectively.

We found the following tendencies from Table 3:

- Annual electricity and primary energy usages were significantly lower in Type S.
- Annual electricity use for AC in LDs was highest in the order of Types Ws, Sw, and S, and they were significantly different from each other.
- Gas use in winter was significantly high in Type Sw.

From these results, we estimated that more than three quarters (Types Sw + S) of the flats use mainly gas floor heating for LDs in winter rather than AC and less than a quarter (Type Ws) of the flats mainly use AC for LD in winter rather than floor heating.

The energy use in Type S was less than that in the other two types. We divided the flats of each of the three types into two groups based on the number of energy-saving behaviours: more than seven items or less than six items. The group with more than seven items comprised 66% S, 45% Sw, and 21% Ws, and the number of items practised was significantly different ($p < 0.01$) among the three types according to χ^2 tests. From these results, we concluded that the household of Type S has a more 'energy-saving' lifestyle.

3.2.3. Number of Months Using AC in the LD

To analyse the relationship between the period of AC use in a year and the daily use of AC, we classified the flats into seven groups by dividing each of the three types into two or three groups based on the number of months in which AC in the LD was used. Figure 6 shows the monthly mean electricity use per day for AC in the LD for each group.

Table 3. Energy use variables by groups with three different types of AC use patterns in the LD.

Variable	Type of AC Use in LD						*p*-Value of *t*-test		
	S (n = 73)		Sw (n = 175)		Ws (n = 60)		S: Sw	Sw: Ws	S: Ws
	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.			
Annual electricity use (kWh/household)	2871	1127	3500	1039	3521	1052	<0.001	0.90	0.001
Annual AC use in LD (kWh/household)	144	121	223	149	342	221	<0.001	<0.001	<0.001
Number of months where AC was used	5.1	1.4	9.2	2.2	10.4	1.7	<0.001	<0.001	<0.001
AC use in LD in summer (kWh/household)	141	118	162	101	108	77	0.17	<0.001	0.06
AC use in LD in winter (kWh/household)	0	0	53	67	219	147	<0.001	<0.001	<0.001
Gas use in winter (m^3/household)	360	177	434	169	361	116	0.002	<0.001	0.96
Annual primary energy (GJ/household)	60	24	73	22	68	18	<0.001	0.11	0.02

S: AC use in summer but not in winter; Sw: max. AC use in summer and also in winter; Ws: max. AC use in winter and also in summer; Avg.: average; S.D.: standard deviation; electricity use was the sum of the purchased electricity and the electricity generated by the fuel cell cogeneration system (FC-CGS).

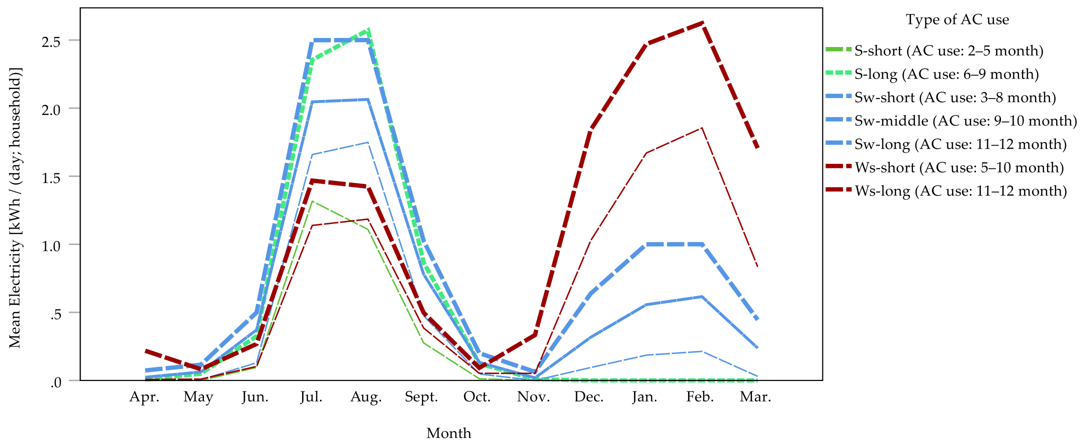


Figure 6. Monthly mean electricity use per day for AC in the living-dining room (LD) of each group, based on the number of months where AC was used (S: AC use in summer but not in winter; Sw: max. AC use in summer and also in winter; Ws: max. AC use in winter and also in summer).

