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Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study

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ABSTRACT

World Heritage Site – Nanjing Tulou buildings, which were built of rammed earth and in a wooden framework, are large-scale civilian residential buildings distributed across the southeastern China. The information of energy consumption as well as its characteristics in Tulou buildings is however unavailable in the literature. In this study, a survey of energy consumption and indoor environmental quality in Nanjing Tulou buildings was conducted. Based on the data obtained by the survey and an energy consumption model, the characteristics of energy consumption, including energy consumption per household breakdown based on energy sources and usage, seasonal variation of energy consumption, and energy consumption distribution in Nanjing Tulou buildings were investigated by comparing the Tulou buildings with other normal rural buildings in that region. The results show that the total primary energy consumption per household in Nanjing Tulou buildings was 2.43×10^4 MJ/year, which was lower than that in normal rural buildings in the region (3.37×10^4 MJ/year). Furthermore, residents in Nanjing Tulou buildings responded with better thermal comfort than that in normal rural buildings. The reasons for the characteristics of energy consumption in Tulou buildings, such as influence of cooling and heating requirements and human behavior, were analyzed. The potential energy savings as well as the implications for future low-energy rural housing construction were discussed.

1. Introduction

In China, about 56% of the total population (or 737 million people) live in rural areas. In 2006, the total rural housing floor area reached approximately 60% of the total building floor area in China [1]. In 1990, the estimation of annual rural household energy consumption of China was between 4.01×10^{12} MJ to 8.58×10^{12} MJ [2]. A large scale national survey of energy consumption and indoor environmental quality of Chinese rural housing was performed by Tsinghua University in 2006–2007. The survey results showed that the total annual energy consumption in rural housing (for heating, cooking, lighting and cooling) had reached 9.37×10^{12} MJ [3]. Therefore, it is important to understand the characteristics of energy consumption in Chinese rural housing in order to achieve potential energy savings in the future.

There have been several studies focusing on the characteristics of energy consumption in Chinese rural area. For instance, an energy consumption survey was conducted in six counties distributed in Hunan, Jiangxi, Liaoning, Sichuan, Jiangsu and Shandong Province in 1987–1991 [4]. Later, the characteristics of energy consumption in Yangzhong County [5], Sheyang County [6], Xian City [7], Yunnan Province [8], Loess Hill Region, Gansu Province [9] and Huantai County [10] were investigated. These studies provided useful data for characterizing the energy consumption in normal rural housing in several regions of China. There have been studies on rural energy consumption in other countries as well [11,12]. Furthermore, questionnaire survey has been widely used for characterizing the energy consumption [7,13–17].

Tulou ("earthen house" by direct meaning in Chinese) is a kind of large-scale civilian residential building built mainly of rammed earth and in a wooden framework, distributed across the southeastern China such as Fujian, Jiangxi and Guangdong provinces. A total of 3000 Fujian Tulou buildings, which are the best-preserved with the broadest coverage, largest quantity and richest variety, have been found across Fujian province alone [18]. As an enclosed communal house with two or more storey in double load-bearing design, i.e. rammed earth wall plus column and tie construction, Fujian Tulou is mainly built in a certain scale to meet the needs of the whole clan living together and a sound defensive function [18]. In 2008, the United Nations Educational, Scientific and Cultural Organization (UNESCO) declared 10 Tulou buildings or clusters in Yongding County, Nanjing County and Hua'an County as the World Heritage Site. The existence of these Tulou buildings allow us to investigate the characteristics of energy consumption in buildings with the unique construction by comparing with normal rural

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Fig. 1. An overview of Tulou buildings, (a) Tianluokeng Tulou cluster, (b) Hekeng Tulou cluster, (c) Huaiyuan Tulou, (d) Hegui Tulou, (e) normal rural building with earthen envelopes, and (f) normal rural building with brick envelopes.

buildings in the region, which may give us some insight on the future low-energy rural housing construction. However, the information of energy consumption as well as its characteristics in Tulou buildings is unavailable through extensive literature survey.

In this study, a survey of energy consumption and indoor environmental quality was conducted in heritage Nanjing Tulou buildings and normal rural buildings. Based on the data obtained by the survey and an energy consumption model, the characteristics of energy consumption in Nanjing Tulou buildings, including energy consumption per household breakdown based on energy sources and usage, seasonal variation of energy consumption, and energy consumption distribution were investigated. Through comparing with the normal rural buildings, the potential reasons for the characteristics of energy consumption in Tulou buildings were analyzed. Furthermore, the potential energy savings as well as the implications for future low-energy rural housing construction were discussed.

2. Methods

2.1. Introduction of the survey

The field survey was conducted in summer 2011, in Nanjing County, Fujian Province, China. The studied Tulou buildings included Tianluokeng Tulou Cluster, Hekeng Tulou Cluster, Huaiyuan Tulou, Hegui Tulou, which are all on the World Heritage list, and two other Tulou buildings, as shown in Fig. 1. The studied normal rural buildings all belong to Kanxia village, which is in the same area as the Tulou buildings. Fig. 2 shows the location of the Tulou buildings and Kanxia village. Table 1 lists the basic information of studied Tulou and normal rural buildings. For Tulou buildings, the average thickness of envelope is 1.2 m while that of normal rural buildings is 0.4 m. The average cover area of Tulou buildings is 1250 m^2 while that of normal rural buildings is 90 m^2. 139 households in the Tulou buildings (approximately 88% of the total households) participated in the questionnaire survey. 97 households in normal rural buildings in Kanxia village (approximately 24% of the total households) were randomly chosen as comparison. There were a total number of 236 valid questionnaires received.

