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Influence of resident behaviour on building energy consumption of ultra-low energy residential buildings

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Abstract. He ultra-low energy building is considered to be an important path to achieving carbon neutrality in buildings. In order to profoundly investigate the correlation between behaviour and building energy efficiency, the influence of behaviour on energy consumption in ultra-low energy buildings was investigated by means of theoretical analysis and field tests. Results revealed that the difference in energy consumption was caused by the household situation, living habits and subjective consciousness of the occupant. It can be seen that studying the behaviour of ultra-low energy building occupants can provide valuable insights for achieving low and zero carbon social housing.

Keywords: severe cold region; ultra-low energy building; building energy efficiency; occupant behaviour

1. Introduction

The process of urbanization in China has led to increasing energy consumption in the construction sector. Consequently, the growth of ultra-low energy residential buildings has been vigorously pursued in China. The annual primary energy consumption of heating, cooling and lighting in ultra-low energy residential buildings in severe cold regions is less than 60 kWh/(m2·a). The performance of ultra-low energy buildings in cold regions was studied by Chen et al. [1] through simulation, and they proposed a multi-energy complementary energy supply scheme based on photovoltaic photothermal and ground source heat pumps, which provided practical guidance for the growth of energy-efficient buildings and green buildings in cold regions. Indoor sound environment control standards for ultra-low energy buildings were explored by Yang et al. [2] through a theoretical analysis approach, and they concluded that noise reduction design of equipment in the design and pre-installation stages could achieve better results at a lower cost. The heat transfer coefficients of the external walls of ultra-low energy buildings with different external insulation constructions were analyzed by Tian et al. [3], it was found that the parts with greater thermal impact of thermal bridges on the external walls were passive external doors and windows and cast-in-place reinforced concrete pickets between floors.

In addition, it was found that building energy consumption was closely related to the behavior of occupants in buildings [4]. The energy consumption of nine campus buildings was examined by Zhang et al. [5] The outcomes showed that there was a significant relationship between classroom lighting distribution and lighting behavior and electrical energy consumption, the more illumination measured in the classrooms, the more electrical power was used in the academic building. Based on office buildings, Zhang et al. [6] revealed the influence of factors on the energy saving behavior of employees, it was revealed that environmental values, psychological ownership, publicity and education were the main factors influencing employees' energy saving behavior. Two low-carbon buildings were compared by Ridley et al. [7], it was found that the factors that strongly influence the energy performance of a house were the electricity consumption behavior of the occupants and the choice of appliances.

Therefore, based on an ultra-low energy residential building, the influence of behavior on the energy consumption is analyzed through theoretical analysis and on-site field testing, which provides valuable insights for achieving low and zero carbon social housing in a severe cold region.

2. Demonstration project and key technology introduction

The building has a floor area of 7,775 m2, it is located in Harbin. According to the building thermal division, this area is in the severe cold climate zone. The heating period is 180 days, the average maximum outdoor temperatures and minimum outdoor temperatures are 27.9°C and -24.1°C, respectively. The extreme maximum temperatures and minimum temperatures are 36.7°C and -37.7°C. Energy-saving measures (high-efficiency composite external wall insulation system, high-efficiency external window and door system) were applied to the building, which improved the energy-saving rate of the building. In addition, a centralized full fresh air system was used for auxiliary heating and a biomass boiler for domestic hot water.

2.1 Building envelope

The graphite polystyrene panels with a thickness of 300 mm were used for the external walls, roof and first-floor slabs of ultra-low energy building. The external windows of the building adopted aluminum-clad wood energy-saving windows. Among them, the glass U-value is 0.7 W·(m2·K)-1, the wood is Russian larch, the frame heat transfer U-value is 0.76 W·(m2·K)-1, the whole window U-value is 0.8 W·(m2·K)-1. The external windows were installed in the form of overhanging windows, and the whole windows were overhanging outside the main body of the structure by galvanized iron parts. The sealing tape should be applied to the position of plumbing pipeline through the external wall with insulation, the position of air permeable pipe out of the roof, the position of rainwater pipe fixings, the position of wire box installation, etc. The following sealing treatments were applied.

