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How do urban residents use energy for winter heating at home? -A large-scale survey in the hot summer and cold winter climate zone in the Yangtze River Region.

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Abstract

The increased demand for improving indoor thermal environment in the hot summer and cold winter climate zone (HSCW) in the Yangtze River region in China poses enormous challenges in terms of energy policy and design solutions for this unique region. A comprehensive understanding of people's habits and behaviors involving winter heating is imperative for decision making for urban heating infrastructure investment strategies that significantly impact on the decarbonization of heating. However, there has been little knowledge gained from large-scale studies in this region. The aim of this study is to develop a rigorous survey method in order to obtain reliable data for analysis. Five municipal/capital cities across the upper, middle and downstream Yangtze River are surveyed based on 30 randomly generated locations in each city. A total of 8,471 valuable samples were obtained in the survey conducted in the winter from November 2017 to March 2018. It is revealed that air conditioning/air source heat pumps are the predominant systems, accounting for 63% and 58% for bedroom and living room heating respectively. The use patterns of heating are diverse featuring 'part-time-part-space' systems in accordance with the occupancy patterns. There is significant evidence of the habit of opening a window to provide a gap for fresh air irrespective of whether the heating is in use. Two-step cluster analysis is employed to subdivide occupants' heating-related behaviors into three clusters to characterize households. This study fills the knowledge gap of winter-heating-related behaviors. The research outcomes will benefit building energy simulations for energy prediction and help policy makers make decisions on providing strategic guidance in terms of winter heating solutions in this region.

Keywords

Hot summer and cold winter zone; residential buildings; socio-tech survey; winter heating behaviors;

1. Introduction

Due to its vast territory, China has a diverse climate which has been categorized into five typical climate zones: severe cold, cold, hot summer and cold winter (HSCW), hot summer and warm winter (HSWW) and mild, according to GB50178 [1] for building designs. Arising from China's historical energy policies in the 1950s, the Qinling Mountains - Huaihe River Line (hereafter called the QinHuai Line and denoted as the QH line in this paper) was set up as a geographical boundary to provide distinct heating (northern) and non-heating (southern) regions based on climate conditions (see Figure 1). As a result, in the severe cold and cold zones of northern China, the urban district central heating system has been the most popular mechanism for winter heating and people have been privileged with this heating policy thanks to the urban heating infrastructure and heating incentives. By contrast, the HSCW zone in China shows a typical characteristic of a hot summer and cold winter climate, where the average air temperature in the coldest month is between 0^{o}C and 10^{o}C. However, due to the traditional heating division line for northern and southern China, the winter indoor thermal environment in this area is even worse than that in northern China [2]. The average indoor temperature in winter is usually below 10 ^{o}C without central space heating facilities [3]. Therefore, space heating in cold winters has been expected to be one of the most necessary measures demanded in order to maintain a basic indoor environmental quality for people's health and wellbeing.

The QH boundary heating policy was made mainly due to the economic capacity and energy resource scarcity at the time and it has been challenged by the increased heating demand of the region due to economic reform and growth over the last four decades. Especially, the Yangtze River region accommodates more than 55% of the population and shares more than 40% of China's GDP [4]. Thus, it has become one of the well-developed regions of the country. It is not hard to imagine people living in the HSCW climate zone increasing their demand for improved indoor environmental quality [5-8]. However, the national targets pertaining to the cap on primary energy consumption and the peak of CO_2 emissions have applied specific pressures in this region. Therefore, a trade-off between thermal environment improvement and building energy efficiency is urgently required in the Yangtze River region, to maintain a healthy growth in energy demand and consumption in buildings.

Currently, the question “should district/central heating systems be considered in the HSCW climate zone in China?” has become a hotly debated topic among scholars, policy-makers, and citizens in the region. The issue relates to many factors which could affect the decision making on the investment in urban heating infrastructure from environmental, economic, and social perspectives. There were no detailed policies that could solve the winter heating problems for the HSCW zone. However, for those involved in energy conservation, the fast-growing demand for space heating in the HSCW zone is significantly increasing the national energy consumption, which also causes related problems involving carbon emissions and air pollution. Therefore, in response to this problem, it is necessary to have comprehensive and reliable knowledge of how people use energy for winter heating in their homes, which could be useful for policy recommendations and design guides.

