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A Case Study on Household Electricity Uses and Their Variations Due to Occupant Behavior in Chinese Apartments in Beijing

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Abstract

In order to gain a good understanding of residential building energy consumption in China, a case study about occupants' use of electricity for lighting, appliances and room air conditioners was carried out in 44 identical apartments in Beijing. Additionally, two apartments with significantly different energy consumption levels were chosen for a detailed study about the impact of occupants' daily behavior in using lighting, appliances and room air conditioners. The results of this study demonstrate the important contribution of occupant behavior to the significant variation of electricity consumption among residential buildings. The detailed measurement of occupant behavior showed a potential in better understanding how energy is consumed in buildings and relevant information gathered from this process can help occupants change their behavior for energy saving.

Keywords: household electricity use; occupant behavior; lighting and appliances; room air conditioners; quantitative relationship

1. Introduction

Along with China's rapid development in the past several decades, housing construction has shown a quick expansion in most big cities of this country. Such expansion has resulted in a dramatic increase of energy consumption in residential space heating, cooling, lighting and appliances, to provide occupants with a comfortable living environment. Statistics have shown that except for heating, residential energy consumption in other categories in urban areas of China has increased by nearly 400% between 1996 and 2011, which was from 36 million tce[1] in 1996 to 153 million tce in 2011[1)]. Therefore, energy efficiency/saving in residential sectors is now a serious issue in China.

In Chinese residential sectors, electricity demand for lighting, appliances and space cooling has been growing quickly in recent years, due to a higher need of using new types of appliances and room air conditioners[1)]. In order to obtain a better understanding on how electricity use is consumed in Chinese residential sectors, many studies have been carried out to investigate actual residential electricity use, either using a field survey method or based on statistical data[2)-12)]. Most of these studies focused on the averaged/accumulated characteristics of electricity use on the basis of either a whole city level or a whole climatic region, except Wu *et al.*[2)] and Chen *et al.*[3), 4)]. Wu *et al.*[2)] investigated energy use among 410 apartments in Beijing in 1999 and found significant variations in household electricity use. Chen *et al.*[3, 4)] calculated the mean, maximum and minimum values of household electricity use in some Chinese cities, as well as the standard deviations. These studies have provided evidence that occupant behavior has a significant impact on buildings' energy performance especially at an individual household level[11)-17)]. As the averaged/accumulated values cannot reflect the influence of individual behavior on household energy consumption, the characteristics of residential energy consumption cannot be understood comprehensively. Furthermore, improving occupant behavior in residential sectors can also greatly help to reduce their energy consumption[18, 19, 20, 21)], but this needs to be based on a good understanding of occupant behavior at the individual level.

Occupant behavior was not a hot research topic in China until its importance was highlighted in a study on household electricity use for space cooling in Beijing[11)]. In this study, Li *et al.*[11)] monitored the household electricity use by air conditioners (AC) in 25 identical apartments located in one low-rise building in Beijing, in the summer of 2006. From the study, they realized great variations

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in annual AC electricity use among these apartments, in which the maximum, minimum and mean values were 991 kWh, 0 and 170 kWh, respectively. This study, together with the studies performed by Chen *et al.*[3, 4] and Wu *et al.*[2], have sufficiently demonstrated the significant variations in household electricity use due to occupants' personal behavior. However, further explorations on the actual energy use patterns for room air conditioners, lighting and appliances, as well as their influences on household electricity use are still highly required.

In the past several decades, a number of studies on occupant behavior in residential buildings have been carried out in European countries, Australia, the USA and Japan[13-17, 19-24], before the importance of occupant behavior was officially realized in China. For example, in addition to emphasizing the variation of household electricity use among dwelling units, the variations of major end-use loads have also been described and analyzed based on field measured data. Some efforts have been made to identify typical use patterns of individual appliances[15-16]. To explore the energy saving potential relating to electric appliance purchase, Anibal *et al.*[16] analyzed the annual electricity saving from replacing existing inefficient technologies with the Best Available Technology (BAT), in a typical household. Moreover, Lopes *et al.* [17] have provided detailed information about the use patterns of major domestic appliances such as TVs, rice cookers and refrigerators, for both their operation mode and length of use. Finally, they evaluated the impact of these use patterns on residential electricity use.