(1) The special sealing tape and sealant were applied to the outside window of the external door, and the breathable impervious sealing tape was used on the outside of the window. Impermeable sealing tape was installed on the inside of the window.
(2) The polyurethane foam treatment technology was applied between the seams of the external window benzene panels and between the screw holes through the walls.
(3) All indoor pipes and wires were closed with weather-resistant adhesive.
(4) The gap between the back of the socket box and the wall was sealed with sealant.
(5) All ducts through walls and floors were filled with polyurethane foam and sealed with sealing tape.
(6) The detailed parameters of the ultra-low energy residential building envelope are shown in Table 1.

Table 1. Performance parameters of the building envelope.

Performance parameters	Value
Heat transfer coefficient of the roof /[W·(m2·K)-1]	0.11
Heat transfer coefficient of the wall /[W·(m2·K)-1]	0.11
Body shape factor	0.25
Heat transfer coefficient of whole window /[W·(m2·K)-1]	0.8
Airtightness /h-1	0.44
Heat transfer coefficient of external window /[W·(m2·K)-1]	0.73
Structural thermal bridge	NO

2.2 Energy supply system

Ultra-low energy residential building was powered by a combined biomass boiler and ground source heat pump system. The thermal efficiency of the boiler is 80%, and the cooling (heating) COP of the ground source heat pump system is 6.5 (5.05). The depth of the ground source well is

120 m and the well spacing is 6 m. The soil heat is extracted as the heat source for garage heating in winter, the soil cold is withdrawn as the cooling source for the residence in summer.

The end of the energy supply system was a radiant roof heating (cooling) system, which made the human body feel more comfortable than the traditional radiator heating. The PB pipe (polybutylene plastic pipe) with a diameter of 20 mm was buried in the concrete floor with a pipe spacing of 200 mm or 250 mm, and the hot and cold water was used as the medium to exchange heat with the room through radiation. The design supply (return) water temperature in winter was 30℃ (28℃) or 33℃ (31℃), and the design supply (return) water temperature in summer was controlled at 20℃ (22℃). The winter heating interior design temperature was 20℃, and the summer air-conditioning interior design temperature was 26℃.

2.3 Fresh air system

The fresh air system was used in the ultra-low energy residential building, in which fresh air units sent the outdoor air from outside to inside after filtering. The fresh air outlet was set on the floor of the bedroom and living room near the external window, and the fresh air entered the personnel activity area from the floor air outlet, and the indoor air was replaced with fresh air in the form of piston flow, which was gathered in the vent located in the ceiling part of the room and discharged from the bathroom. The fresh air system was equipped with sensible heat recovery, and the heat recovery efficiency of the unit could reach more than 75%.

The start and stop times of the fresh air units, as shown in Table 2.

Table 2. Operation schedule of the fresh air unit.

Season	Fresh air unit opening hours
Spring	8:30-11:30, 15:30-20:30
Fall	8:30-11:30, 15:30-20:30
Summer	7:00-11:00, 16:00-21:00
Winter	10:00-14:00

In addition, the survey discovered that the start and stop status of the fresh air unit were variable based on weather, indoor (outdoor) temperature, and air quality changes. When the outdoor temperature was low, the temperature difference between morning and evening was significant and the heating stopped in spring, turn off the fresh air unit or turn it on in the morning and evening. When the temperature was high at noon, turn on the fresh air unit to keep the indoor air fresh.

3. Research Methodology

The data on the electricity consumption of ultra-low energy residential buildings were analyzed by means of theoretical analysis and field research tests.

3.1 Actual operational situation of energy supply system and fresh air system

The results of the field research showed that municipal central heating heat sources replaced biomass boilers in ultra-low energy residential buildings. In addition, a special mixing device was set up before hot water entered the occupants. A soil source heat pump was used for underground garage heating.

The field test found that the fresh air outlet valve was always open. Simultaneously, the field test of the heat exchange efficiency of the fresh air unit of the fresh air system revealed that the heat recovery efficiency of the fresh air unit decreased as the fan frequency increased, and when the fan frequency was higher than 30 Hz, the minimum fresh air volume per capita met the requirement of 30 m3/h. When the fan frequency was 30 Hz and 40 Hz, the sensible heat exchange efficiency of the fresh air unit was not less than 75%, when the fan frequency was 50 Hz, the sensible heat exchange efficiency was 70.77%. Therefore, when the outside air temperature was low in winter, the efficiency of the fresh air unit was also reduced, leading to an increase in heating load and building energy consumption.