The more months a flat uses AC, the higher the amount of AC used for the peak months. The correlation analysis of both variables showed a significant difference in all types of AC use (Type S: $p < 0.005$; Sw and Ws: $p < 0.01$). The flats that use AC in LD for 11–12 months also use more AC in another room. We noticed that the households with a high dependence on AC also had a tendency to use more gas and water. We found that the households belonging to these groups are very dependent on AC; thus, they are partaking in an 'energy-intensive' lifestyle.

3.2.4. Type of AC Use in the LD and Energy-Saving Behaviour

The practising rates of energy-saving behaviour for each type are shown in Figure 7. The practising rates of '2. Use the fan instead of AC in summer' were significantly higher (22% points) in Type S than in Type Sw ($p = 0.03$). '1. Set AC temperature to a moderate level', '8. Hang the bamboo blind at the window in summer', '11. Open the windows for ventilation positively', and '12. Clean the AC filter regularly' were also 5–20% points higher in Type S than in Types Sw or Ws. We found that the households of Type S reduce AC use through various energy-saving behaviours, including the active use of fans in summer. Conversely, the practising rates in the households with a high dependence on AC had low incidences of fan use (items 2 and 3); item 3 in particular was significantly low in Ws. The information to encourage energy-saving measures, including the active use of fans in summer, might be effective for the households of Type Sw and Ws, especially for those with an 'energy-intensive' lifestyle.

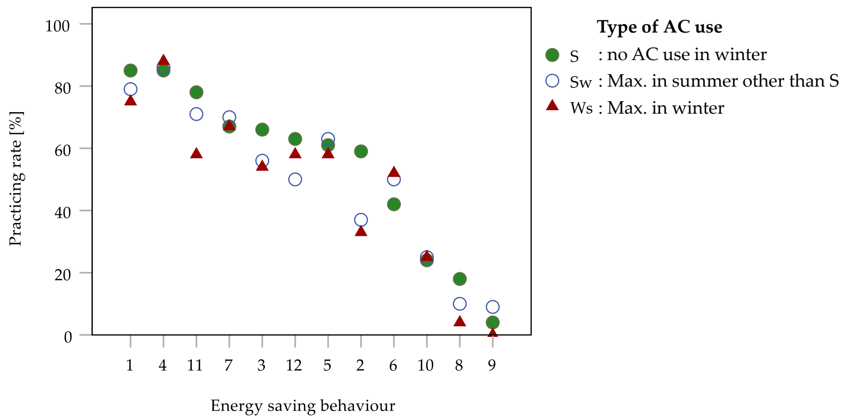


Figure 7. Practising rate of energy-saving behaviour in each AC-use type (see Figure 3 for the behaviour corresponding to the number).

3.3. *The Influence of the Type of Flats on AC Use in the LD*

In this section, the differences in energy use and energy-saving behaviours were analysed according to the location or floor plan type of the flat. Mizutani et al. [28] showed that energy consumption tends to be lower in the flats located at intermediate levels on the middle floors, because the envelope is in less contact with the outside air, thereby having an advantage for thermal insulation and airtightness.

Table 4 shows the amount of energy use factors for each AC use category in the LD, divided into corner flats and intermediate flats, as well as the lowest (2nd) floor, the middle floor, or the top (18th) floor. In all comparable categories of Types S and Sw, the gas use, including floor heating, was higher in the corner flats. In particular, the gas use at the corner flats on the 18th floor (in Sw only) was significantly high. In terms of the electricity use for AC in LD in winter for the households of Type Sw, the corner flats were more than 48% higher than the intermediate flats on the middle or top floor.

The primary energy consumption of the corner flats was significantly higher than that of the intermediate flats on the entire middle floor ($p < 0.05$), and this trend was particularly noticeable in Type Ws. The households of Type Ws accounted for a significantly larger share than those in the intermediate flats ($p < 0.001$). The households of Type Ws use more AC than the other types; therefore, the need for heating may be higher in winter.

As for the floor plan type, there was no significant difference in the energy use, including AC use, between the flats with three bedrooms (3LDK) and four bedrooms (4LDK) for each corner and intermediate flat; however, the mean annual primary energy consumption was higher in 4LDK for each location. From these results, it can be considered that the energy use for heating in winter at the corner flats is higher than that of the intermediate flats, regardless of the difference in the floor plan composition or area range between them.