1.1. Literature Review

In the HSCW climate zone, winter heating is an extremely challenging problem due to its complex nature related to the local climate, historical habits, thermal comfort, and socio-economic, energy and environmental, technical, and occupant behavior issues. To understand the research gap for winter heating in the HSCW zone, a series of previous relevant studies were critically reviewed, as follows.

1) The current low level of indoor thermal comfort in winter

By reviewing the historical development of the thermal environment in the HSCW zone in China, it can be seen that the level of thermal comfort in winter is at a very low level. Even in recent years, the majority of residential buildings still do not have a full set of winter heating equipment [9]. People in the HSCW zone have lived for many years with no heating. They do not tend to introduce heating devices, but they do put on extra clothes, which has created a local habit of ‘enduring the cold winter without heating[10].

However, this low level of indoor thermal comfort in winter is being rapidly improved due to the rapidly growing economic development in this region. From the study by Wang *et al.* [11], it is clear that the trend of pursuing better indoor thermal comfort for homes is significantly influencing heating behaviors in the HSCW zone, especially for new generations and the elderly groups. Therefore, it is predicted that the future potential energy consumption for heating in the HSCW zone could be enormous [10], and it is an urgent task to understand the existing winter heating situations in this region and find solutions.

2) Building energy policy

The development of building energy policy in the HSCW zone had a late start and made slow progress. In 2001, the building design standard for the HSCW zone [9] started to raise the issue of the requirement for auxiliary space heating measures for public buildings on cold winter days. Since then, there has been no heating policy relating to residential buildings until the first code [9] was issued in 2010. Disappointingly, there were no detailed policies that could solve the winter heating problems for the HSCW climate zone and the situation remained unchanged until recently. This means in the majority of homes, the poor thermal insulation designs are not well-prepared for space heating [12].

Consequently, although the living standard in cold winters in the HSCW region is improving by the increased use of a variety of heating measures, the energy consumed by the diffusion of individual heating devices has also increased incredibly by more than 500 times from 1998-2013 [10], which is contrary to the building energy conservation policies for China. Therefore, the question about what would be the appropriate solution for winter heating in this region remains unanswered.

3) Appropriate winter heating systems for HSCW climate

As the demand of winter heating is increasing, the types of heating become an essential concern. Currently, the majority of people living in the HSCW zone who use winter heating, are using individual electrical heating devices or air-conditioners [9]. These individual systems used for space heating are often argued to be inefficient and expensive for energy due to their low efficiency of performance, and furthermore, because of the poor thermal insulation in the building envelope in this region. By contrast, in northern China, the policy support for district central heating systems has been developed for a long time [13] and has contributed to comfortable indoor environments. Therefore, whether or not to apply the district heating system in the HSCW zone has been argued over for many years on social media and within official civil channels [14, 15].

However, many studies have analyzed and provided evidence that it is inappropriate to apply district central heating in the HSCW zone. Studies [7, 13, 16, 17] have suggested that it is unnecessary to provide district heating for southern China. These scholars claim that the proposed development of large scale urban heating infrastructure would obviously burden the country's environmental impact and hinder the progress of energy conservation [18]. It is also discussed that a personalized dispersed heating system is more suitable for the climate conditions of the HSCW zone as there is a much shorter period of heating compared to the severe cold and cold zones. Moreover, Hu *et al.* [17] state that a dispersed heating system has the advantages of flexibility and easy installation, which does not require huge amounts of engineering work for network refurbishment. As a result, it appears that a dispersed heating system is the appropriate option for winter space heating in the HSCW zone.

4) Occupant behaviors using dispersed heating systems

Importantly, when using dispersed heating systems, occupants' behaviors become the main controlling factor, but pose many challenges [19]. Many studies [20-22] have verified that occupants' behaviors have a pivotal role in building energy consumption, alongside the thermal performance of building envelopes and the efficiency of heating devices [23-25]. Studies have proven that the occupancy profiles, different occupancy patterns, the habit of meeting the demand for fresh air by opening windows [7, 26, 27], and variations in the occupants' thermal preferences for the use time and the temperature setting points of air-conditioning [28-30] have significant impacts on building energy consumption, along with the usage patterns [22, 23], local diversity[10], and family structure [31]. Therefore, compared to the heating behavior in northern China, the residential heating behaviors in the HSCW zone are more diverse and complicated in terms of family structure, economic level, thermal comfort requirements, heated room space, and local climate conditions [32]. The elucidation of this situation requires further detailed research.