In order to provide more evidence regarding the influence of occupant behavior on electricity use in Chinese residential sectors, a longitudinal study was performed in forty-four apartments located in one apartment building in Beijing, China. Additionally, as previous efforts on reducing residential building energy consumption in China were mostly focused on upgrading building insulation and system efficiency[25, 26], a deeper study was performed to investigate how and to what extent a better understanding of occupant behavior can help to change such behavior for energy saving.

2. Methodology

2.1 Case Study Building

The study was carried out in a 17-storey apartment building (as shown in Fig.1.) located in Beijing, China. The building was built in 2007, with a reinforced concrete wall structure and a conventional plate shape. It was designed and constructed complying with the Beijing Design Standard for Energy Efficiency of Residential Buildings (DBJ01-602-2004)[27]. The building contains 136 three-bedroom apartments, with identical floor areas of 105 m^2. Split air conditioners are used to keep the indoor thermal environment comfortable in summer. In winter, all apartments in the building are centrally heated by the city district heating system.

2.2 Data Collection

In order to explore the impact of occupant behavior on the electricity use of individual apartments, a year-long study (between October 2008 and September 2009) was carried out in 44 individual apartments in the investigated building, in terms of their electricity use for lighting, appliances and room air conditioners. During the survey period, the occupants of all monitored apartments performed a normal working schedule in China, which was from 9:00 to 17:00, so the occupancy condition of these apartments was considered to be similar. During the whole survey period, the household electricity use for each apartment was recorded twice a week (every 3 or 4 days) by manually reading a DDSY201 type electricity meter (Fig.2.). All monitored occupants stated that they had similar daily use patterns concerning lighting and appliances in both free-running periods (neither heating nor cooling is needed) and summer periods, based on which the monthly electricity use by air conditioners in summer was calculated by subtracting the averaged monthly electricity use for lighting and appliances during the free-running period from the total monthly electricity use in summer.

Fig.1. Case Study Building

Fig.2. Electricity Meter for Household Electricity Use

2.3 Energy Information Session

After the survey, an energy information session was performed to the occupants of two apartments, which showed significantly different electricity use during the survey period. In the session, a face-to-face talk with the occupants was carried out, discussing the monitored electricity use from their homes. This session aimed to help them better understand the real status of electricity use in their apartments, and thus to improve their awareness concerning energy saving.

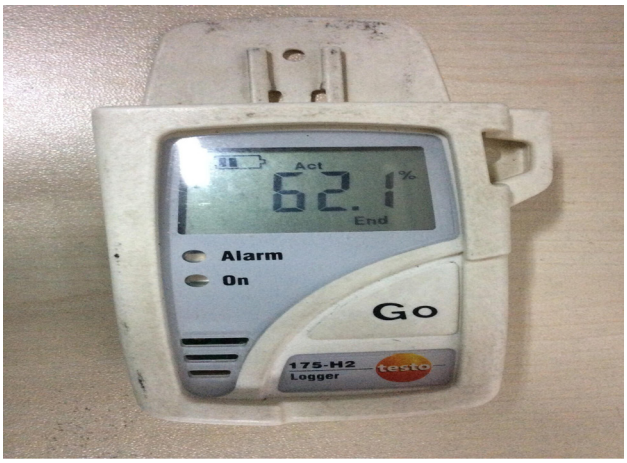
2.4 Measurement

To identify occupants' electricity use patterns in the two apartments, a detailed study was performed to monitor the occupants' use of individual electrical appliances at different times of day. The study was conducted after the energy information session and in October 2009, when neither heating devices nor air conditioners were in use. The electricity load of each individual electrical appliance was recorded at a ten minute interval for a week, using a calibrated S300 Watt Hour Meter installed between the appliance and the power plug, as shown in Fig.3.a. Meanwhile, the daily household electricity use in both apartments was recorded as well.

In order to obtain a comprehensive understanding of household electricity use in the two apartments, occupants were asked to provide quantitative information about the length and frequency of their daily use of lighting and appliances, for both weekdays and weekends, during the monitoring period.