Table 4. Mean energy use values in each location of flat.

Type of AC use in LD		Type S			Type Sw			Type Ws	
Location of Flat	**Floor Level**	**2nd**	**3rd–17th**	**18th**	**2nd**	**3rd–17th**	**18th**	**3rd–17th**	**18th**
Corner	Number of households (units)	1	7	0	1	24	4	21	0
	Annual AC use in LD (kWh)	294	94	-	168	253	268	325	-
	Number of months AC used in LD	5.0	5.0	-	6.0	9.5	10.0	10.4	-
	AC use in LD in summer (kWh)	280	92	-	167	174	178	99	-
	AC use in LD in winter (kWh)	0	0	-	0.2	73	74	212	-
	Gas use in winter (m^3)	659	435	-	521	452	767	380	-
Intermediate	Number of households (units)	5	58	2	11	126	9	36	3
	Annual AC use in LD (kWh)	127	151	79	244	216	200	341	478
	Number of months AC used in LD	5.2	5.1	4.0	10.3	9.2	8.0	10.4	10.3
	AC use in LD in summer (kWh)	126	148	79	175	159	146	107	183
	AC use in LD in winter (kWh)	0	0	0	63	49	49	220	269
	Gas use in winter (m^3)	398	344	303	390	426	388	350	352

S: AC use in summer but not in winter; Sw: max. AC use in summer and also in winter; Ws: max. AC use in winter and also in summer; LD: living-dining room.

Hirose & Takaguchi [39] compared buildings with the thermal insulation performance at the level of the next-generation energy conservation standard and buildings with no insulation, and found a 2.4-fold difference in the secondary energy consumption by AC. The building investigated in our study is a certified low-carbon building with a thermal insulation performance that is 10% higher than the next-generation energy conservation standard; however, it would be more effective if the thermal insulation of corner flats were improved.

3.4. The Influence of the Type of Residents on AC Use in the LD

In this section, the differences in AC use in the LD, as well as gas use and energy-saving behaviours, were analysed according to family size, the age of residents, and the employment status of the married women.

3.4.1. The Influence of Family Size on AC Use in the LD

Mizutani et al. [28] showed that the energy use for heating increased as the number of household members increased, whereas the energy use per capita decreased. Otsuka et al. [42] showed that electricity use had a significant relationship with family size in all four seasons, based on a survey of all-electric apartments. Figure 8 shows the annual electricity use for ACs in the LD, according to the family size, for each type. This indicates that electricity use increased as the number of household members increased, which is consistent with the results of previous studies [28,42].

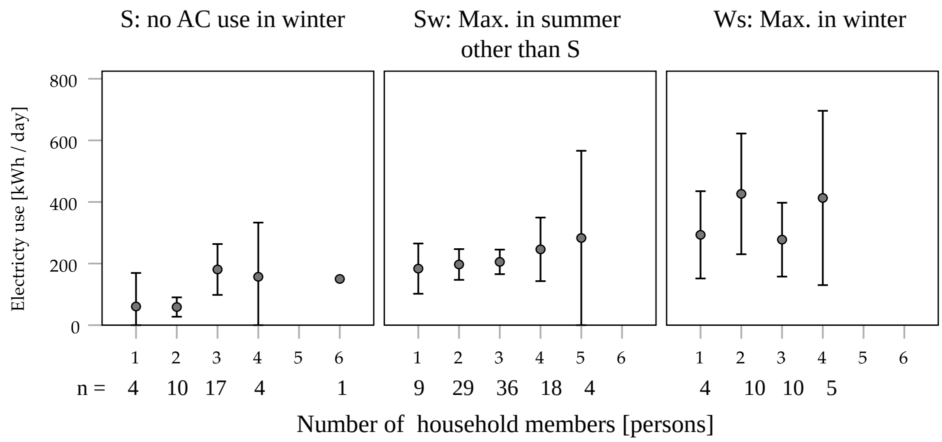


Figure 8. Annual AC use in LD according to family size in three AC usage types.