The questionnaire survey covered characteristics of cooking, heating, cooling, lighting, hot water and appliances. Based on the data collected in the survey as well as an energy consumption model described in the next section, the total energy consumption, energy consumption breakdown based on energy source and usage were obtained.

Table 1
Basic information of studied Tulou and normal rural buildings.

Investigated location	Number of buildings	Name of buildings	Thickness of envelope (m)[a]	Cover area (m^2)[a]	Height (m)[a]	Number of floors[a]	Number of rooms per storey[a]	Number of investigated households[d]	Population per household[d]
Tianluokeng Tulou cluster	5	Ruiyun	1.2	1063	11.2	3	26	51	3.9
		Zhenchang	1.2	976	11.5	3	26		
		Buyun	1.2	1050	11.9	3	26		
		Hechang	1.2	1268	12.3	3	22		
		Wenchang	1.2	1288	11.8	3	32		
Hekeng Tulou cluster	14	Chaoshui	1.7	729	11.3	3	20	62	3.4
		Yongsheng	1.4	676	14.4	4	30		
		Shengqing	1.0	2310	12.0	3	24		
		Yongrong	0.8	525	11.5	3	18		
		Nanxun	N/A	729	12.6	3	21		
		Yangzhao	1.8	1156	12.0	3	26		
		Yonggui	0.7	1680	10.3	3	32		
		Yuchang	1.2	1838	11.1	3	36		
		Dongsheng	1.0	870	11.0	3	22		
		Chungui	1.0	1808	11.5	3	32		
		Xiaochun	1.0	1808	11.0	3	32		
		Yongqing	1.1	1661	11.0	3	32		
		Yuxing	0.9	907	11.0	3	20		
Huaiyuan Tulou	1	Huaiyuan	1.2	1385	13.5	4	29	14	4.4
Hegui Tulou	1	Hegu	1.4	1547	18.0	5	28	6	3.3
Other Tulou buildings	2	Fuyuan Degui	N/A	N/A	N/A	N/A	N/A	6	3.5
All Tulou buildings[b]	23		N/A	N/A	N/A	N/A	N/A	139	3.7
Normal rural buildings[c]	97		0.4	90	N/A	1–2	4	97	4.1

[a] These data were obtained from UNSECO (2008).
[b] The data of all Tulou buildings were average values.
[c] The data of normal rural buildings were average values, which were obtained from the questionnaire survey.
[d] These data were obtained from questionnaire survey.

Fig. 2. The location of Tulou buildings and normal rural buildings (UNSECO, 2008).

2.2. Computing methods for energy consumption of each household

Electricity, liquefied petroleum gas (LPG), coal and wood were the energy sources that the households used in their daily life according to the survey results. The energy consumption of electricity, converted into primary energy in the power plant, can be calculated by

$$E_{\text{ele}} = \beta_{\text{ele}}(E_{\text{ele-cook}} + E_{\text{ele-heat}} + E_{\text{ele-cool}} + E_{\text{ele-light}} + E_{\text{ele-hotwater}} + E_{\text{ele-appliance}}) \quad (1)$$

where β_{ele} is the thermal power generation conversion coefficient between electricity (kWh) and standard heat equivalence (MJ), which was given as 9.66 MJ/kWh based on the current average power generation efficiency level in China [19].

$E_{\text{ele-cook}}$ is the electricity consumption for cooking, which can be calculated by

$$E_{\text{ele-cook}} = \sum_i (n_i P_i t_i d_i)_{\text{cooking}} \quad (2)$$

where i represents electric cooker, induction cooker and microwave oven. P is the power of a cooker (W), which was determined as the average power of the top ten best selling equipment from three most popular e-shops in China. For electric cooker, P was set at 560 W; for induction cooker, P was set at 2000 W and for microwave oven, P was set at 790 W. The n is the number of equipment, t is the average hour for which the equipment was used in each day (h), d is the total day for which the equipment was used in one year, which were all obtained from the questionnaire survey. Throughout the rest of this paper, the average hours for which the equipment was used in each day and the total days for which the equipment was used in one year were obtained in the same way. It should be noted that the "d" includes information of energy consumption variation for the appliances during the year (for example, heating only occurs in winter).

$E_{\text{ele-heat}}$ is the electricity consumption for heating, which can be calculated by

$$E_{\text{ele-heat}} = \sum_i (n_i P_i t_i d_i)_{\text{heating}} \quad (3)$$

where i represents electric blanket, electric heater or unit heater. P is the power of the equipment (W): for the electric blanket, P was set at 60 W, for electric heater, P was set at 700 W and for unit heater, P was set at 1400 W.