Moreover, during the whole survey period, indoor air temperature and relative humidity were also measured in the living room and the bedroom using Testo 175-H2 data loggers (Fig.3.b), at an interval of ten minutes.

(a) Electric power



(b) Thermal environment

Fig.3. Power and Thermal Measurement

3. Results

3.1 Variation of Household Electricity Use

Based on the field measured data, the annual household electricity uses for lighting, appliances and room air conditioners were calculated for all 44 apartments and ranked based on the total annual household electricity use, as shown in Fig.4.

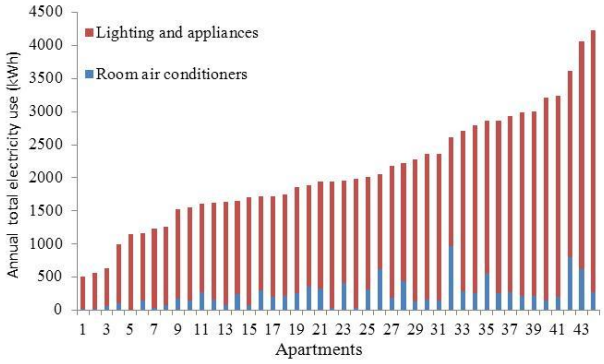


Fig.4. Annual Household Electricity Use by the Monitored 44 Apartments

As all apartments are identical with respect to both construction and outdoor weather conditions, the significant differences in electricity use among individual apartments in Fig.4. must be caused by occupant behavior. As shown in Fig.4., the electricity use among individual apartments for lighting and appliances, and for space cooling varied significantly, with AVG (average value)/SD (standard deviation) being 1848.9/761.4kWh for lighting and appliances, and 245.8/203.7kWh for space cooling, respectively. The relatively high SD values statistically reflect the great impact of occupant behavior on residential electricity use.

The results in Fig.4. also give a real picture of the current electricity use status for lighting and appliances and for space cooling at the individual household level. Currently, there are still no benchmarks at both the national and local levels concerning household electricity use for lighting and appliances in Chinese residential sectors, as well as for space cooling. In that context, the current situation of household electricity use measured in this study was compared with that measured in 1999 from 410 three-bedroom apartments in Beijing [2]. In that study, the electricity use of each apartment was measured monthly, lasting for a whole year. From the measurement, it was observed that the monthly household electricity use during the free-running period was between 70.0 kWh and 100.0 kWh, with an AVG of 88.8 kWh for all 410 apartments. Therefore the average annual electricity usage for lighting and appliances for those apartments can be estimated as 1065.6 kWh. Additionally, the electricity use for air conditioning each apartment in summer in that study was calculated using the same method as used in this study, and the average annual household electricity use for space cooling in those 410 apartments was 65.6 kWh. Comparing the two sets of data (1848.9/245.8kWh in this study and 1065.6/65.6kWh in the 1999 study), it was found that the household electricity use in Beijing has increased significantly in the past 10 years due to occupants' behavioral change concerning lighting and appliances, and also concerning room air conditioners. Due to the high proportion of household electricity use for lighting and appliances and for space cooling in the total energy consumption of residential sectors, changing occupant behavior should have a big potential regarding the saving of residential energy consumption.

3.2 Occupant Behavior Concerning Lighting and Appliances

For a detailed analysis of occupants' use of lighting and appliances, two apartments (Apartment 10 and Apartment 43 in Fig.4.) with significantly different electricity use levels for lighting, appliances and space cooling were chosen for a detailed study on how occupants use electricity in their homes. Apartment 43 is occupied by a couple, with a child who goes to the university during weekdays. Apartment 10 is also occupied by a couple and an adult child, and their daily schedules were almost the same as the corresponding people in Apartment 43. Additionally, all families have reported that they almost followed regular daily lifestyles and used lighting and appliances almost in the same way every day. A change may occur on weekends when their children come back from their universities.

