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Multiple Influencing Factors Analysis of Household Energy Consumption in High-Rise Residential Buildings: Evidence from Hong Kong

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Abstract

Buildings account for more than 90% of total electricity consumption in Hong Kong, one third of which comes from the residential sector. High-rise buildings dominate Hong Kong, but energy use in high-rise buildings has been insufficiently examined in previous studies, especially at the household or occupant level. This paper aims to explore the multiple factors that influence energy consumption in high-rise residential buildings, including the impact of occupant behaviours. The research was conducted through a questionnaire and face-to-face interviews with 135 households of a typical forty-floor residential building in Hong Kong. The survey examined technical and physical factors, human-influenced factors and social factors of energy consumption, including building information, social demographics, energy-related occupant behaviour modes and the residents' energy-saving attitudes. The results show that the monthly electricity bills of households at the twentieth floor or lower were 26% higher than those of households at higher floors during spring, summer and autumn, but similar during winter. This difference was attributed to various occupant behaviours, such as

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operating air-conditioners and opening windows. These findings expand the knowledge of occupant behaviour in high-rise residential buildings and inform building energy conservation policy-making in Hong Kong.

Keywords: High-rise residential building, energy consumption, multiple influencing factors, occupant behaviour, energy conservation

1. Introduction

Buildings account for more than 90% of Hong Kong's total electricity consumption, and one third of total building energy consumption is attributable to the residential building sector (EMSD 2019). Hong Kong also has a high-ranking Energy Use Intensity (EUI). The electricity consumption in residential buildings in Hong Kong was reported as 1583 kWh/capita/y in 2017 (EMSD 2019), which was higher than that in Singapore (1306 kWh/capita/y, 2015 (EMA 2016, DOS 2018)), South Korea (1236 kWh/capita/y, 2014), Russia (977 kWh/capita/y, 2014), Thailand (582 kWh/capita/y, 2014) and many other Asian countries (IEA and IPEEC 2015, Enerdata 2016). In addition, the government has set a target of a 40% reduction of energy intensity in the 'Energy Saving Plan for Hong Kong's Built Environment 2015–2025+' (EB et al. 2015). Increasing energy efficiency is thus a top priority for the residential building sector in Hong Kong.

Previous studies revealed the importance of building energy conservation (IEA and IPEEC 2015, OECD/IEA 2017). However, there are gaps in knowledge in three aspects of energy efficiency of high-rise residential buildings in Hong Kong.

First, previous studies focused primarily on buildings and overlooked detailed study at the household or occupant level. Some researchers examined the influence of household numbers and economy on the energy end–use in the residential sector in Hong Kong from 1990 to 2007 (Chung et al. 2011). Other researchers explored how engineering factors such as the cooling system performance, window-to-wall ratio and wall U-value determined the cooling energy consumption of residential buildings from 2004 to 2013 in Hong Kong (Jia and Lee 2016). This building-centric research revealed much information on human-influenced energy consumption trends but failed to examine energy bill distribution and its sensitivity to household or occupancy-level factors.

Second, there is insufficient knowledge of the human-influenced factors that affect energy consumption in residential buildings in Hong Kong. Factors that influence the energy consumption of a building can be categorised into technical and physical factors, human-influenced factors and social factors (Yoshino et al. 2017). There are numerous studies of technical and physical factors, but not enough studies of the effect of human-influenced factors on local buildings. Domestic energy-usage patterns have been collected by diary survey and questionnaire in Hong Kong (Tso and Yau 2003, Wan and Yik 2004, Lin and Deng 2006), but the energy consumption calculation was not particularly accurate due to the simplified method used for data collection, such as self-reported operation schedules to describe the operation modes of air-conditioners. A review of building energy research and practices in Hong Kong (Ma and Wang 2009) indicated that far fewer discussions were available on human-influenced factors than on policy environment and technical memoranda. Later studies (Chen et al. 2015, Kwok et al. 2017) also paid more attention to technical and physical factors to realise energy efficiency.

Third, the energy consumption features of households in high-rise buildings are seldom discussed. High-rise buildings are defined in the local Hong Kong code as 'any building of which the floor of the uppermost floor exceeds 30 m above the point of staircase discharge at ground floor level' (FSD 2012). High-rise buildings are the dominant building type in Hong Kong due to urban development needs (Pan et al. 2017). A review of high-rise buildings (Lotfabadi 2014) described the material efficiency in their construction phase and indoor thermal environment benefits in their operation phase, according to building height. Another energy simulation study (Weerasuriya et al. 2019) also elaborated the energy savings achieved using natural ventilation at the twentieth and fortieth floors of a high-rise residential building in Hong Kong. However, a model with one typical floor representing the whole building is not as accurate a model for high-rise buildings as for low or middle rise buildings. Thus, with the increasing number of megacities that contain many high-rise buildings (Guedes and Cantuária 2017), it is crucial to fully understand the energy-use profiles of high-rise residential buildings.

Overall, previous studies investigated the building-centric energy performance of residential buildings in Hong Kong and analysed technical and physical factors that affect energy consumption. However, research on actual energy consumption has been limited in terms of human-influenced energy-usage factors in high-rise buildings at the household level. Thus, this study aims to examine the multiple factors that influence energy usage in high-rise buildings, especially human-influenced factors, and explore the energy consumption features of households in high-rise residential buildings in Hong Kong. To fulfil these objectives, a list of influencing factors was identified via literature review, data on these factors were gathered from the occupants of a typical high-rise residential building in Hong Kong via questionnaire, the questionnaire results were analysed, and conclusions were drawn.

2. Review of influencing factors

The classification of influencing factors was performed according to the report by EBC-IEA (Yoshino et al. 2017) enumerating technical and physical factors, human-influenced factors and social factors. The choice of factors and the questionnaire design was based on previous reviews and practices in the USA, the UK, Australia, China and other countries. Since excessive variables make such studies unnecessarily costly and may lead to inaccurate results, this study collected data from one building with the same climate conditions, building characteristics and energy systems to control non-human factors and to improve the accuracy of the results. The influencing factors and descriptive variables addressed in this paper are given in Table 1.

Insert Table 1 about here.

The technical and physical factors included variables of climate, building characteristics and service systems. Since the survey was conducted in one building, the climate and building characteristics remained consistent. Energy consumption systems in the target residential building include lighting, domestic hot water, cooking, ventilation, heating and air conditioning systems, and other appliances (Hu et al. 2017, Sakah et al. 2019).

The human-influenced factors included variables of building operation and maintenance, occupant activities and behaviour and indoor environment quality. Important occupant activities include the use of building openings, lighting and shading devices, HVAC systems (e.g., on-off status and set point temperature) and hot water and electrical appliances (Delzendeh et al. 2017, Zhao et al. 2017, Simone et al. 2018). The energy consumption of lighting, domestic hot water, cooking, ventilation (Calì et al. 2016, Yao and Zhao 2017) and heating and air conditioning systems (Feng et al. 2016) can be described with the operation schedule or specifications of related appliances, whilst the energy consumption of other appliances, such as plug-ins, can be described by the type and number of the plug-ins (Sanquist et al. 2012, Fan et al. 2015, Xie et al. 2016, Guo et al. 2018). The occupancy schedule of a certain room can be determined from the residents' routines and activities. The indoor environmental quality can be evaluated by the indoor temperature and the predicted mean vote (PMV) value.

The social factors included the variables of energy-related attitudes and social demographics. The energy-related attitudes of occupants can be quantified by self-reported energy-saving efforts (Fan et al. 2015, Azar and Al Ansari 2017). In addition, the occupants' knowledge of building systems is known to directly correlate with their behaviour and household energy consumption (Zhao et al. 2017). Other variables include the household structure, income and educational background (Sanquist et al. 2012, Fan et al. 2015, Huebner et al. 2015, Xie et al. 2016).

Insert Table 2 about here.

3. Methods

The study was conducted via a questionnaire and face-to-face interviews with the households of a typical forty-floor residential building in Kowloon, Hong Kong. Household energy consumption was calculated, and the multiple influencing factors were quantitatively described before analysis of their impacts on energy consumption of households in high-rise buildings.