$E_{\text{ele-cool}}$ is the electricity consumption for cooling, which can be calculated by

$$E_{\text{ele-cool}} = \sum_i (n_i P_i t_i d_i)_{\text{cooling}} \quad (4)$$

where i represents electric fan or split type air conditioner. P is the power of the equipment (W): for electric fan, P was set at 50 W and for split type air conditioning, P was set at 880 W. It should be noticed that P for an air conditioner is the rated power. During the usage time period of an air conditioner, the actual power consumption may not be constant. However, given that residents mainly rely on small fans to cool and the usage time of air conditioners in these buildings was very short, the energy consumption due to air conditioning in both Tulou buildings and normal rural buildings was very small (around 0% of total household energy consumption in Tulou and 1% in normal rural buildings as given in Section 3). Thus, in this study, we did not further calibrate the air conditioning energy use based on actual performance data.

$E_{\text{ele-light}}$ is the electricity consumption for lighting, which can be calculated by

$$E_{\text{ele-light}} = \sum_i (n_i P_i t_i d_i)_{\text{lighting}} \quad (5)$$

where i represents daylight lamp, energy saving lamp and filament lamp. P is the power of the equipment (W): for daylight lamp, P was set at 37 W; for energy saving lamp, P was set at 7 W and for filament lamp, P was set at 40 W.

$E_{\text{ele-hotwater}}$ represents the electricity consumption for hot water, which can be calculated by

$$E_{\text{ele-hotwater}} = \frac{n_{\text{p}} m_{\text{ht}} c_{\text{p}} \sum_i n_{\text{f},i}(t_{\text{hw}} - t_{0,i})}{\eta_{\text{ele}} \beta'_{\text{ele}}} \quad (6)$$

where i represents different seasons: spring is from March to May, summer is from June to August, fall is from September to November and winter is from December to February. n_{p} is the population of the household, $n_{\text{f},i}$ is the frequency of a resident taking baths in a season, which were obtained from the questionnaire survey. c_{p} is the heat capacity of water, which is 4200 J/(kg °C). m_{ht} is the amount of hot water that a resident needs for a bath (kg): for shower, m_{ht} was assumed as 25 kg, while for bath with hot water in a bucket, m_{ht} was assumed as 10 kg according to site measurement. t_{hw} is the temperature of the bath water (°C), which was set at 40 °C [20]. $t_{0,i}$ is the water temperature before heating up (°C), which is between dry-bulb and wet-bulb temperatures. According to the local meteorological data: for spring, t_0 was set at 18 °C; for summer, t_0 was set at 26 °C; for fall, t_0 was set at 22 °C; for winter, t_0 was set at 14 °C. η_{ele} is the efficiency of the electric water heater, which was set at 90% [21]. β'_{ele} represents the direct heat equivalence (without considering power generation efficiency) between electricity (kWh) and standard heat equivalence (MJ), which equals to 3.51 MJ/kWh [19].

$E_{\text{ele-appliance}}$ represents the electricity consumption for appliances, which can be calculated by

$$E_{\text{ele-appliance}} = \sum_i (n_i P_i t_i d_i)_{\text{appliance}} \quad (7)$$

where i represents refrigerator, washing machine, television, computer and disinfection cabinet. P is the power of each appliance (W): for refrigerator, P was set at 20 W, which was the average power consumption in a day (considering the fact that the refrigerators are continuously in use but do not consume constant amount of electricity during a day since they usually work for some time and then stop for some time); for washing machine, P was set at 290 W; for television, P was set at 160 W; for computer, P was set at 310 W and for disinfection cabinet, P was set at 400 W.

LPG was mainly used for cooking and hot water supply. The energy consumption of LPG can be calculated by

$$E_{\text{LPG}} = \beta_{\text{LPG}}(E_{\text{LPG-cook}} + E_{\text{LPG-hotwater}}) \quad (8)$$

where β_{LPG} is the heat equivalent coefficient between LPG and standard heat, which equals 50.18 MJ/kg [19].

$E_{\text{LPG-cook}}$ is the LPG consumption for cooking, which can be calculated by

$$E_{\text{LPG-cook}} = \frac{m_{\text{LPG}} d}{d_0} \quad (9)$$

where m_{LPG} is the mass of a jar of LPG (kg), which was assumed as 15 kg. d_0 is the days for which a jar of LPG was used, which was obtained from the questionnaire survey.

$E_{\text{LPG-hotwater}}$ represents the LPG consumption for hot water, which can be calculated by

$$E_{\text{LPG-hotwater}} = \frac{n_p m_{\text{ht}} c_p \sum_i n_{f,i}(t_{\text{hw}} - t_{0,i})}{\eta_{\text{LPG}} \beta_{\text{LPG}}} \quad (10)$$

where η_{LPG} is the efficiency of the water heater, which was set at 80% [21].

Coal was mainly used for heating and hot water supply. The energy consumption of coal can be calculated by

$$E_{\text{coal}} = \beta_{\text{coal}}(E_{\text{coal-heat}} + E_{\text{coal-hotwater}}) \quad (11)$$

where β_{coal} is the heat equivalent coefficient between coal and standard heat, which equals 20.91 MJ/kg [19].

$E_{\text{coal-heat}}$ is the coal consumption for heating, which can be calculated by

$$E_{\text{coal-heat}} = m_{\text{coal}} d \quad (12)$$

where m_{coal} is the mass of coal used for heating in one day (kg), which was obtained from the questionnaire survey.