Hosoi et al. [40] analysed the energy use for heating in winter and found that the gas used for heating and other purposes tended to increase as the number of household members increased. They estimated that households with more people who are at home for a long time tend to use floor heating, which is more comfortable despite the time it takes to start up, whereas the households with a small number of people who are not at home for a long time tend to use ACs, which start up quickly. Table 5 shows the correlation coefficients between family size, the amount of energy used, and the time spent away from home per day. There was a significant positive correlation between the gas use in winter and family size in the households of Types S and Sw, who may be using mainly gas floor heating in winter. We also found a significant correlation between family size and time spent away from home on weekdays and holidays in Type S, and on weekdays in Type Sw. The periods of absence might be affecting household energy usage.

Table 5. Correlation coefficient with the number of household members.

Items	Description	Type S	Type Sw	Type Ws
Energy use	Annual AC use in LD	0.31	0.16	0.01
	Number of months AC used in LD	0.08	−0.10	−0.04
	AC use in LD in summer	0.31	0.19	−0.05
	AC use in LD in winter	-	0.07	0.07
	Gas use in winter	0.36 *	0.37 **	0.12
Absence time	Weekday	−0.49 *	−0.30 *	−0.23
	Weekend	−0.51 **	−0.26	0.38

S: AC use in summer but not in winter; Sw: max. AC use in summer and also in winter; Ws: max. AC use in winter and also in summer; LD: living-dining room; significance level: ** $p < 0.01$; * $p < 0.05$.

Figure 9 shows the practising rates of energy-saving behaviours for each family size. For most energy-saving practises, the more people in the household, the higher the practising rate. In particular, fan use (Item 3) and window opening (Item 11) are high in households with more than four family members. The lifestyle of energy use or energy-saving behaviours is related to family size; therefore, proposals for effective energy-saving measures that fit each family size should be considered.

3.4.2. The Influence of Resident Age on AC Use in the LD

Figure 10 shows the annual electricity use of AC in the LD according to the age of the household members. Those aged 35–54 years old tend to use more electricity, and those more than 55 years old tend to use less electricity.

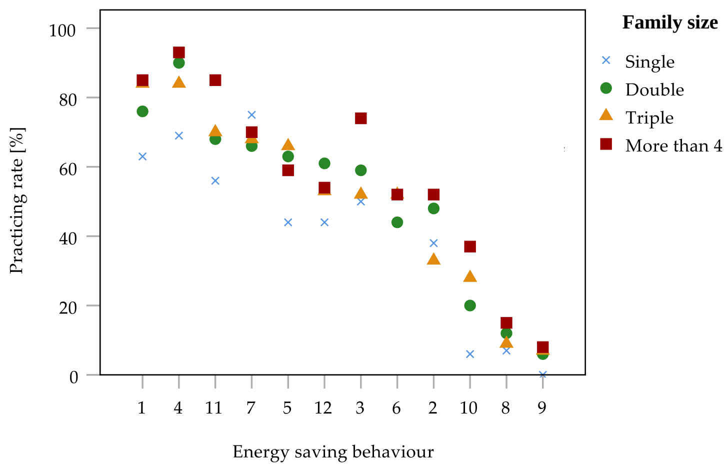


Figure 9. Practising rate of energy-saving behaviour according to family size (see Figure 3 for the behaviour corresponding to the number).

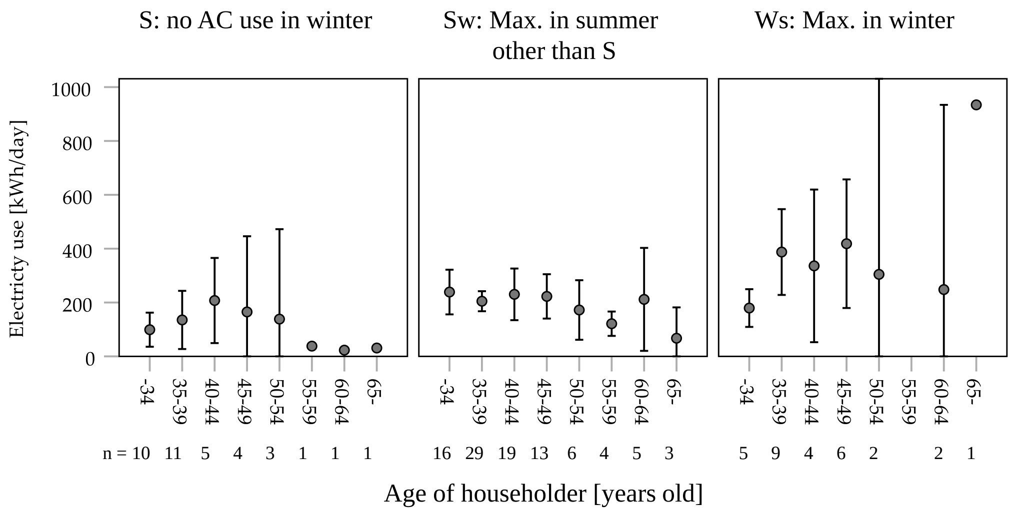


Figure 10. Annual AC use in LD according to family size in three AC-use types.