3.1 Case building description

Public housing policy was developed more than 60 years ago and has progressed robustly ever since. Publicly available rental housing currently provides accommodation for 2 million people, or approximately 30% of the total population in Hong Kong (HA 2018). The study was conducted in one of these public housing estates. The target building is a Y-shaped forty-floor building in Kowloon with 988 units. The building has four types of units with housing areas ranging from 13.9 m^2 to 35.8 m^2, designed to accommodate 1 to 5 people with a living room and up to two bedrooms. The large number of residents in the single high-rise building makes it possible to collect a large set of data and thus acquire reliable results by questionnaire.

3.2 Questionnaire design and on-site survey

The questionnaire was designed to provide a comprehensive understanding of energy consumption in high-rise residential buildings in Hong Kong. The factors that influence energy consumption are summarised above, and the details of the questions are shown in Table 2. The survey was conducted in Hong Kong using both Cantonese and English as text languages and was designed by the same researchers to avoid the problem of two-way translation. The question text and answer types were carefully designed with reference to existing sophisticated survey mechanisms (Leeuw et al. 2008, Bethlehem 2009, Thompson 2012, Simone et al. 2018) and successful surveys (BRE and DECC 2013, AEFI 2014, H. Fan et al. 2015, Hu et al. 2017, EIA 2018, EIA 2018, Aragon et al. 2019). The participants were recruited with a snowball sampling method. The recruitment was performed around the entrance of the building for 3 days, and all adult residents passing by had an equal chance to voluntarily participate. During the survey, researchers remained beside the participants to make sure that the participants understood the questions and to make note of any additional information that was not elucidated by the questionnaire. Ultimately, 135 effective responses were obtained.

3.3 Methods of statistical analysis

Both descriptive and comparative analyses were used to achieve our research objectives.

1) Descriptive analysis

Descriptive analysis provided a quantitative evaluation of the energy consumption and multiple influencing factors of households in Hong Kong. This pre-treatment also compiled the influencing factors for the follow-up analysis. The results of descriptive analysis can be adopted as inputs for household-energy simulation models and as a reference for future post-occupancy energy audit research of residential high-rises in Hong Kong.

2) Comparative analysis

Multi-linear regression analysis was inappropriate for this study because the sample size may prevent accurate analysis of many influencing factors and generate the collinearity problem mentioned in the literature (Huebner et al. 2015, Huebner et al. 2016). Although principle component analysis can help to solve the collinearity problem (Xie et al. 2016), the factors generated from such analyses have no practical application. In addition, energy bills and their logarithmic transformation both fail the parametric test, the Shapiro-Wilk test (SPSS software), confirming that these data do not follow a normal distribution. It is invalid to apply parametric analysis to non-normally distributed data because it may sacrifice the reliability and validity of statistical results (Ghasemi and Zahediasl 2012). Accordingly, non-parametric testing is the better method for analysis of a high-rise household's energy consumption features.

This comparative analysis aimed to explore the energy consumption differences between households at higher and lower floors in high-rise buildings and to find the causes for the observed differences. It was recognised that the statistical methods should use sufficient data to produce meaningful results (Thompson 2012). Thus, the sample was divided into two independent groups: the lower-floor group, comprising households on and below the twentieth floor, and the higher-floor group, comprising households above the twentieth floor.

First, non-parametric testing was applied to test the hypothesis that the distribution of the monthly energy bill differed between higher-floor and lower-floor groups. Good methods for this testing include the Kruskal-Wallis test and Mann-Whitney U test (SPSS software). These two independent tests are commonly used to compare the distribution of ordinal or continuous data, especially for data that are not normally distributed. Second, this study compared the factors that influence energy usage in the two groups and attempted to discern the reasons for any differences between the groups.

4. Results and analyses

4.1 Information of participants

The social demographic information of the participants in the survey is elaborated below. The questionnaire was answered by one occupant from each household who was familiar with the household's energy use habits and bills.

Household structures of the sample were categorised as one member (11.7%), two members (8.6%), three members (14.1%), four members (8.6%), and more than four members (0.8%). Most participants were female (65%) and showed better knowledge of household energy consumption. The sample covered all flat types and household structures and was in line with the distribution of flat types in the target building, such that the results can be representative of the target building (as shown in Figure 1).

Insert Figure 1 about here.

Figure 2 shows educational attainment and total monthly household income. The monthly income value was set according to the Housing Authority's income limits for public renting house applicants (HA 2017). Most households earned below 17350 HKD per month, and the unemployment rate of the participants (60%; 73 of 122 effective answers) partly supports this result. More than 80% of the participants held a certificate for a secondary or above degree course.

Insert Figure 2 about here.

4.2 Technical and physical factors

In addition to flat floor and flat type, appliances are one of the technical and physical factors that were considered in this study. Table 3 shows the category and the number of the appliances used by households. Most households had one refrigerator, one washing machine, one electric cooker, and one television. Fewer than half of the residents surveyed had a microwave oven in their home, and fewer than half had electric blankets or ceiling fans.

Insert Table 3 about here.

The installation locations and number of lights were also investigated, and most households had one light per room, as shown in Figure 3.

Insert Figure 3 about here.

4.3 Human-influenced factors

Human-influenced factors such as air conditioning, ventilation, heating, showering and cooking were explored extensively in this study. The occupant behaviour modes with respect to these energy-related activities were described in both qualitative and quantitative ways to inform future research on behaviour modelling.

4.3.1 Air conditioning

Air-conditioners are the most common type of cooling equipment used by residents in Hong Kong, and the questionnaire results showed that only 5% of residents did not have or use air-conditioning (AC) in their homes. Among those who had at least one air-conditioner, a window-type air-conditioner was their first choice, rather than a split air-conditioner, as displayed in Figure 4. In addition, 46% of the participating residents (58) had installed an air conditioner in a bedroom, 31% (39) in both a bedroom and a living room, and 23% (29) only in a living room.

Insert Figure 4 about here.

AC can be defined in terms of being open mode/close mode, set point temperature- or set point wind level-controlled, its interrelationship with other cooling methods, and the cooling requirements of the season.

The open and close modes of AC are shown in Figure 5 and Figure 6. The multiple-choice questions were about incentives for AC operation. The ratio indicates the number of participants who chose certain answers compared to the number of participants who gave effective answers. In a bedroom, typical AC operation behaviours by users were to turn when feeling hot and to keep the AC on overnight. In the living room, typical AC operation behaviours by users were to turn on when feeling hot and turn off when feeling cold.

Insert Figure 5 and Figure 6 about here.

The minimum, general and maximum set-point temperatures of split AC are shown in Figure 7, and the medians of the set-point temperature in these different scenarios were 21°C, 24°C and 26°C (40, 55 and 37 effective answers) for operation settings of split air-conditioner.

Insert Figure 7 about here.

Similarly, set-point fan speed of window-type AC is shown in Figure 8. The residents gave 55, 68 and 53 effective answers about the set fan-speed in three scenarios (i.e., the minimum, general and maximum set-level situations). There were two findings: (1) residents preferred a higher set-point level when it was hot; (2) 65% residents preferred to use the middle fan-speed level in all three thermal scenarios.

Insert Figure 8 about here.

Figure 9 illustrates the exclusive relationship between the simultaneous operation of electric fans and air-conditioners. This relationship was determined by asking whether the residents would turn on electric fans when the air-conditioner was already on. It turned out that only 6% and 7% (118 effective answers) of residents would choose to turn on electric fans when the air-conditioner was on. Another 87% would not open the electric fan when they had already turned on an air-conditioner. Obviously, there was an exclusive relationship between the operation of electric fan and air-conditioner.

Insert Figure 9 about here.

Finally, households with AC units gave answers (124 effective answers) about the season during which AC was used (i.e., the 'cooling season'). The monthly operating proportion of AC units over a year showed a positive relationship exists with respect to outdoor temperatures in Hong Kong: the 'cooling season' was from May to October.