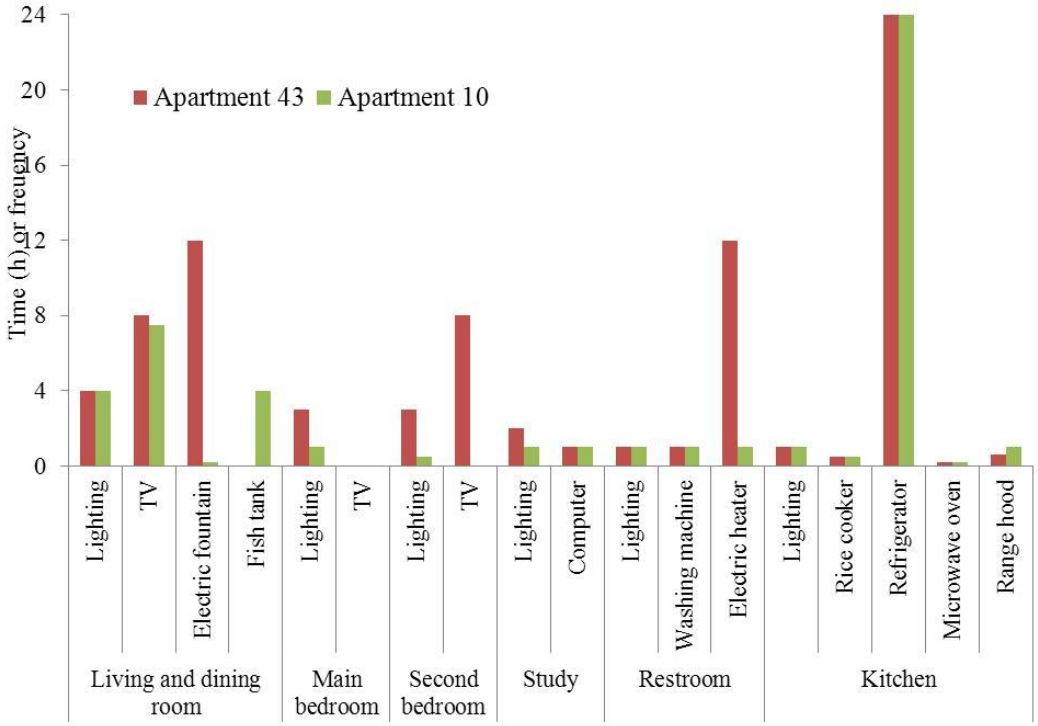
According to the survey data of electricity use collected every 3 or 4 days for one year, the average daily household electricity use on weekdays for the two apartments was calculated to be in the range of 10.5-12.5 kWh and 2.5-3.5 kWh, respectively, and the corresponding results on weekends were in the range of 15.0-17.0 kWh and 3.5-4.5 kWh, respectively. Additionally, the annual household electricity use for space cooling in the two apartments was 625.9 kWh and 145.1 kWh, respectively.

As mentioned above, household electricity use for lighting and appliances and for room air conditioners is highly dependent on occupants' use of these facilities, including the actual electrical consumption of these devices and their daily length and frequency of use. With regards to daily length and frequency of use for lighting and appliances, occupants in the two apartments were asked to fill out a paper questionnaire to provide relevant facility usage information for each room in their apartments, for weekdays and weekends, respectively, as shown in Fig.5.a and 5.b. The electrical consumption of each appliance was measured using Watt Hour Meters at a 10-minute interval and was lasting for two hours when that appliance was in use. As an example, Fig.5.c shows the ten-minute actual energy consumption for the computers in the two apartments.