Figure 11 shows the practising rates of energy-saving behaviours for young, middle-aged, and elderly individuals. The elderly group (n = 17) practised '1. Set AC temperature to moderate levels'. In addition, the practising rates of '5. Save cooling/heating use during the days' and '6. Save cooling/heating use at night' were high. While the proportion of single and double occupancy is high in the elderly group, the time spent at home on weekdays might be long; therefore, they might be highly conscious of reducing the use of AC.

We further examined AC use in LDs among the elderly during summer. For Type S, who tend to have an energy-saving lifestyle, the mean electricity use for AC per household in summer was 141 kWh (Table 3); however, the amount used by the elderly (n = 3) was extremely low at 30 kWh.

Among the elderly of Type Sw (n = 12), the mean electricity use for AC per household in summer was also low at 141 kWh, whereas the mean amount for all in Type Sw was 162 kWh (Table 3). The practising rates of the use of fans (items 2 and 3) were high at 50 and 75%, respectively, and '11. Open the windows for ventilation positively' was also high at 83%. The elderly group of Type Sw might have a similar energy-saving lifestyle as that of Type S.

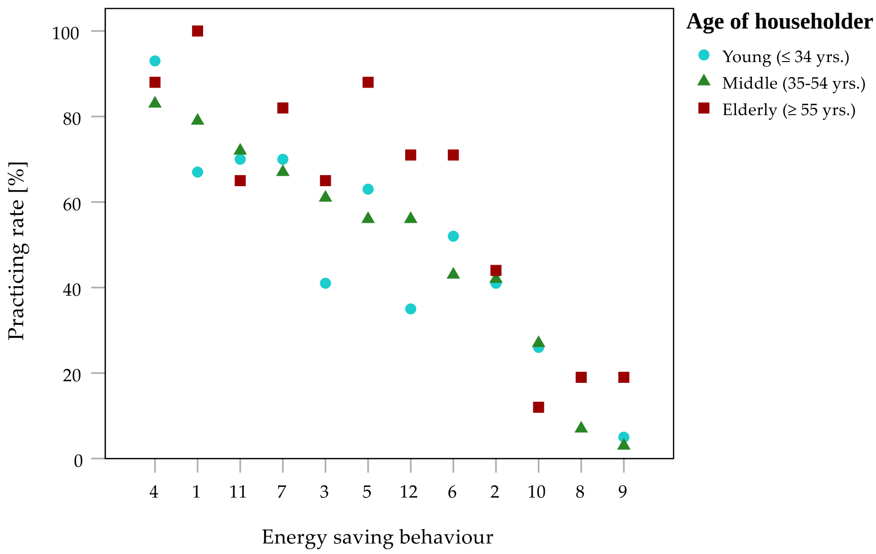


Figure 11. Practicing rate of energy-saving behaviour according to resident age (see Figure 3 for the corresponding behaviour number).

Nevertheless, the elderly group of Type Ws (n = 3) used AC throughout the year, and the mean electricity use for AC per household in summer was high at 156 kWh, which is higher than the mean value for all Type Ws at 108 kWh. They did not use fans (energy-saving behaviour items 2 and 3), and the practising rate of window opening (Item 11) was also low at 33%.

The elderly tend to use less AC overall; however, some households use AC throughout the year, and some households have energy-saving lifestyles. Therefore, effective energy-saving measures must be implemented to fit each lifestyle. For example, passive ducts can be installed at the entrance, windows can be opened to promote ventilation [60], and fans can be used to reduce AC use. Nevertheless, for households with extreme energy-saving lifestyles, it is necessary to promote AC and fan use to reduce the risk of heat stroke.

3.4.3. The Influence of the Employment Status of Married Women on AC Use in the LD

Table 6 shows the correlation coefficient between the employment status of married women and the amount of energy used. Gas use was significantly higher in households with full-time housewives; conversely, AC use tended to be higher in households with married women working outside of the home (i.e., dual-earners) both in summer and winter.