4.3.2 Ventilation

Natural ventilation is introduced through the windows of flats in the target high-rise residential building. Time and thermal incentives determine the operation of windows (Hong et al. 2016). In addition to the thermal comfort demand of the occupants discussed above, window on-off status was collected at various periods during a day, and for windows in kitchens, living rooms and bedrooms (123, 104 and 122 effective answers), as shown in Figure 10. There were three findings: (1) the two main operating modes were 'open all-day' and 'open during daytime'; (2) 13%, 6% and 7% of the residents never opened windows in the kitchen, living room or bedroom, respectively; and (3) the residents often kept windows half-open, according to observations made during the site visit.

Insert Figure 10 and Figure 11 about here.

In Figure 11, the interrelationship between the operation of windows and air-conditioners is illustrated. Overall, more than 80% residents would not keep windows open and run the AC simultaneously. This shows another exclusive relationship exists, this time between the operation of windows and air-conditioners.

4.3.3 Heating

About 76% residents did not have heating equipment in winter (124 effective answers). The other 24% residents used fan heaters, electric blankets, air-conditioners, and/or hot water bottles. Residents in Hong Kong used little heating in winter, compared to other energy consuming activities, such as cooking or domestic hot water usage/showering.

4.3.4 Cooking and showering

Cooking mode is described by the frequency and duration of daily cooking activities. According to the answers collected for weekdays (106 effective answers), approximately 9% of residents would not use natural gas and 74% residents would spend less than an hour cooking with natural gas. The corresponding answers collected for weekends (99 effective answers) were 14% and 73%, respectively.

Showering mode is characterised by the temperature of water supplied for showering and the duration of showering. Effective answers were collected with 116 for summer, 102 for spring and autumn and 106 for winter. The median showering duration was 70 minutes per week. The median values of lower and upper limits of the temperature of water supplied for showering were 37°C and 40°C.

The survey results of human-influenced factors can inform the settings of both deterministic and probabilistic occupant behaviour models and improve the accuracy of building energy simulation. Yu et al. (2019) compared two building energy models with and without consideration for human-influenced factors and used results of this present study as inputs. How to transform the survey data into input parameters was discussed, and the accuracy of simulated household energy consumption was improved by 16%.

4.4 Social factors

In addition to the participants' social demographic information, this study examined the effect of social factors on participants' attitudes to energy-related topics. Five areas of energy-related attitudes were participation in energy management, energy-saving activities via purchase, energy-saving activities via operation, self-evaluation of energy consumption levels, and self-evaluation of energy efficiency levels.

Participation in energy management was determined by a question about the lights in communal areas. Briefly, the communal areas of the target residential building have controllable lights. The residents were asked whether they knew about the lights and whether they had ever changed the lighting level. Only 3% of the residents knew about and used the controllable lights in communal areas, which indicates that residents pay little attention to energy management in communal areas.

The purchase behaviour of energy efficient appliances is shown in Figure 12. The relevant multiple-choice question collected 131 effective answers. A light was the most popular energy-efficient appliance, purchased by 69% residents, followed by a refrigerator (47%) and an air-conditioner (40%).

Insert Figure 12 about here.

Participants ranked the energy-saving measures according to the measure's perceived ability to save energy during operation, as shown in Figure 13 (127 effective answers). The residents preferred to reduce the air-conditioner's operation time rather than increase its set point temperature, which suggests that residents follow different behaviour principles when conducting different energy-saving activities, such as purchase and operation. The energy-saving activities were therefore influenced not only by energy-saving desires but also by marketing and promotional aspects.

Insert Figure 13 about here.

Self-evaluation of energy consumption levels was achieved by asking for the residents' perception of how their energy bill compared to that of their neighbours. As shown in Figure 14, approximately 34% of residents had 'no idea', and might have never thought about this question before. Otherwise, 9%, 41% and 16% of residents thought they had higher, similar and lower energy bills compared with their neighbours, respectively.

Self-evaluation of energy efficiency is shown in Figure 15. Approximately 60% of residents reported that the energy efficiency of their household was good or very good, 38% reported it was average, and the rest (2%) reported that it was poor or needed much improvement. It was evident that most residents had high confidence in the energy efficiency of their households.

Insert Figure 14 and Figure 15 about here.

4.5 Energy consumption

Energy consumption was calculated by analysis of values for the monthly electricity and gas bills, as given by those who filled out the questionnaire survey. Monthly electricity and gas bills are shown in Figure 16 and Table 4.

Insert Figure 16 and Table 4 about here.

According to the Hong Kong Observatory (Synnefa et al. 2017), summer is from June 1 to August 31 and winter is from November 1 to the following January 31. This information was used to examine the seasonal effects on household energy bills, according to the results of the survey. Monthly gas bills were similar through the year. Almost 30% of residents consumed 100–200 HKD of gas per month, and 30% residents consumed 200–400 HKD per month. Few residents did not use gas, and only 10% of residents paid more than 400 HKD per month for gas.

However, the monthly electricity bills were significantly different between seasons, generally decreasing from summer to winter. In summer, around 30% residents paid 400–600 HKD per month for electricity, whilst in winter around 40% residents paid 200–400 HKD a month. In particular, the 'last month' electricity and gas bill (November), provided a reliable data point for researchers because people always had a more accurate memory of the latest received electricity and gas bill.

The average annual electricity bill was 4631 HKD per household (hh), equating to an estimated electricity consumption of 4089 kWh/hh (CLP 2017, CLP 2018); the average annual gas bill was 2983 HKD/hh, equating to an estimated gas consumption of 10.57 GJ/hh (Towngas 2018). The average annual total energy bill was 7571 HKD/hh, and thus the average annual energy consumption was 25.28 GJ/hh (median, 23.20 GJ/hh). In addition, the average annual energy consumption per capita was calculated as 9.1 GJ/capita, which was comparable with 8.1 GJ/capita in 2017 reported from the EMSD (EMSD 2019). Thus, the survey data is in line with general energy consumption status in Hong Kong, meaning that these findings of human-influenced factors and energy actions can be generally applicable to high-rise households in Hong Kong.

5. Discussion

The technical and physical factors, human-influenced factors and social factors examined above expanded the existing knowledge of energy consumption and energy-related activities in high-rise residential buildings in Hong Kong. A better understanding of the multiple influencing factors will enable discussion of how residents select and adopt energy-saving measures according to their subjective energy-saving attitude and how various factors influence the energy consumption of households in high-rise residential buildings.

5.1 Residents' energy-saving attitude and measures

The residents showed confidence in the energy efficiency of their households and displayed good energy-saving knowledge in this survey. In totally, 60% residents (out of 131 effective answers) provided positive comments on their own energy saving behaviour, characterising it as 'good' or 'very good'.

Two energy saving measures promoted by the Environment Bureau (EMSD 2017) were investigated: 'to maintain average indoor air temperature between 24–26°C' and 'to procure energy efficient appliances and systems'. First, according to results from the survey, the median set-point temperature of a split room air-conditioner is generally 24°C (40 effective answers). This confirms that the energy efficient measures suggested by the government (EEO and EMSD 2017, EMSD 2017) to set and maintain air-conditioned room temperature between 24°C and 26°C in summer have been adopted by residents. Second, 69% residents (131 effective answers) had bought energy-efficient lights, much higher than the percentage who had bought an energy-efficient refrigerator (49%), air-conditioner (40%), or electric fan (18%), and almost all households had at least one energy efficient appliance, which again reflects successful education and market-guidance from the government.

In addition, the residents' preference for energy-efficient appliances was not simply due to the energy-saving capacity of appliances. The electricity end-uses of public households in 2017 consisted of air conditioning (38%), cooking (18%), hot water (12%), refrigeration (8%), office equipment (8%), laundry (7%), lighting (5%)and others (5%; The total is 101% because of rounding) (EMSD 2019). Obviously, there is a much larger energy-saving potential for air conditioning and refrigeration than for lighting. Accordingly, the Mandatory Energy Efficiency Labelling Scheme (MEELS) (HKeL 2014) has been effective for air-conditioners, refrigerating appliances and compact fluorescent lamps since 2009.