$E_{\text{coal-hotwater}}$ represents the coal consumption for hot water, which can be calculated by

$$E_{\text{coal-hotwater}} = \frac{n_p m_{\text{ht}} c_p \sum_i n_{f,i}(t_{\text{hw}} - t_{0,i})}{\eta_{\text{coal}} \beta_{\text{coal}}} \quad (13)$$

where η_{coal} is the efficiency of coal stove used for boiling water, which was set at 60% [22].

Wood is mainly used for cooking, heating and hot water. The energy consumption of wood can be calculated by

$$E_{\text{wood}} = \beta_{\text{wood}}(E_{\text{wood-cook}} + E_{\text{wood-heat}} + E_{\text{wood-hotwater}}) \quad (14)$$

where β_{wood} is the heat equivalent coefficient between wood and standard heat, which equals 17.56 MJ/kg [19].

$E_{\text{wood-cook}}$ is the wood consumption for cooking, which can be calculated by

$$E_{\text{wood-cook}} = m_{\text{wood-cook}} d \quad (15)$$

where $m_{\text{wood-cook}}$ is the mass of wood used for cooking in one day (kg), which was obtained from the questionnaire survey.

$E_{\text{wood-heat}}$ is the wood consumption for heating, which can be calculated by

$$E_{\text{wood-heat}} = m_{\text{wood-heat}} d \quad (16)$$

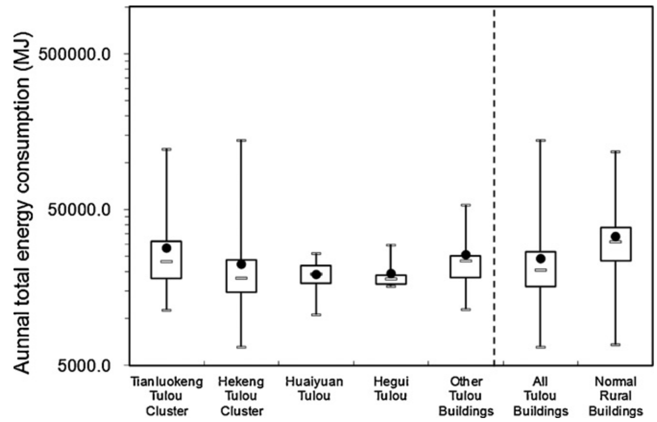

Fig. 3. Comparison of annual total energy consumption in Tulou and Normal rural buildings. (Minimum, 25%, median, 75%, maximum values were presented. Black points represent the mean values.)

where $m_{\text{wood-heat}}$ is the mass of wood used for heating in one day (kg), which was obtained from the questionnaire survey.

$E_{\text{wood-hotwater}}$ represents the wood consumption for hot water, which can be calculated by

$$E_{\text{wood-hotwater}} = \frac{n_p m_{\text{ht}} c_p \sum_i n_{f,i}(t_{\text{hw}} - t_{0,i})}{\eta_{\text{wood}} \beta_{\text{wood}}} \quad (17)$$

where η_{wood} is the efficiency of firewood stove used for boiling water, which was assumed as 20% according to our previous measurement results.

According to the equations above, the total energy consumption and energy consumption break down based on energy sources can be obtained. Furthermore, the energy consumption can be broken down based on usage. The energy consumption of cooking, heating, cooling, lighting, hot water and appliances can be calculated by

$$\begin{cases} E_{\text{cook}} = \beta_{\text{ele}} E_{\text{ele-cook}} + \beta_{\text{LPG}} E_{\text{LPG-cook}} + \beta_{\text{wood}} E_{\text{wood-cook}} \\ E_{\text{heat}} = \beta_{\text{ele}} E_{\text{ele-heat}} + \beta_{\text{coal}} E_{\text{coal-heat}} + \beta_{\text{wood}} E_{\text{wood-heat}} \\ E_{\text{cool}} = \beta_{\text{ele}} E_{\text{ele-cool}} \\ E_{\text{light}} = \beta_{\text{ele}} E_{\text{ele-light}} \\ E_{\text{hotwater}} = \beta_{\text{ele}} E_{\text{ele-hotwater}} + \beta_{\text{LPG}} E_{\text{LPG-hotwater}} \\ \quad + \beta_{\text{coal}} E_{\text{coal-hotwater}} + \beta_{\text{wood}} E_{\text{wood-hotwater}} \\ E_{\text{appliance}} = \beta_{\text{ele}} E_{\text{ele-appliance}} \end{cases} \quad (18)$$

3. Results

3.1. Energy sources and total energy consumption

The main energy source in Nanjing Tulou and normal rural buildings is electricity, with LPG, coal and wood as supplementary sources. In Tulou buildings, the percentages of households that use the above energy types of energy were 100% for electricity, 86.3% for LPG, 0.7% for coal and 11.5% for wood, respectively. In normal rural buildings, the percentages were 100% for electricity, 83.5% for LPG, 7.2% for coal and 7.2% for wood, respectively.