3.2 Acquisition of power consumption data

The statistical analysis of building electricity consumption was conducted using the on-site survey method. Firstly, the electricity consumption data were read from meters or transcribed, and then actual household surveys were conducted to obtain various information related to residents' electricity consumption behavior, and the data were finally analyzed.

The annual electricity consumption and energy data of four typical households were collected. However, daily electricity consumption data were obtained from March to December due to the epidemic, which mainly involved lighting, cooking, and household appliances.

4. Analysis of test results

The annual electricity consumption data of four typical households were obtained by on-site survey and testing methods, as shown in Table 3.

Table 3. Month-by-month electricity consumption of the four typical households.

Month	Household 1 /kWh	Household 2 /kWh	Household 3 /kWh	Household 4 /kWh
March	615.0	328.0	303.0	262.0
April	406.0	309.0	314.0	197.0
May	241.0	322.0	300.0	252.0
June	257.0	334.0	274.0	209.0
July	295.0	334.0	303.0	158.0
August	189.0	273.0	241.0	228.0
September	320.0	297.0	290.0	228.0
October	396.0	318.0	289.0	207.0
November	190.0	326.0	309.0	257.0
December	134.0	326.0	303.0	282.0
Average monthly	304.3	316.7	292.6	228.0
Annual total	3043.0	3167.0	2926.0	2280.0

The data in Table 3 showed that the annual electricity consumption of the four typical households was arranged in the following order from largest to smallest: Household 2 > Household 1 > Household 3 > Household 4. The electricity consumption of household 4 was the lowest with 2280.0 kWh, the electricity consumption of household 2 was the highest with 3167.0 kWh. The electricity consumption levels of the four typical households were divided according to the standard of 200.0 kWh as a level, as shown in Figure 1.

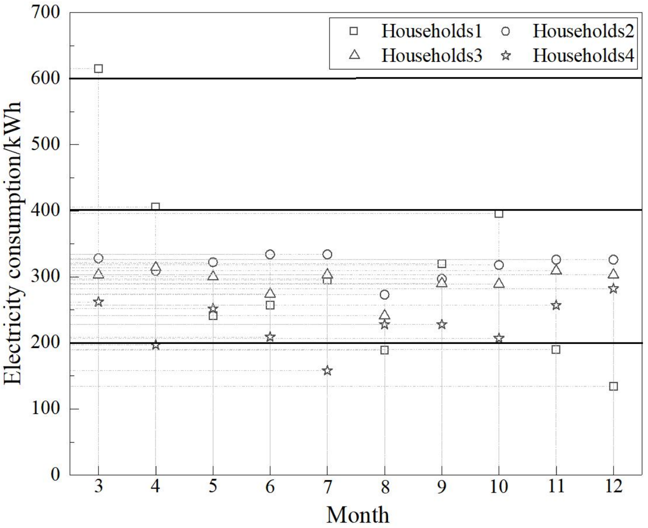

Figure 1. Classification of electricity consumption levels of typical households.

Figure 1 displayed that the annual electricity consumption of household 4 was not only the lowest, but also the trend of monthly electricity consumption fluctuated more slowly. However, for Household 1, although monthly electricity consumption was below 200.0 kWh in both November and December, there were large fluctuations in electricity consumption every month. On the contrary, the electricity consumption of Household 2 and Household 3 basically maintained a flat trend between 200.0 kWh and 400.0 kWh per month. Therefore, a simple comparison of the month-by-month electricity consumption of a typical household was not sufficient to provide a comprehensive analysis of the impact of household behavior on building electricity consumption.

The average daily electricity consumption of the four typical households on weekdays and non-weekdays were analyzed, which further analyzed the electricity consumption of the four typical households. The average daily electricity consumption of households1 on weekdays and non-weekdays was shown in Figure 2.