However, the payback of the investment in an air-conditioners or refrigerator for energy conservation is longer-term than that for lights. A comparison of payback years was calculated based on the product list (EMSD 2018), the energy calculator (EMSD 2018) from the website of MEELS and the suppliers of relevant products (Philips 2016, Easybuy 2018, ECLink 2018, Hitachi 2018). Light products are from Philips and air-conditioners and refrigerating appliances are from Hitachi in this comparison, as both companies are the most popular suppliers in Hong Kong.

It was determined that when energy efficient lights have longer service lives and perform better, the price gap between products with average energy efficiencies (Grade 3) and high-energy efficiency (Grade 1) is minimal. Most lights in the mature energy-efficient lighting market are priced below 60 HKD.

Table 5 shows the comparison of performance and price for window-type room air-conditioners (W-AC), split room air-conditioners (S-AC) and refrigerators. The compared ACs have the same rate of cooling capacity, and the two refrigerators have the same food volume. High energy efficiency (Grade 1) appliances are significantly more expensive and have much longer payback periods compared to average energy efficiency (Grade 3) appliances. It thus seems a more economical choice to buy ACs and refrigerators of Grade 3. This supports the survey results from the residential building (year of intake: 2013) that more energy efficient lights are bought than other appliances, highlighting the role played by price leveraging in the promotion of MEELS.

Insert Table 5 about here.

5.2 Relationship between households' energy bills and building height

This sample is divided into two groups according to the sample size to explore the energy consumption characteristics of high-rise residential buildings. The two groups are the lower-floor group (i.e., 65 households from the twentieth floor or lower) and the higher-floor group (60 households from higher than the twentieth floor). The floor number of households was evenly distributed inside each group. The comparative analysis was performed between the two groups.

The independent variables were the monthly electricity bills and the gas bills of: summer ($Electricity_s$,Gas_s); spring and autumn ($Electricity_{sa}$,Gas_{sa}); and winter ($Electricity_w$,Gas_w). Since these data failed to meet the normal distribution, non-parametric tests were applied to compare the higher- and lower-floor groups (categories H/L). The sample sizes of $Electricity_s$,Gas_s, $Electricity_{sa}$,Gas_{sa}, $Electricity_w$,Gas_w were 60, 54, 51, 48, 59 and 54 for the lower-floor groups and 55, 49, 49, 44, 53 and 47 for the higher-floor groups. At a significance level of 0.05, the null hypothesis of same distribution was retained for monthly gas bills of all seasons and was retained for electricity bills of winter. This meant that no difference was reported for monthly gas bills and winter electricity bills. However, by both Mann-Whitney U test and Kruskal-Wallis Test, as shown in Table 6 and Table 7, the electricity bills in summer and the transition seasons showed statistically significant variance at the 0.05 level. The median monthly electricity bills in transition seasons and summer were 400 HKD and 535 HKD, respectively, for lower-floor households, which was 38% and 26% more than the higher-floor households (290 HKD and 425 HKD, respectively), as shown in Figure 17.

Insert Table 6, Table 7 and Figure 17 about here.

This poses the question: what is the underlying cause of the energy bill difference between the households at higher and lower floors? A comparative analysis was conducted of influencing factors, including technical and physical factors, human-influenced factors and social factors. The only statistically significant difference between households at higher and lower floors was the number of ceiling fans, displayed in Table 7: 35% of households in higher floors and 17% in lower floors had ceiling fans. According to the estimated electricity cost of common appliances (HKElectric 2017) from EMSD, a typical ceiling fan has a 150-W power rating. However, the monthly electricity bill mostly ranged from 400 HKD to 600 HKD in summer, meaning the electricity consumption ranged from 356 kWh to 520 kWh, which far exceeds the electricity consumed by ceiling fans. Thus, the difference in the number of the ceiling fans in higher- and lower-floor households was not the direct reason for the differences in energy consumption between these two groups of households.

Technical and physical factors, social factors and the quantifiable human-influenced factors failed to explain such a difference, and no statistically significant difference in these factors was seen between the two groups (as shown in Table 8). The declining outdoor air temperature in Hong Kong (HKO 2018) by itself could also not explain the electricity bill difference. The height of the target building is 124 m, and the vertical air temperature change is limited within 1°C, so the direct effect of climate was also insufficient to explain the large variance of energy consumption between two groups as being ascribable to a decreased cooling load at higher levels improving air-conditioner performance.

Insert Table 8 about here.

However, differences in occupant behaviours may underlie the energy bill difference. First, households on lower floors benefited less from natural ventilation and preferred diverse cooling equipment. Frequent window operation behaviours were reported by participants and households at higher floors to enable better use of natural ventilation than households at lower floors on cooler days (Weerasuriya et al. 2019). Another piece of evidence was that more households at higher floors owned ceiling fans, as mentioned above, indicating more operation of less energy-intensive cooling equipment. It follows that natural ventilation and ceiling fans can replace other energy-intensive and strong cooling equipment on 'not-very-hot'/cooler days, e.g. transition seasons, thus reducing cooling costs. Building energy simulation results suggested that different operation modes of windows could cause different electricity bills in high-rise residential buildings (Du and Pan 2019). Advantageous environment of households at higher floors and using natural ventilation for cooling caused up to 18% variance in cooling load of Floor 3 and Floor 39 in the target high-rise residential building.

Second, the operation modes of AC differed between households at higher and lower floors (Figure 18 and Figure 19). (1) In bedrooms at lower floors (47 effective answers), more occupants would turn on the AC only when feeling hot and keep it on the whole night, whilst those at higher floors (46 effective answers) preferred to turn on the AC when sleeping and keep it on the whole night. As mentioned above, 77%, 92%, 91% and 82% surveyed residents used the air-conditioner in June, July, August and September, when it can be extremely hot for a whole day: the mean air temperature of these four months were 28.8°C, 28.7°C, 29.3°C and 29.0°C, as observed by Hong Kong Observatory 2017 (HKO 2017). With cooling load from other sources, it would be necessary to operate AC overnight in bedrooms at lower floors for indoor thermal comfort. Air conditioners are used for 10 to 12 h per day (Chen et al. 2019) and the overnight AC operation mode in bedrooms is indeed the dominant usage mode, according to 68% of the participants in another survey in Hong Kong (Lin and Deng 2006). Under these operation modes, during sleeping, residents in households at higher floors and lower floors would keep AC on, but those on lower floors would also turn the AC on before sleeping when feeling hot. Bedrooms at higher floors can thus use less electricity for air conditioning. (2) In addition, in the living room at lower floors (34 effective answers), more occupants would turn the AC on when feeling hot and turn it off only when leaving home, whilst those at higher floors preferred to turn the AC on when feeling hot and turn it off when feeling cold. The operation modes of AC in living rooms of households at higher floors can therefore lead to smaller electricity bills for higher-floor households than lower-floor households.

Insert Figure 18 and Figure 19 about here.

According to the discussion above, the significant difference in the electricity bills for higher- and lower-floor households was attributed to the occupant behaviour modes. In that case, what causes the different behaviour modes and leads to the difference in energy consumption? Potential triggers and contextual factors that influence occupant behaviours include internal (biological, psychological and social) and external (building and building-equipment properties, physical environment and temporal) factors (IEA-EBC 2013, Yan et al. 2017). In this study, the data suggest an interaction between the indoor physical environment and the operation of AC and windows by residents, leading to the difference in electricity bills for higher- and lower-floor households in a high-rise building. A field measurement of indoor environment quality of four households in a high-rise residential building with the same ventilation situation in Malaysia supports this hypothesis (Aflaki et al. 2016). The measurement was taken across the first 2 weeks of July 2013, and the indoor environment quality of four living rooms is shown in Table 9. The households at higher floors had better indoor thermal comfort according to ASHRAE Standard 55-2017 (Tyler et al. 2017).

Insert Table 9 about here.

Air conditioning accounted for 38% of the electricity end-uses of public households in Hong Kong in 2017 (EMSD 2019), which means that variations in occupant behaviour actually have large impacts on the residential building sector. Future research on the interaction of indoor environment and occupant behaviours in high-rise residential buildings is strongly suggested, together with investigations of methods to improve energy conservation and thermal comfort for residents in high-rise households.

6. Conclusions

This paper has examined energy consumption of households in typical high-rise residential buildings in Hong Kong and investigated multiple factors that influence building energy use.