Table 6. Energy use in each group according to the employment status of married women.

Description	Dual-Earner	Full-Time Housewife	*p*-Value of *t*-Test
Annual AC use in LD (kWh)	224	206	0.53
Number of months AC used in LD	8.5	8.5	0.95
AC use in LD in summer (kWh)	144	138	0.76
AC use in LD in winter (kWh)	74	61	0.52
Gas use in winter (m^3)	390	479	0.003

Figure 12 shows the distribution of the period of absence. The peak absent hours on weekdays was 10 h for dual-earner households and 2 h for households with full-time housewives, and there was a significant difference between them.

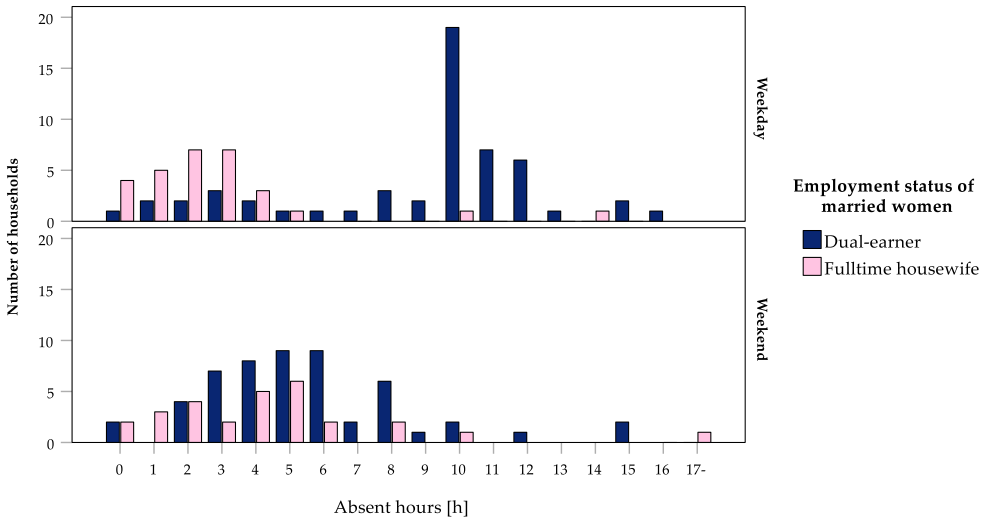


Figure 12. Periods of absence from home in a day.

Figure 13 shows the practising rates of energy-saving behaviours for each status of married women. Items '2. Using the fan instead of AC in summer' and '6. Saving cooling/heating use at night' were significantly lower in dual-earner households than in households with full-time housewives ($p = 0.005$ and $p = 0.019$, respectively).

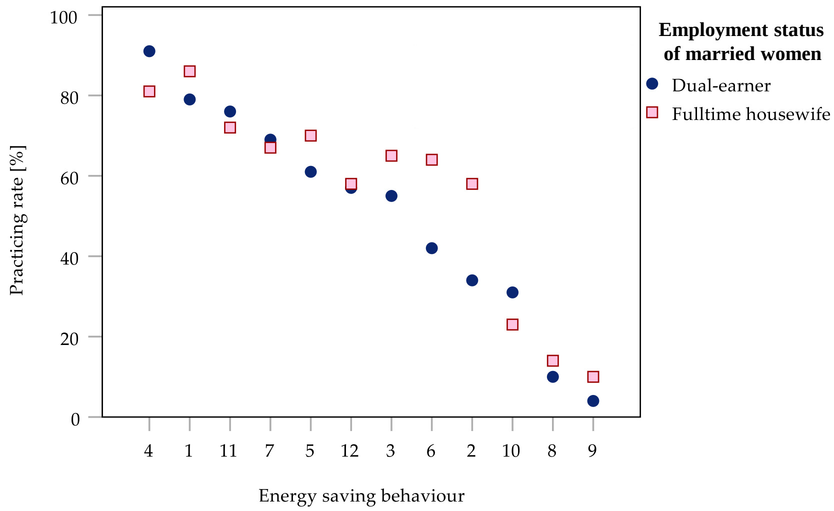


Figure 13. Practising rate of energy-saving behaviour according to the employment status of married women (see Figure 3 for the corresponding behaviour number).