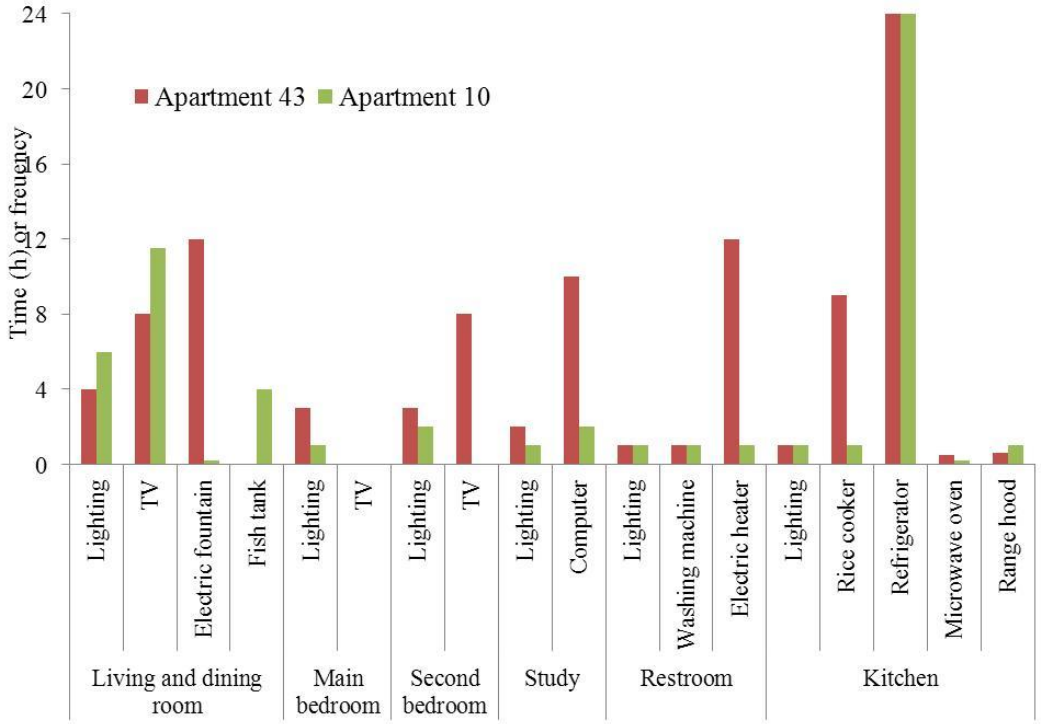
Combining the measured electrical consumption profile of each appliance and the reported daily length and frequency of use for lighting and appliances, the contribution of each device to the total household electricity use for lighting and appliances in the two apartments was estimated, as shown in Fig.6., for weekdays and weekends, respectively.

The total daily electricity use for lighting and appliances in the two apartments was calculated to be 10.5 kWh and 3.9 kWh on weekdays, and to be 15.8 kWh and 4.8 kWh on weekends, respectively. These numerical values have a good agreement with the real measured values by electrical devices, as mentioned already in previous contents. Therefore, what occupants reported with respect to their behaviors relating to the use of lighting and appliances is consistent with the calculated household electricity use for the two apartments.

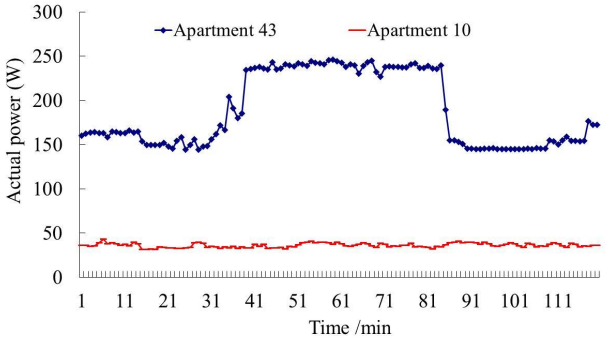
Considering the contribution of lighting and each appliance to the total electricity use, Fig.6. also shows that in Apartment 43 5.3 kWh electricity was used by an electric heater on weekdays, accounting for about half of the household electricity use. This was followed by lighting that accounts for 15.9% of the total electricity use. The contributions of other devices were between 2% and 8%. For weekends, the electric heater was still the biggest energy consumer in the apartment (35.0%), followed by lighting (10.9%). Additionally, the electricity use by rice cookers and computers increased by 2.4 kWh and 1.8 kWh, comparing to that for weekdays. These account for 17.8% and 13.2% of household electricity use on weekends, respectively. For Apartment 10, it used much less electricity for lighting and appliances than Apartment 43, with a daily electricity use of about 4.0 kWh.