The first conclusion of the paper is that various types of interventions should be used simultaneously to successfully shape the energy-saving behaviours of high-rise residents. As discussed, residents properly practised some government-suggested energy-saving measures such as 'to maintain average indoor air temperature between 24–26°C', whilst to some extent resisting other energy-saving measures such as 'to procure energy efficient appliances and systems'. That is, energy-efficient lights were more widely adopted by occupants than energy-efficient air-conditioners and refrigerators, due to financial considerations. Thus, education about energy conservation should be coordinated with economic incentives to help residents establish successful energy-saving behaviours.

The second conclusion is that occupants of the upper floors of a high-rise residential building will be more likely to display energy-saving behaviours. According to our results, residents of households at or lower than the twentieth floor have statistically significantly higher electricity bills than the residents of households at higher floors during the summer and transition seasons. This can be attributed to different operation modes of air-conditioners and windows by residents in higher and lower floors, which could be caused by the different indoor environment in high-rise buildings. Everyday interaction between residents and their indoor environment gradually shapes statistically different behaviour modes between the residents of households at higher and lower floors, ultimately leading to larger electricity bills for those on the lower floors.

Previous studies have not sufficiently discussed the energy consumption gap in high-rise residential buildings. The reported investigation was limited by sample size, and more surveys are needed to examine the conclusion. The preliminary conclusion is that the differences in behaviour modes should be considered carefully in developing further studies of energy usage in high-rise residential buildings. This study expands the knowledge of occupant behaviour in high-rise residential buildings and indicates that more investigations are needed on the energy saving potential and stratification of thermal comfort benefits in high-rise residential buildings. This and future studies will inform the government's energy policy for high-rise residential buildings, such as 'Energy Saving Plan for Hong Kong's Built Environment 2015–2025+' (EB et al. 2015). Future research is required to examine microclimates in high-rise residential buildings and the adaptive behaviours of occupants that affect household temperature regulation in these buildings.

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Tables

Table 1 A framework of influencing factors of building energy use addressed in the paper

Concept	Sub-concept	Description
Technical and physical factors	Climate	Not included in this paper
	Building characteristics	Floor, flat type
	Building service systems	Energy supplying and transformation: not included in this paper Energy consumption: appliances for lighting, domestic hot water, cooking, ventilation, heating and air conditioning, and other appliances
Human-influenced factors	Building operation and maintenance	The number and the operation schedule of appliances: lighting, domestic hot water, cooking, ventilation, heating and air conditioning The number of appliances: other appliances
	Occupant activities and behaviour	Occupants moving, using of openings and energy consumption system
	Indoor environment quality provided	Indoor thermal, lighting and air environment
Social factors	Energy-related attitude	Self-reported energy saving effort
	Social demographic	Household structure, income and educational attainment

Table 2 Summary of variables in the questionnaire

Section	Variable	Description	Concept
Information of participants	Age	Short answer, numerical	Social demographic
	Gender	Multiple choice question: female, male	Social demographic
	Educational attainment	Multiple choice question: 5 choices according to Census and Statistics Department	Social demographic
	Household structure	Short answer: number of children, employed adult, unemployed adult	Social demographic
	Household total income	Multiple choice question: 6 choices according to the Housing Authority	Social demographic
Technical and physical factors	Flat type	Multiple choice question: 4 flat types	Building characteristics
	Flat floor	Short answer, numerical	Building characteristics
	Number of appliances	Short answer, numerical	Building service systems
Human-influenced factors	Type of air-conditioner	Multiple choice question: window type, split type	Building operation and maintenance
	Location of air-conditioner	Multiple choice question: in bedroom, in the living room, both, others	Building operation and maintenance
	Cooling season with air-conditioner	Short answer, numerical: months to start and end cooling	Building operation and maintenance
	Operation modes of air-conditioner	Checkboxes: incentives of turning on or off air-conditioners in the living room and bedroom	Occupant activities and behaviour
	Set point temperature of air-conditioner	Short answer, numerical	Indoor environment quality provided
	Operation schedule of windows	Checkboxes: open or closed schedule in the morning, the daytime, before sleeping, all day	Occupant activities and behaviour
	Exclusive relationship in operation of window, electric fan and AC	Multiple choice question: 5 choices, never, seldom, sometimes, frequently, always; Exclusive relationship between AC and window, AC and fan	Occupant activities and behaviour

	Duration of showering	Short answer, numerical	Occupant activities and behaviour
	Frequency of showering	Short answer, numerical, seasonal and weekly frequency of showering	Occupant activities and behaviour
	Set point temperature of domestic hot water	Short answer, numerical	Occupant activities and behaviour
	Duration of cooking	Short answer, numerical	Occupant activities and behaviour
	Frequency of cooking	Short answer, numerical, weekly cooking frequency	Occupant activities and behaviour
	Daily schedule pf occupants	Multiple choice question: occupancy schedule in the living room, in bedroom, outside for weekdays and weekends	Occupant activities and behaviour
	Workdays and rest days of occupants	Multiple choice question: workdays in a week	Occupant activities and behaviour
Social factors	Participation in energy management	Multiple choice question: Do you know that the lights in the communal area have switches for raising a higher lighting level?	Energy-related attitude
	Energy-saving activities via purchase	Checkboxes: Have you ever bought "energy efficient" appliances?	Energy-related attitude
	Energy-saving activities via operation	Checkboxes: What do you think are the most energy efficient measures?	Energy-related attitude
	Self-evaluation of energy consumption levels	Multiple choice question: 4 choices, higher, similar, lower, no idea; How do you think of your household energy bill, compared with your neighbour?	Energy-related attitude
	Self-evaluation of energy efficiency	Multiple choice question: 5 choices, very good, good, average, poor, much to improve; How will you evaluate your household energy saving status?	Energy-related attitude
Energy consumption	Household monthly energy consumption	Short answer, numerical: seasonal monthly electricity bill and gas bill [HKD]	

Table 3 Appliances category information

Number of appliances (N)	**Number of households**				
	N=0	N=1	N=2	N=3	N=4
Refrigerator	4	130	1	0	0
Washing machine	10	125	0	0	0
Microwave oven	81	53	1	0	0
Electric cooker	13	119	3	0	0
Computer	49	76	8	2	0
Ceiling fan	101	28	4	1	1
Induction cooker	82	52	0	0	0
Electric blanket	123	11	1	0	0
Electric water heater	72	62	1	0	0
Gas water heater	50	85	0	0	0
Electric stand fan	54	65	12	3	1
TV	13	111	10	1	0
Air-conditioner	7	78	37	12	1

Table 4 Monthly energy bill

Season	Summer	Spring and autumn	Winter
Median of monthly electricity bill [HKD]	500	335	300
Sample size	124	108	122
Median of monthly gas bill [HKD]	240	250	250
Sample size	111	99	109

Table 5 Comparison of Grand 1 and Grand 3 energy efficiency appliances

MEEL	Item	W-AC	S-AC	Refrigerator
Grade 1	Appliance Model	RA-10MDF	RAS/C-DX10CSK	R-H310P4H
	Electricity Bills	499 HKD/yr	283 HKD/yr	235 HKD/yr
	Appliance Price	5280 HKD	5800 HKD	4280 HKD
Grade 3	Appliance Model	RA-10LEF	RAS/C-E10CAK	R-T310E1H
	Electricity Bills	544 HKD/yr	418 HKD/yr	465 HKD/yr
	Appliance Price	4110 HKD	4580 HKD	3160 HKD
Service life [year]		8~15 years	8~15 years	9~13 years
Payback years Grade 3 v Grade 1		26 years	9 years	5 years

Table 6 Mann-Whitney U test of electricity and gas bill

Test Statistics	$Electricity_s$	$Electricity_w$	$Electricity_{sa}$	Gas_s	Gas_w	Gas_{sa}
Asymp. Sig. (2-tailed)	.030	.072	.033	.426	.537	.991

Table 7 Kruskal-Wallis test of electricity bill

	Null Hypothesis	Sig.	Decision
1	The distribution of $Electricity_s$ are the same across categories of H/L.	.035	**Reject** the null hypothesis.
2	The distribution of $Electricity_w$ are the same across categories of H/L.	.066	Retain the null hypothesis.
3	The distribution of $Electricity_{sa}$ are the same across categories of H/L.	.031	**Reject** the null hypothesis.
4	The distribution of Gas_s are the same across categories of H/L.	.280	Retain the null hypothesis.
5	The distribution of Gas_w are the same across categories of H/L.	.748	Retain the null hypothesis.
6	The distribution of Gas_{sa} are the same across categories of H/L.	.436	Retain the null hypothesis.