From these results, we can say that the households of full-time housewives, who stay at home longer, prefer floor heating. In contrast, dual-earner households, who are away from home for a long time on weekdays, use AC intensively after they return home to immediately cool down in summer or heat up in winter due to the indoor temperature that rises or falls during the daytime. In households where the residents are away from home for a long time, the control of the indoor temperature during periods of daytime absence would be effective for both energy-saving efforts and improving the thermal comfort in summer. This includes using the bamboo blinds or green curtains for shading or using passive ducts at the entrance for ventilation. Making use of the low outdoor air temperature in the evening, by opening the window and using a fan, is also effective.

4. Overall Discussion

There are many studies on the heating and cooling use in condominiums. However, there are not enough field studies based on data measured by HEMSs. Furthermore, few studies have analysed the relationship between the seasonal change in energy use and the characteristics of the residents, family type, or energy-saving behaviours.

First, the Type S households, which do not use AC in winter, use less energy all year round, and the practising rate of energy-saving behaviours was high. It can be said that they are living an energy-saving lifestyle.

As for family size, we found that large households preferred gas floor heating over AC heating in winter, which is similar to the results of a previous study [40]. Larger families need to save heating/cooling energy without sacrificing their thermal comfort by appropriate energy-saving behaviours during longer periods of at-home stay. Evaluating the lifestyle of the Type S group may reveal some tips to accomplishing this.

As for the age of residents, the elderly tended to use less AC despite longer periods of staying at home. This result is consistent with that of a study in China [17]. However, some households were very dependent on AC use. Elderly residents who lead frugal lives carry a risk of heat stroke in summer or heart attacks in winter. However, elderly households with a 'high dependence on AC' need to acknowledge effective passive energy-saving measures without sacrificing thermal comfort.

As for the employment status of married women, the AC use was not lower for households with employed women, despite staying at home for a shorter time. We found that they used AC intensively after returning home to cool down quickly in summer or heat up quickly in winter. Nevertheless, they need to acknowledge measures to control the indoor environment during their absence. Residents who spend longer periods at home tend to shade from solar radiation using bamboo blinds or green curtains in summer. Alternatively, the passive use of a fan or opening a window at night would be effective.

This survey was conducted before the COVID-19 outbreak. As teleworking is expected to increase, more energy-efficient practises for adapting to the thermal environment at home might be needed. This study also indicated that the time spent at home might be a key factor in energy-saving efforts.

This study shows the characteristics of each type of AC use based on a monthly analysis. As a step further, we need to analyse energy use on a daily or hourly basis to propose energy-saving measures that respond to the characteristics of residents more precisely. It would also be useful to consider methods that can improve both thermal comfort and energy-saving efforts.

5. Conclusions

Through a field study using HEMS data and a questionnaire survey in a condominium, we analysed AC use in the LD and energy-saving behaviours to obtain the following results:

1. Eighty percent of all households used the gas floor heating installed in the LD as their main heating source instead of AC. In particular, the households of Type S, who do not use AC in the LD at all during winter, use less energy than those of the other types throughout the year. Furthermore, they practised more energy-saving behaviours.
2. In the corner flats, the energy used for heating tends to be higher than that of the middle flats. By improving the thermal insulation performance of the building, the energy efficiency and thermal comfort in the corner flats can be improved, even in Japanese low-carbon certified buildings.
3. We found that the gas floor heating was more dominantly used in the larger families where someone stayed at home for a longer time, whereas AC was more dominantly used in the smaller families because floor heating takes more time to start up.
4. Dual-earner households used AC intensively after their occupants returned home. The measures to control the indoor air temperature during periods of absence would be effective for maximizing energy-saving efforts and thermal comfort. These measures include the use of fans and opening windows in summer.

Through this field study, we found several effective measures, such as fan use instead of the intensive use of AC and the use of a bamboo blind or green curtain for shading in summer. The results of this study will be helpful in measuring the anticipated future changes regarding staying at home during and after the COVID-19 expansion.

Author Contributions: As a primary author, K.Y. contributed to the data collection, analysis, and manuscript writing, and prepared the final draft of the manuscript. H.B.R. revised the content of the paper, contributed to the editing and structuring of the paper, and gave advice on the data analysis. K.B., A.M. and H.A. also provided advice for the data analysis. All authors have read and agreed to the published version of the manuscript.

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