The total annual primary energy consumption per household in Tulou buildings was 2.43×10^4 MJ with the highest 2.84×10^4 MJ in Tianluokeng Tulou cluster and the lowest 1.93×10^4 MJ in Huaiyuan Tulou, while that in normal rural buildings was 3.37×10^4 MJ, as shown in Fig. 3. The annual total energy consumption per household in Tulou buildings was 28% lower than that in normal rural buildings.

3.2. Energy consumption breakdown based on energy sources

Fig. 4 shows the comparison of energy consumption percentage breakdown based on energy sources in Tulou and normal rural

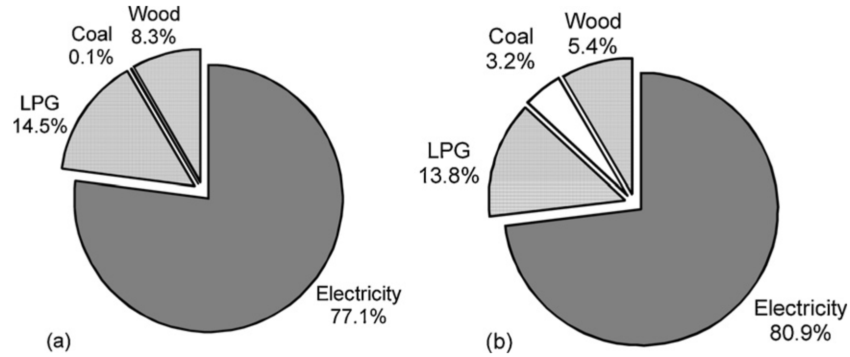

Fig. 4. Comparison of energy consumption percentage breakdown based on energy source in (a) Tulou buildings and (b) normal rural buildings.

buildings. In Tulou and normal rural buildings, electricity as the dominating energy source was of 77.1% and 80.9%, respectively. The percentages of LPG were similar in both Tulou (14.5%) and normal rural buildings (13.8%). The percentages of wood in Tulou buildings (8.3%) were higher than that in normal rural buildings (5.4%). However, coal was barely used in Tulou buildings. The percentage of coal in normal rural buildings (3.2%) was higher than that in Tulou buildings (0.1%).

The comparison of energy consumption per household breakdown based on energy sources in Tulou and normal rural buildings is shown in Fig. 5. In Tulou buildings, the use of wood only occurred in Tianluokeng and Hekeng Tulou Clusters. The energy consumption of electricity in Tulou buildings was 5.89×10^3 MJ lower than that in normal rural buildings, which was the dominating influencing factor for the difference of total energy consumption between Tulou and normal rural buildings. Although the percentages of LPG and wood were larger in Tulou than that in normal rural buildings, the energy consumption of LPG and wood in normal rural buildings was respectively 1.14×10^3 MJ and 0.81×10^3 MJ higher than that in Tulou buildings.

3.3. Energy consumption breakdown based on usage

Fig. 6 shows the comparison of energy consumption percentage breakdown based on usage in Tulou and normal rural buildings. Cooking consumed most of the energy in both Tulou and normal rural buildings, 65.7% and 55.5%, respectively. The percentage of appliance energy consumption came the second in Tulou buildings (20.7%) and the third in normal rural buildings (19.2%), and that of hot water energy consumption came the second in normal rural buildings (21.1%) and the third in Tulou buildings (12.3%). Furthermore, energy consumption of cooling in Tulou and normal rural buildings was only of 0.8% and 3.5%, respectively. And energy consumption of heating in Tulou and normal rural buildings was as small as 0.5% and 0.7%, respectively. The percentages of energy consumption of lighting were lower than 0.1% in both Tulou and normal rural buildings, which were not included in the analysis.

The comparison of energy consumption per household breakdown based on usage in Tulou and normal rural buildings is shown in Fig. 7. Although the percentages of cooking and appliance in Tulou buildings were higher than in normal rural buildings, the absolute energy consumption per household in Tulou buildings was 2.74×10^3 MJ and 1.46×10^3 MJ, respectively, lower than in normal rural buildings. The energy consumption of cooling and hot water in normal rural buildings was 0.97×10^3 MJ and 4.16×10^3 MJ, respectively, higher than that in Tulou buildings.

3.4. Seasonal variation of energy consumption

Fig. 8 shows the comparison of seasonal energy consumption based on usage in Tulou and normal rural buildings. The energy consumption in Tulou buildings was very similar in both summer and mild seasons, while that in winter was higher due to the larger energy consumption of hot water. In normal rural buildings, the energy consumption per household in summer and winter was higher than that in mild seasons, due to larger energy consumption of cooling in summer and hot water in winter.

3.5. Energy consumption distribution

Energy consumption distributions in Tulou buildings and normal rural buildings were shown in Fig. 9. The distributions of energy consumption fit Gaussian Distribution well both in Tulou buildings ($R^2 = 0.96$) and in normal rural buildings ($R^2 = 0.92$), according to Table 2. However, energy consumption distribution in Tulou buildings differed from that in normal rural buildings. Compared with that of normal rural buildings, the distribution of Tulou buildings was of lower mathematical expectation (μ) and lower standard error (σ). The smaller standard error of the Gaussian distribution in Tulou buildings indicated a more concentrative nature of the energy consumption distribution.