Table 8 Mann-Whitney test of two independent samples on influencing factors

Asymptotic significance (2-tailed)		Categories H/L and sample Size
Gender	0.066	59 H/ 64 L
Flat type	0.902	59 H/ 64 L
Age of participant	0.463	56 H/ 64 L
Educational attainment	0.339	59 H/ 65 L
Income	0.651	57 H/ 63 L
Self-evaluation of energy efficiency	0.335	58 H/ 64 L
Number of employed adult	0.195	60 H/ 61 L
Number of unemployed adult	0.891	60 H/ 61 L
Number of children	0.903	60 H/ 61 L
Number of refrigerator	0.700	60 H/ 65 L
Number of washing machine	0.430	60 H/ 65 L
Number of microwave	0.940	60 H/ 65 L

Number of electric cooker	0.914	60 H/ 65 L
Number of computer	0.477	60 H/ 65 L
Number of ceiling fan	0.038	60 H/ 65 L
Number of induction cooker	0.784	60 H/ 64 L
Number of electric blanket	0.840	60 H/ 65 L
Number of electric water heater	0.697	60 H/ 65 L
Number of water heater using gas	0.893	60 H/ 65 L
Number of electric stand fan	0.830	60 H/ 65 L
Number of TV	0.647	60 H/ 65 L
Number of light	0.744	47 H/ 41 L
Number of air-conditioner	0.551	60 H/ 65 L
Number of split AC	0.371	60 H/ 65 L
Number of window type AC	0.321	57 H/ 63 L
Installation location of AC	0.909	56 H/ 63 L
Cooling season	0.571	62 H/ 58 L
Set point temperature of AC	0.455	27 H/ 22 L

Table 9 Living rooms' environment quality measured in four households in Malaysia (Aflaki et al. 2016)

Case	**Orientation**	**Floor**	**Mean temperature [℃]**	**Mean relative humidity [100%]**	**Mean air velocity ratio [m/s]**
1	Northeast	3	28.62	73.51	0.13
2	Northeast	13	27.42	65.49	0.52
3	Southeast	3	29.5	78.34	0.07
4	Southeast	13	28.29	70.55	0.26