(a) Daily length or frequency of using facilities on weekdays



(b) Daily length or frequency of using facilities on weekends



(c) Variation of actual electrical consumption of computers

Fig.5. Occupants' Use of Lighting and Appliances

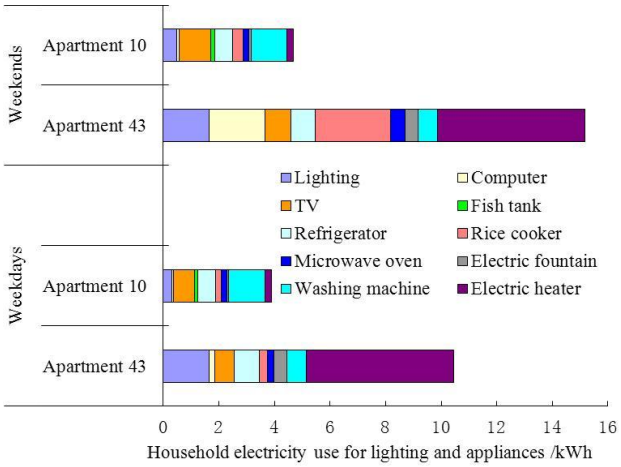
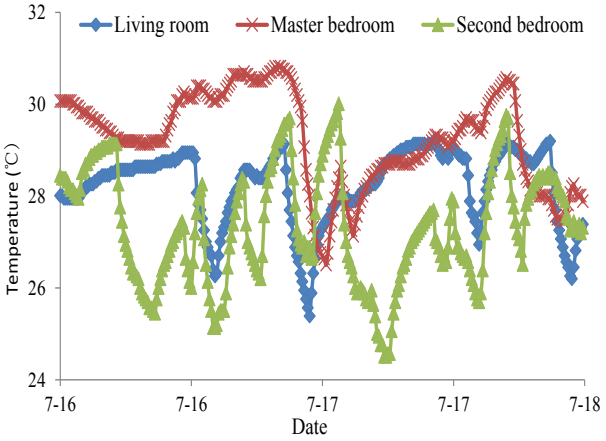
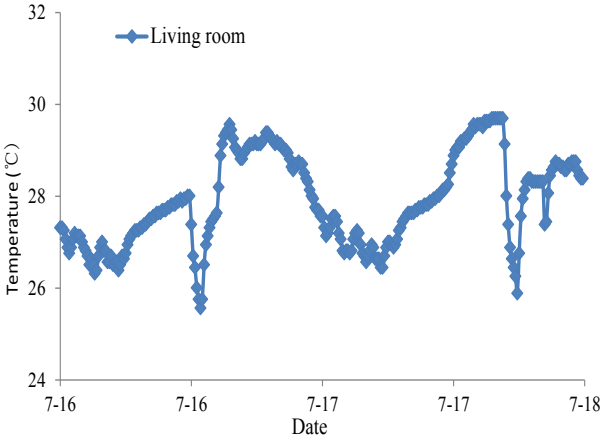


Fig.6. Estimated Weekday and Weekend Electricity Use for Lighting and Appliances in Both Apartments



(a) Apartment 43



(b) Apartment 10

Fig.7. Change of Indoor Air Temperature for Rooms with Air Conditioners in Two Consecutive Days

3.3 Occupant Behavior Concerning Room Air Conditioners

There are one and three split air conditioners in Apartment 10 and Apartment 43, respectively. The one split air conditioner in Apartment 10 is placed in the living room, and the three air conditioners in Apartment 43 are placed in the living room, the main bedroom and the second bedroom, respectively. As an example, the changes of indoor air temperature in two consecutive summer days are depicted in Fig.7.a and 7.b, in order to reflect the use pattern of air conditioners in the two apartments.

Currently, split air conditioners are the most common air conditioning system in residential sectors in Beijing, and their operation is controlled manually by occupants. Occupants usually turn on the room air conditioner when they feel hot, and turn it off when they feel cold[28]. Therefore, indoor air temperature has been considered to be an adequate predictor of air conditioning usage in residential sectors. As shown in Fig.7.b, indoor air temperature dropped dramatically from 29.7°C to 29.1°C during the first 10 minutes after the room air conditioner was turned on. Conversely, after it was turned off, a significant increase of indoor air temperature can be observed.