4. Discussion

4.1. Influence of cooling and heating requirements

The results show that the energy consumption of cooling in Tulou buildings was lower than that in normal rural buildings. In Tulou buildings, the percentages of households that use electric fans and air conditioners for cooling were 74.8% and 0.0%, respectively, which were lower than that in normal rural buildings (96.9% and 11.3%, respectively). In average, residents in normal rural buildings used electric fans about 5.0 h a day and 3.6 months a year, which was longer than that in Tulou buildings (1.8 h per day and 2.2 months). Therefore, the electric fans in normal rural buildings were more frequently used to achieve thermal comfort than in Tulou buildings, which resulted in higher energy consumption for cooling. To better understand the relationship between energy consumption and indoor thermal comfort, we conducted a thermal comfort questionnaire survey. The results indicated better indoor thermal comfort in summer in Tulou than that in normal rural buildings: satisfaction vote: 0.64 vs 0.50; thermal sensation vote (TSV): 0.29 vs 0.71; thermal comfort vote (TCV): 0.12 vs 0.54. The definitions of these three indexes were listed in Table 3. Although residents in normal rural buildings consumed more energy for cooling, they experienced worse thermal comfort than residents in Tulou buildings.

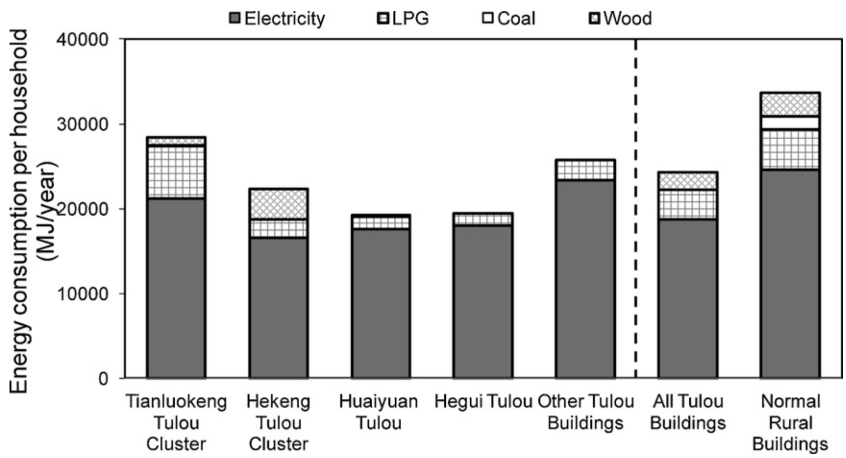

Fig. 5. Comparison of energy consumption per household breakdown based on energy source in Tulou and normal rural buildings.

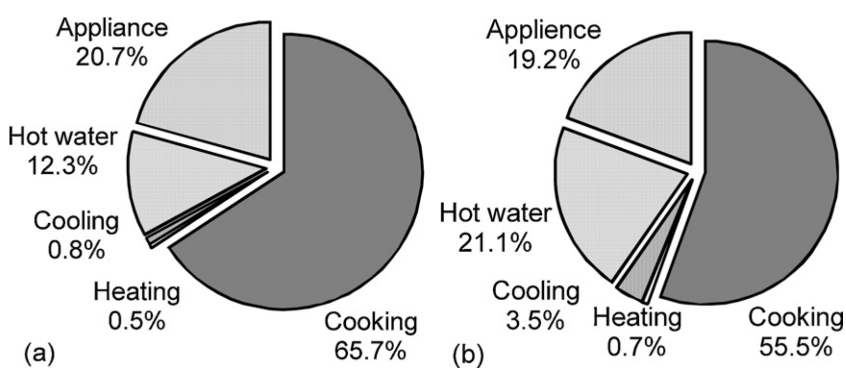

Fig. 6. Comparison of energy consumption percentage breakdown based on usage in the (a) Tulou buildings and (b) normal rural buildings.

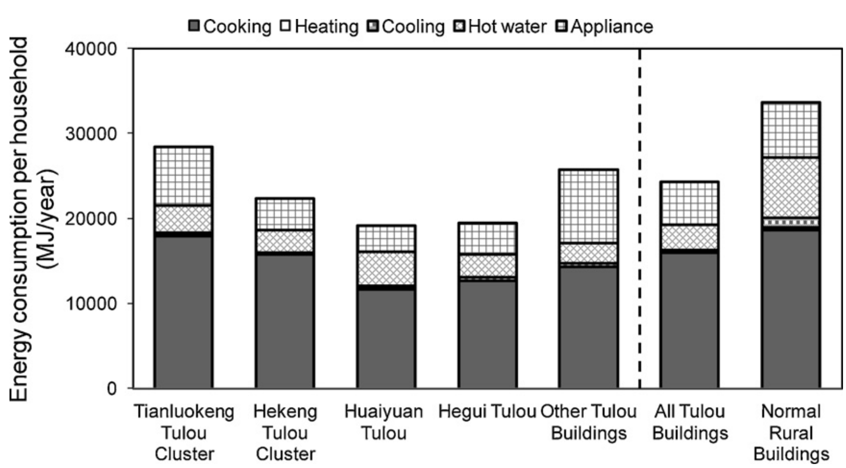

Fig. 7. Comparison of energy consumption per household breakdown based on usage in the Tulou and normal rural buildings.