Figures

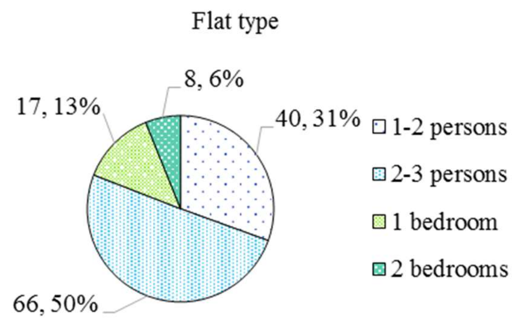

Figure 1 Flat type distribution of the sample

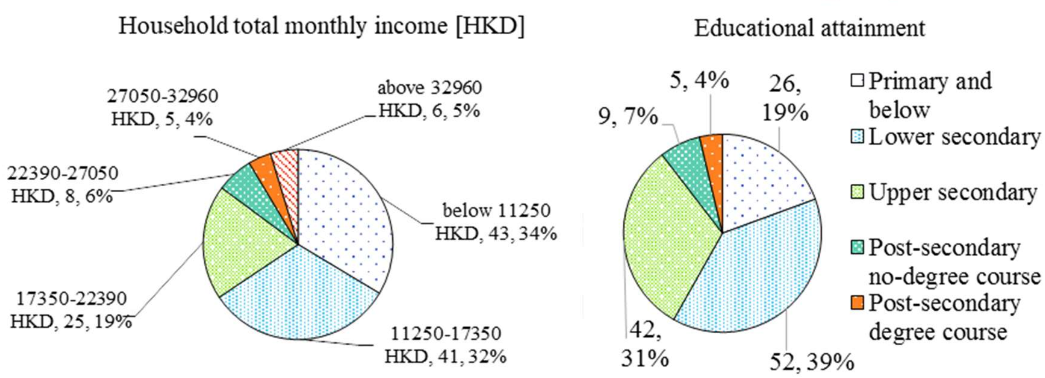

Figure 2 Household total monthly income and educational attainment

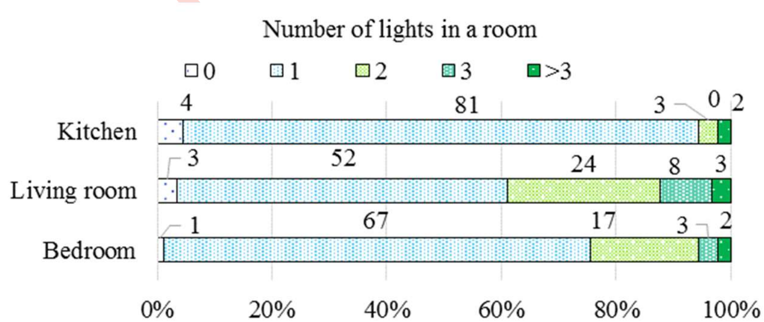

Figure 3 Lighting ownership results

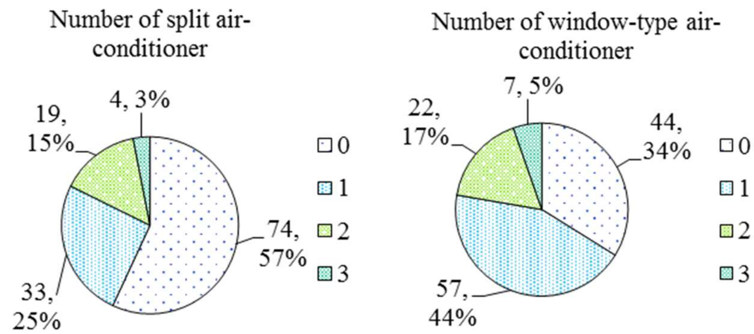

Figure 4 AC possession rate

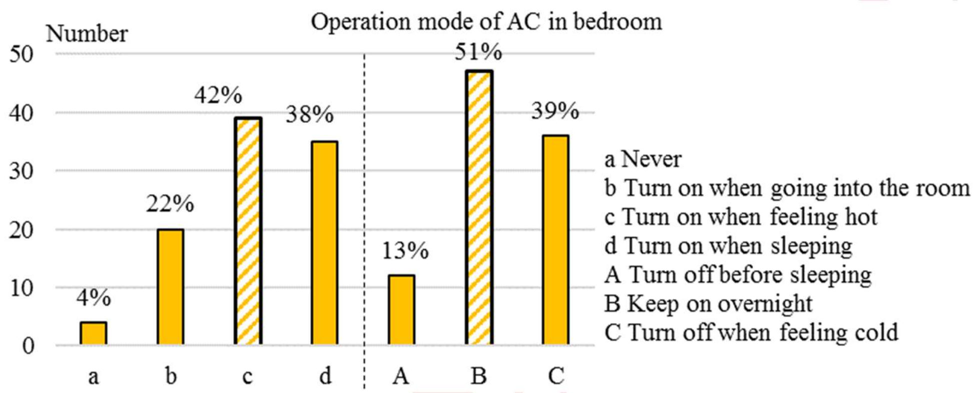

Figure 5 Open and close mode of AC in bedroom

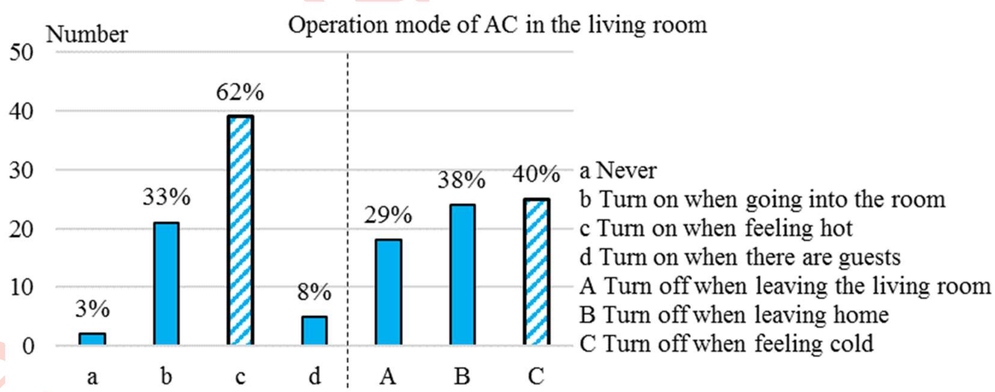

Figure 6 Open and close mode of AC in the living room

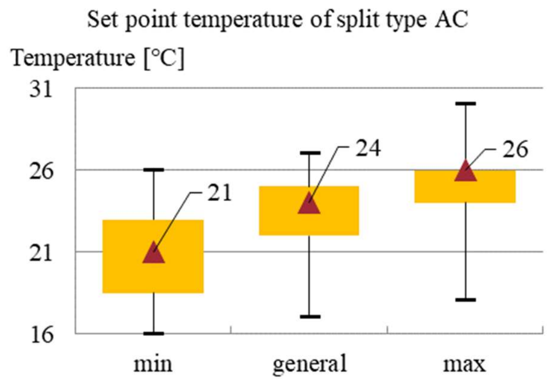

Figure 7 Set point temperature of split air-conditioner

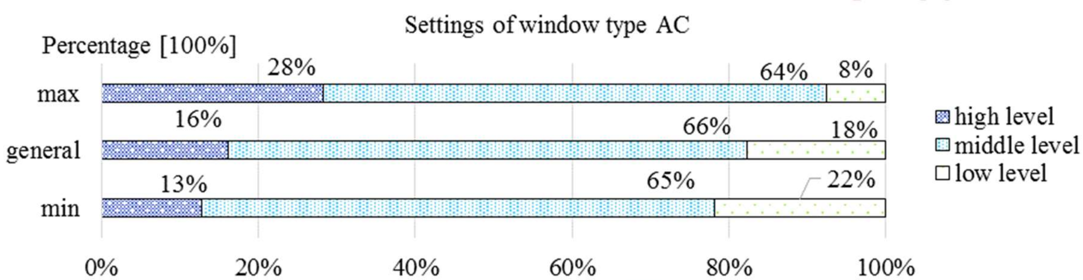

Figure 8 Settings of window type air-conditioner

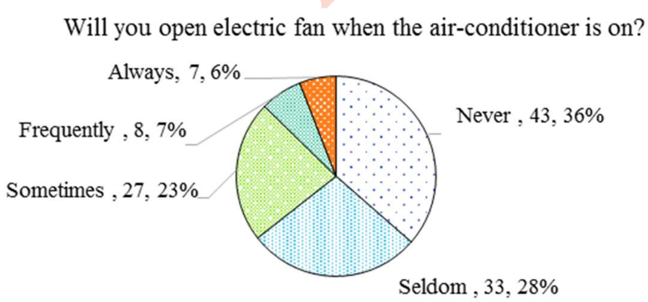

Figure 9 Exclusive relationship between the operation electric fan and air-conditioner

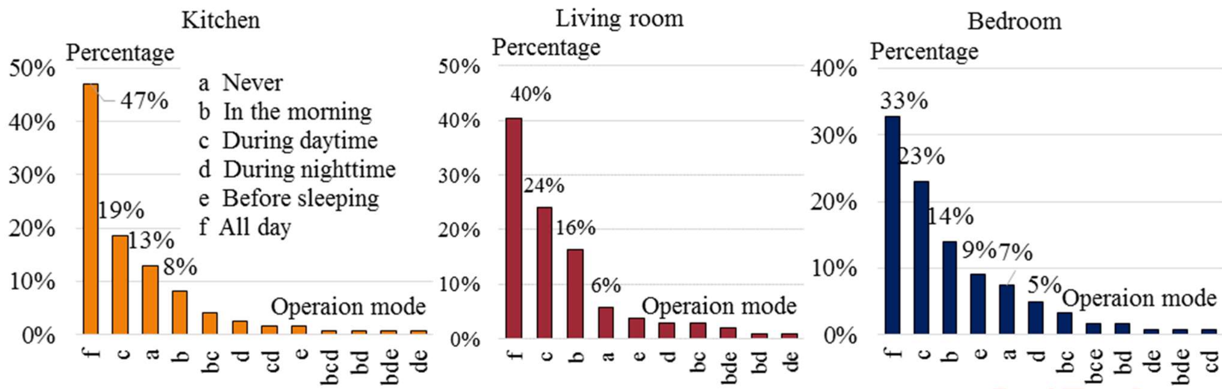

Figure 10 Operation modes of window

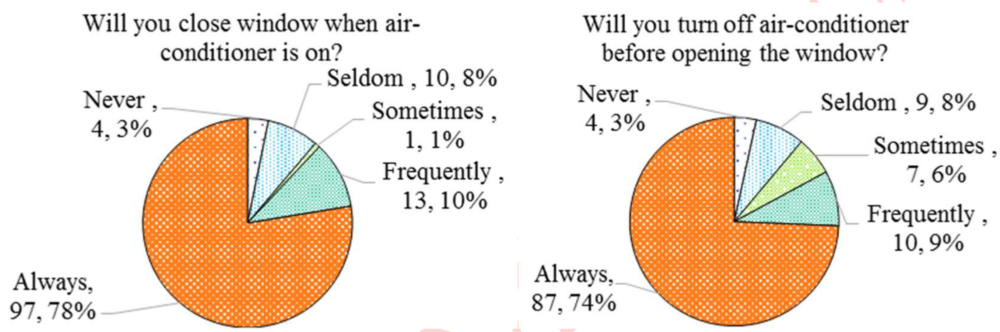

Figure 11 Exclusive relationship between the operation of window and air-conditioner