As shown in Fig.7.b, the only air conditioner in Apartment 10 was used for a short period of time, only about 2 hours and 10 minutes in two days. By contrast, the occupants of Apartment 43 used their air conditioners much longer, and the living room and the bedrooms were air conditioned as long as they were occupied. This resulted in a total running time of 27 hours in two days for all three air conditioners in this apartment.

3.4 Energy Saving through Improved Occupant Behavior

Based on the electrical consumption profile of each appliance and what occupants reported with respect to their use of lighting and appliances, it was found that the high energy consumption from the electric heater in Apartment 43 was mainly linked with its operation mode of 'keeping warm', which means that the water in the heater tank was always kept at a specific temperature. Another big waste of electricity in this apartment was related to the electricity use for lighting in the toilet. In the study, the occupants reported that there were no light bulbs or fluorescent tubes, whose rated power is around 40 W, installed in the toilet.

Instead, a bath heater was used to both light and heat the toilet when it was occupied. The bath heater has a rated power of about 1000 W, so the significant difference in rated electric performance between common bulb and the bath heater has contributed greatly to the high electricity use of this apartment. Additionally, during weekends the child of this family played computer games for a long time and this also contributed to the high electricity demand of the apartment.

Considering the issues mentioned above, suggestions have been given to the occupants of Apartment 43, including 1) use the electric heater only when a shower is needed and turn it off immediately after the shower; 2) install common bulbs in the toilet for lighting; and 3) reduce the number of hours using computers during the weekends. After being provided this information, the occupants were aware of the energy saving potentials of making the above behavioral changes.

After realizing how and to what extent their behaviors influence energy use for lighting and appliances, the occupants in Apartment 43 stated that they would consider these suggestions to reduce their energy use. To evaluate the usefulness of this energy information, a further monitoring regarding daily electricity use in this apartment was carried out for one week, and significant reduction in daily electricity use on both weekdays and weekends has been observed (the energy reduction was 5.2 kWh for weekdays and 6.0 kWh for weekends).

The occupants in Apartment 10 have already considered using lighting and appliances more efficiently to save energy. In this apartment, most appliances have a high efficiency label, and their stated use patterns also reflect that the occupants know how to use lighting and appliances efficiently.

4. Conclusions

Occupant behavior has a significant impact on the energy consumption of buildings. In the past several decades, a number of studies have been carried out to obtain a better understanding of how occupant behavior influences energy consumption of buildings. In China, however, evidence in this area is still highly required, especially with explorations of actual energy use patterns at individual household levels in residential sectors.

In order to increase the level of knowledge about energy consumption in residential sectors in China, a case study about electricity use for lighting and appliances and for room air conditioners at the individual household level was carried out in 44 apartments in Beijing, China. Moreover, a detailed measurement of the electric power of appliances and indoor air temperatures has been performed in 2 of the 44 apartments. Key findings from this study are listed as follows:

- There were significant differences in household electricity use among the monitored apartments, and this demonstrates the significant impact of occupant behavior with respect to using lighting, appliances and room air conditioners on the building energy consumption;
- Occupant behavior has changed in China with the development of society. Due to this change, household electricity use for lighting, appliances and room air conditioners has increased considerably over the past 10 years;
- Household electricity use can be reduced, by using devices more energy efficiently. In contrast, big energy waste will occur if the building is used improperly, for example, 1) always keeping the water in the electric heater at a specific temperature; 2) incorrectly using the bath heater; and 3) using computers for entertainment too much;
- Improper energy use patterns can be changed by energy-saving education. In real buildings, occupants have limited knowledge about how their behavior influences the energy use for lighting, appliances and room air conditioners. Therefore, showing detailed information about how energy is consumed in their buildings is a possible way to increase their awareness of saving energy, and hence changing their behavior in using the building.

This study has a limited number of samples. Future studies are still needed to increase the sample size to 1) validate the conclusions from this study, and 2) develop typical use patterns of lighting and appliances and of air conditioners in residential sectors across Beijing, so a comprehensive understanding about the characteristics of household electricity use in Beijing can be obtained. It is hoped that this study can enhance the Chinese government's awareness concerning the importance of occupant behavior on building energy consumption and implement some policies to encourage changing occupant behavior for energy saving.

Acknowledgements

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Note

[1] tce is ton of standard coal equivalent.

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