Table 2
Comparison of energy consumption distribution in the Tulou and normal rural buildings.

Building type	Distribution type	μ[a]		σ[b]		R^2[c]
		Value	S.E.[d]	Value	S.E.	
Tulou buildings	Gaussian distribution	18.96	0.31	12.14	0.64	0.96
Normal rural buildings	Gaussian distribution	25.07	0.64	18.46	1.39	0.92

[a] μ represents the mathematical expectation of the distribution.
[b] σ represents the standard error of the distribution.
[c] R represents the correlation coefficient.
[d] S.E. represents the standard error of the value.

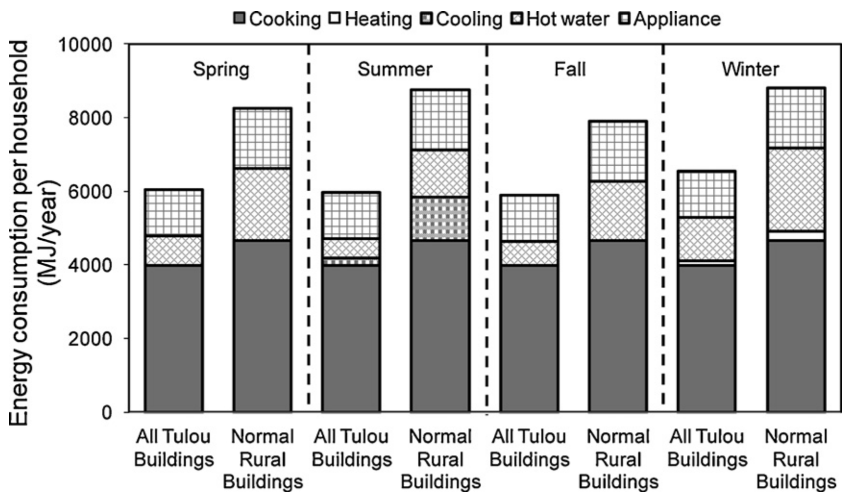

Fig. 8. Comparison of seasonal energy consumption per household breakdown based on usage in Tulou and normal rural buildings.

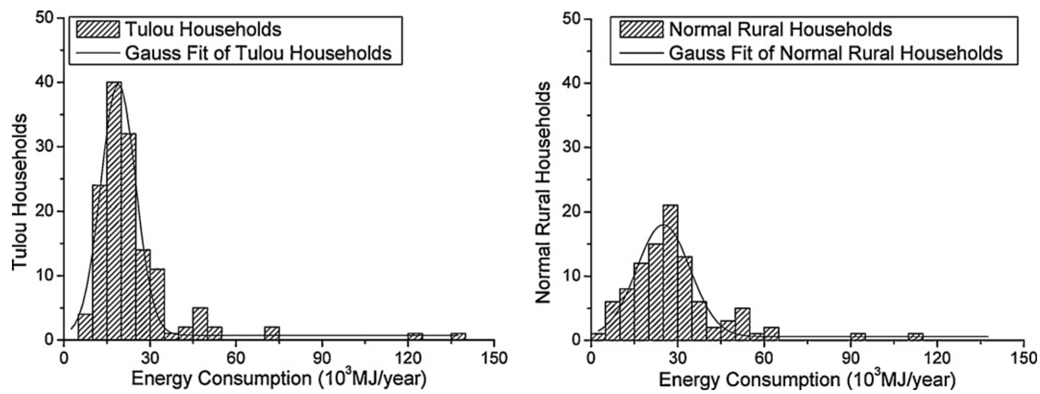

Fig. 9. Comparison of energy consumption distribution in the Tulou and normal rural buildings.

In winter, the energy consumption for heating in both Tulou and normal rural buildings was quite low. However, the results of thermal comfort survey indicated better indoor thermal comfort level in winter in Tulou than in normal rural buildings: satisfaction vote: 0.48 vs 0.30; TSV: −0.50 vs −0.78; TCV: 0.34 vs 0.65. Therefore, the residents in normal rural buildings tend to consume more energy to achieve similar thermal comfort in winter. The detailed analysis of indoor thermal environment will appear in a companion paper.

4.2. *Influence of human behavior*

The results show that the energy consumption of hot water in Tulou buildings was obviously lower than that in normal rural buildings. The bath frequency per week in Tulou buildings was similar to that in normal rural buildings. However, the bath types in Tulou and normal rural buildings were quite different. The percentage of residents who took shower in shower enclosures in Tulou

Table 3
Definitions of satisfaction vote, TSV and TCV.

Index	Questions	Scales/options	Remarks
		Scales/Options	
Satisfaction vote	Are you satisfied with the indoor thermal condition in summer/winter?	-1 -0 +0 +1	+1: Satisfied; +0: Just satisfied; −0: Just unsatisfied; −1: Unsatisfied.
TSV	What's your thermal sensation in summer/winter?	-3 -2 -1 0 +1 +2 +3	+3: Very hot; +2: Hot; +1: Warm; 0: Neutral; −1: Cool; −2: Cold; −3: Very cold.
TCV	Do you feel comfortable with the indoor thermal condition in summer/winter?	0 1 2 3 4	0: Comfortable; 1: Slightly uncomfortable; 2: Uncomfortable; 3: Very uncomfortable; 4: Limited Tolerance.