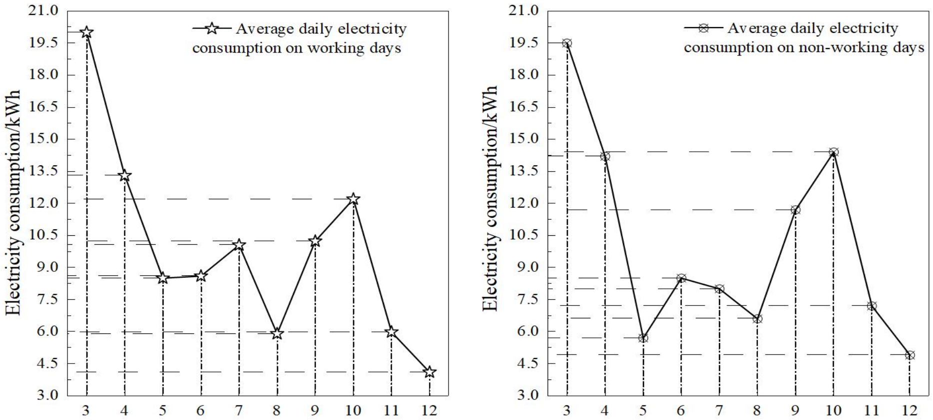

Figure 2. The daily average electricity consumption of household 1.

From Figure 2, it was revealed that the average daily electricity consumption of household 1 was higher in March, April, and October. The average daily electricity consumption of households on weekdays was higher than that of non-working days in March, May and July, and the average daily electricity consumption on non-working days was higher than that of working days in the remaining seven months. The household had four people at home, there were older people taking care of children, and the head of the household was a self-employed businessman, working hours were not fixed, the boundary between working days and non-working days was not obvious. In addition, there were more types of entertainment and other electrical appliances, including stereos and air purifiers. They left their homes at irregular intervals during the week, and the patterns of household activity and electricity consumption behavior were more complex.

The average daily electricity consumption of household 2 on weekdays and non-weekdays were shown in Figure 3.

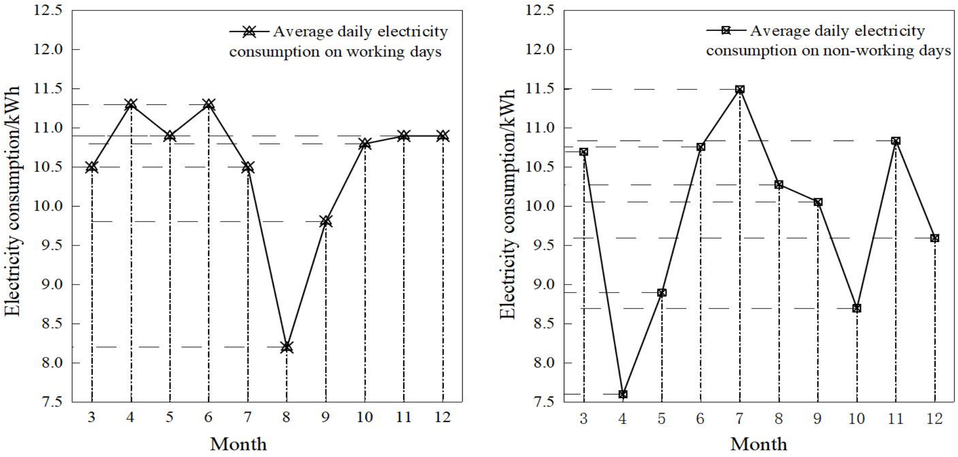

Figure 3. The daily average electricity consumption of household 2.

As can be seen from Figure 3, the average daily electricity consumption of household 2 fluctuated less. The average daily electricity consumption on weekdays was higher than that on non-working days in April and May, and the opposite trend was observed in August. The difference between the average daily electricity consumption on weekdays and non-working days in the rest of the months was not significant. The previous research learned that the number of family members was three, with a housewife always at home, and the frequency of using other electrical appliances was low, except for daily needs. Individual households often left home on business trips and children basically did not use electrical appliances. Therefore, the household's electricity consumption pattern was relatively simple.

The average daily electricity consumption of households 3 on weekdays and non-weekdays were shown in Figure 4.