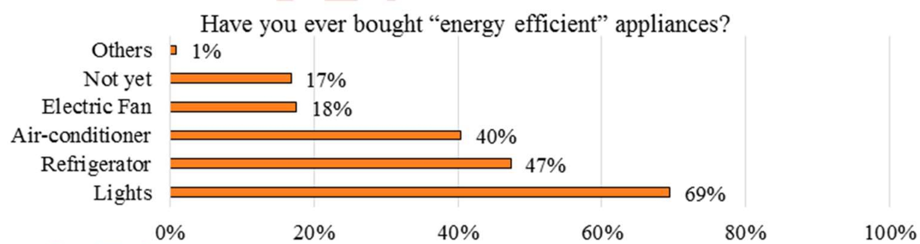

Figure 12 Energy-saving activities via purchase

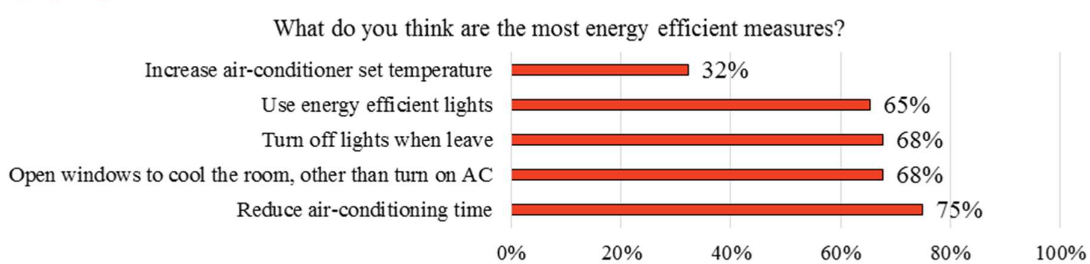

Figure 13 Energy-saving activities via operation

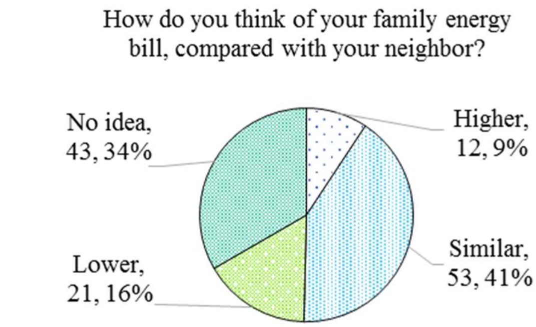

Figure 14 Self-evaluation of energy consumption levels

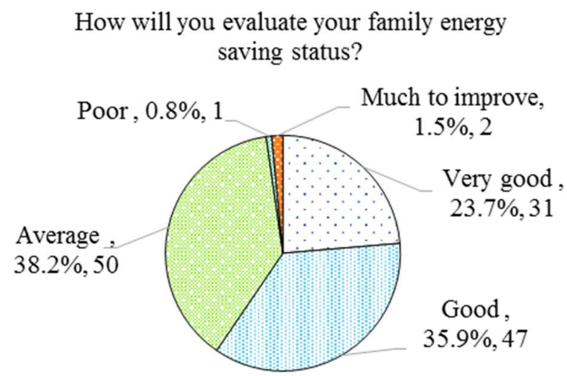

Figure 15 Self-evaluation of energy efficiency

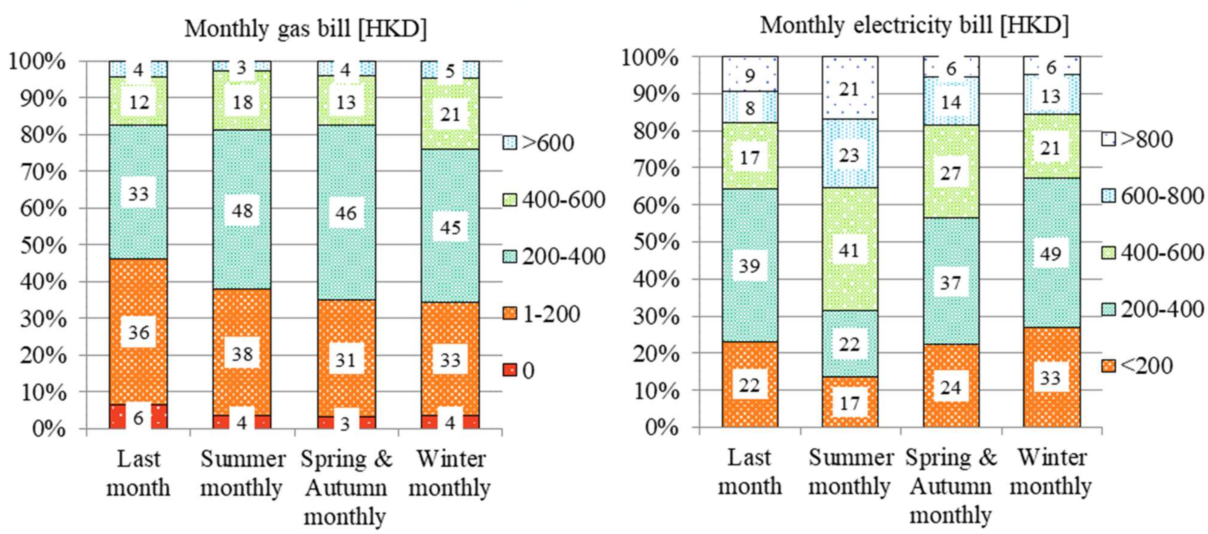

Figure 16 Monthly gas bill and monthly electricity bill

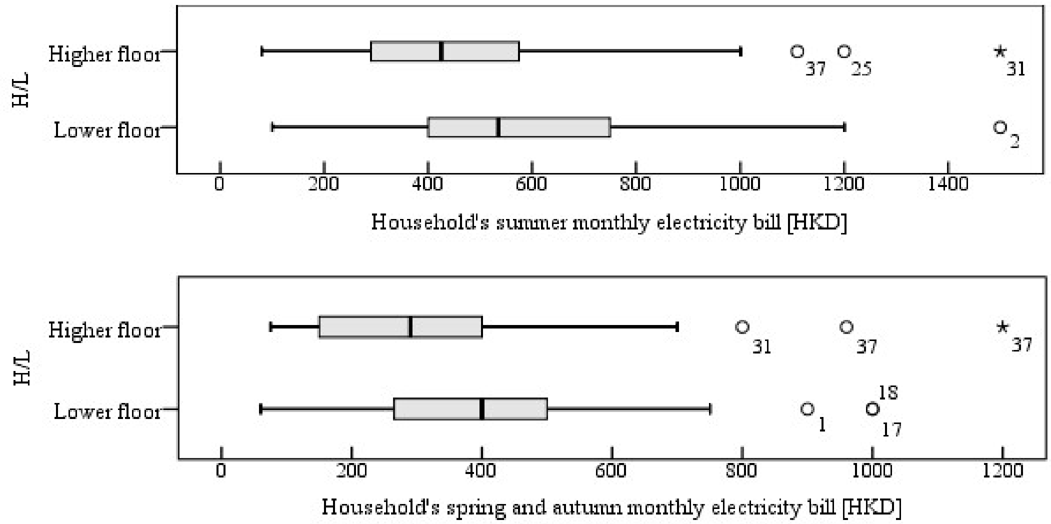

Figure 17 Monthly electricity bill per household distribution of households at higher and lower floors

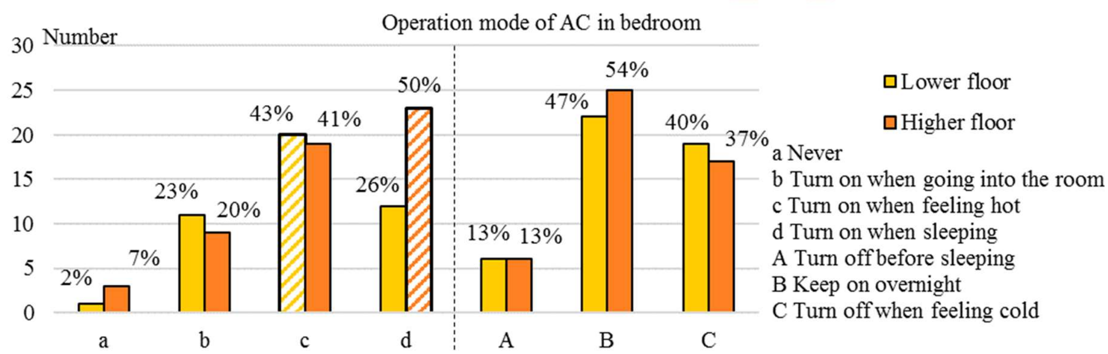

Figure 18 Comparison of bedroom AC operation mode

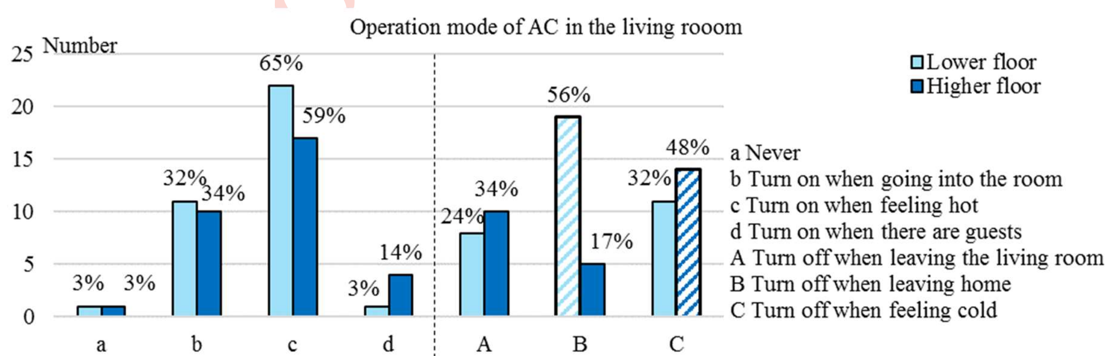

Figure 19 Comparison of living room AC operation mode