(25%) was much smaller than that in normal rural buildings (73%). 75% of residents in Tulou buildings usually flushed oneself with hot water in a bucket, which need less water. The difference of bath types leads to different quantities of bath water per capita in Tulou and normal rural buildings (11.8 and 20.7 kg, respectively), which might be the dominating influencing factor of energy consumption for hot water and partially reflected the influence of human behavior and lifestyle habit.

For energy consumption of appliances, the largest gap between Tulou and normal rural buildings was the energy consumption of television (the difference was 1.71×10^3 MJ). The number of television per household in Tulou and normal rural buildings was quite similar (1.4 and 1.6, respectively). However, the hours that residents watched television per day in normal rural buildings (4.1 h) was higher than that in Tulou buildings (2.6 h), which caused the gap in energy consumption. According to the interviews with the residents during the survey, the residents in Tulou buildings preferred to stay in the "public yards" inside the Tulou buildings during leisure time, while the residents in normal rural buildings preferred to stay indoors (perhaps since they do not have "public yards"). The different human behavior and lifestyle habit again influenced the energy consumption.

4.3. Influence of population per household

The population per household in Tulou buildings was 3.7 persons, while that in normal rural buildings was 4.1 persons. This difference also influenced the energy consumption. For instance, the energy consumption for cooking in Tulou buildings was 14.6% lower than that in normal rural buildings. Correspondingly, the population per household in Tulou buildings was 9.8% lower than that in normal rural buildings, which may partially explain the difference in energy consumption for cooking.

4.4. Comparing with a village in the north

A similar energy consumption survey was conducted in Erhezhuang village, which is located in Beijing, northern China. During June to August, the average outdoor temperatures were lower in Beijing ($25.5 \pm 2.8\,^{\circ}$C) than that in Nanjing, Fujian province ($27.2 \pm 1.7\,^{\circ}$C). However, the energy consumption for cooling per household in Erhezhuang village was 1.78×10^3 MJ, which was 12.2 times higher than that in Nanjing Tulou buildings (0.13×10^3 MJ). This simple comparison may partially reflect the fact that the construction of the Tulou buildings was effective in reducing the heat flow rate and energy consumption for cooling.

4.5. Implications

The survey results indicated that the residents in Tulou buildings were able to achieve better indoor thermal comfort with lower energy consumption than those in normal rural buildings. In the future, with the development of economy in rural China, the residents may consume more energy to achieve better indoor thermal comfort. In that case, the gap of energy consumption would be even larger between Tulou and normal rural buildings. The most likely reason for the gap may be due to the difference in the building envelope. The average wall thickness of Tulou buildings (1.2 m) is much larger than that of normal rural buildings (0.4 m). Thick earthen walls with effective thermal insulation and large thermal mass lead to significant energy savings and better indoor thermal environment.

In this study, approximately 88% of the total households in Nanjing Tulou buildings were investigated. The high sample rate makes the energy consumption distribution analysis relatively convictive. The analysis indicated that the energy consumption in Tulou buildings was of a concentrative nature. Therefore, in the future, the sample rate of an energy consumption survey in other Tulou buildings, e.g. Yongding Tulou, Hua'an Tulou buildings, can be relatively low in order to reduce the time and resource consumption. However, in normal rural buildings, high sample rate is still necessary for obtaining complete characteristics of energy consumption.

4.6. Limitations

In this study, the power of the equipment or appliances was mainly set based on the sale information in e-shops, which may be different from the real values to some extent. When conducting the questionnaire survey, it was quite difficult to record the detailed information of the power of the equipment or appliances in every household. Similarly, the efficiency of the equipment vary from household to household, thus it was impossible to conduct measurements from house to house. We used average efficiency of the appliances for calculation based on our previous measurements and other references.

Drinking hot water was not included in the consumption of hot water, which may result in some error of energy consumption estimation. However, the consumption of hot water for drinking was relatively small compared with that for bathing. Therefore, it should not influence the results of energy consumption in a major way.

5. Conclusions

In this study, a relatively large-scale survey of energy consumption was conducted in Nanjing Tulou buildings (World Heritage Site) and normal rural buildings. Based on the data obtained by the survey and an energy consumption model, the characteristics of energy consumption in Nanjing Tulou buildings were investigated. Within the scope of this study, the following conclusions can be made:

(1) The total annual energy (primary) consumption per household in Nanjing Tulou buildings was 2.43×10^4 MJ, which was lower than that in normal rural buildings (3.37×10^4 MJ) in the region. Electricity was the dominating energy source used in Nanjing Tulou buildings.
(2) The residents in Nanjing Tulou buildings experienced better thermal comfort with lower energy consumption for cooling than that in normal Nanjing rural buildings.
(3) The difference in human behavior resulted in the difference of energy consumption for hot water and appliances in Nanjing Tulou and normal rural buildings.
(4) The energy consumption distribution in Nanjing Tulou buildings was of a concentrative nature.

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