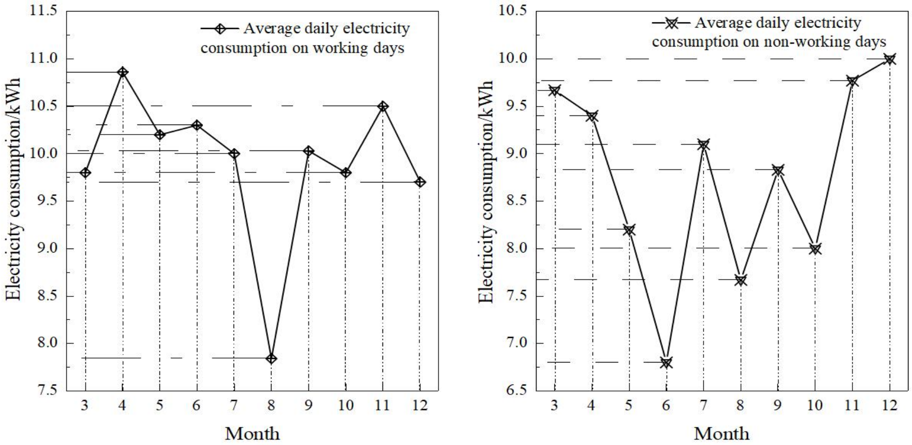

Figure 4. The daily average electricity consumption of household 3.

It can be found from Figure 4 that the situation of household 3 was more similar to that of household 2, with slight fluctuation in the average daily electricity consumption. The average daily electricity consumption on weekdays in July was almost indistinguishable from that on non-working days, while the average daily electricity consumption on weekdays in the remaining months was greater than that on non-working days. The previous research learned that the number of family members was four, with an elderly people always at home, and the frequency of using other electrical appliances was low, except for daily needs. Compared with the electricity consumption of household 2, the per capita electricity consumption level of household 3 was lower, indicating that it had a better awareness of energy saving and more regular life.

The average daily electricity consumption of households 4 on weekdays and non-weekdays was shown in Figure 5.

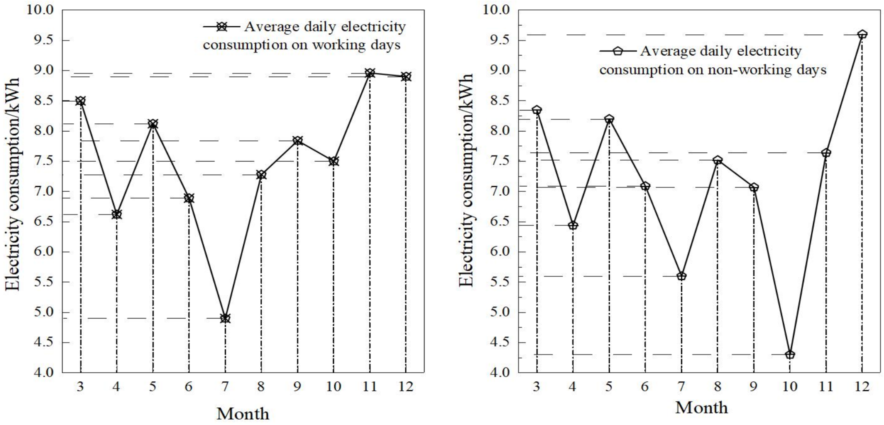

Figure 5. Two or more references.

From Figure 5, we can find that the average daily electricity consumption on weekdays in March, June, July, August and December was lower than the average daily electricity consumption on non-working days. Average daily electricity consumption in October and November on weekdays was lower than the average daily consumption on non-working days. The previous study revealed that the number of family members was three, and the husband and wife had a strong awareness of environmental protection and energy saving. Therefore, their per capita electricity consumption level was low, compared with other households.

5. Conclusion

In general, the electricity consumption of ultra-low energy residential building households is not only influenced by the number of people, their age, occupation, and time at home, but also the awareness of energy saving of the households can have a greater impact. Therefore, the pattern of electricity consumption of households is more subjective and complex, and needs to be further studied in conjunction with households' living habits.

Acknowledgments

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