Furthermore, it is arguable that many studies of occupancy behaviors and their impact on building energy consumption in this region were simplified and thus of questionable reliability [33]. For example, measurement studies by Lin *et al.* [10], Yoshino *et al.* [34], and Wang *et al.* [8] tested the building operating energy and behaviors, but the sample size was less than 30 households, which could be challenged for varying individual factors. Peng *et al.* [35] and Ge *et al.* [36] have studied the energy modeling by combining measurement, simulation, and behavior surveys, but their case studies considered only one city and one type of building. As there were biases in the descriptions of the behaviors, e.g. AC setting points and window operation behavior, the occupant praxeology for winter heating still remains incompletely understood. Thus, with suggestions from statistical modeling in this research field, such as Chen *et al.* [37] and Guo *et al.* [25], studies with comprehensive survey data are necessary and essential to understand how people in this region heat their homes and how they behave to secure and maintain this heating.

1.2 Aims of the study

Building on the literature above, the aim of this study is to acquire a comprehensive understanding of occupants' heating-related behaviors in residential buildings and their demand for heating in winter in the HSCW region. This study contributes to a rigorous large-scale survey of heating demand in terms of identifying locations, sample size, and questionnaire design. The research outcomes are expected to benefit building energy simulations related to occupant behaviors, policy makers and their decision making, and those requiring strategic guidance on producing winter heating solutions in the HSCW region. This fills the knowledge gap arising from the lack of reliable data on how urban residents in the Yangtze River region use energy for winter heating.

2. Method

Among many methods applying social science to human behavior studies, survey methods such as a census, interviews, and polling are widely considered to be efficient ways of collecting preferences, opinions, behaviors, and factual information [38]. The questionnaire survey method has been applied in this study. The extensive information related to building construction, indoor occupancy, occupant behaviors, and the use of heating devices was considered. The detailed processes involved in the questionnaire design, the selection of the cities, and the sample collection and analysis are described in the following sections.

2.1 Selection of cities

To understand the heating situations and occupant behaviors in residential buildings in the HSCW region, five municipality/capital cities - Chongqing, Chengdu, Changsha, Hangzhou, and Shanghai - spread over the upper, middle and lower parts of the Yangtze River, were selected, as shown in Figure 1.

Figure 1: Geographic distribution of the five selected cities in the HSCW zone

Detailed climate data for the five cities in this region are listed in Table 1, which were referred to Ref.[39]. It is clearly seen that the five cities share a similar longitude. This leads to a similar annual average air temperature, with a slight range from $16.6^{o}C$ to $18.5^{o}C$.

In addition, Table 1 shows that the annual average relative humidity for the five cities is high at around 75%-80%, reflecting the characteristic high air humidity in this region.

Table 1: Geographic information and typical meteorological data of the five cities

City	Latitude	Longitude	Altitude (m)	Annual average temp(ºC)	Annual average RH (%)	Annual average radiation (W/m2)	Annual average outdoor wind (m/s)
Chengdu	103.52	30.45	547.7	16.6	80.97	46.60	1.19
Chongqing	106.28	29.35	259.1	18.5	81.54	42.42	1.45
Changsha	112.55	28.13	68.0	17.1	82.24	81.06	2.14
Hangzhou	120.10	30.14	41.7	17.0	75.79	91.33	2.07
Shanghai	121.27	31.24	5.5	16.7	75.96	107.02	3.25

2.2 Sample sizes

When using the survey method, it is important to obtain a representative sample from a population by using simple random, stratified random, or cluster sampling methods [40]. An appropriate sample size determines significantly whether the survey results can truly cover a wide range of situations. To represent the real situations in each city, the cluster sampling method based on probability sampling (i.e. random sampling) was selected. The sample size was determined by using Equation (1) [41].

$$n=\frac{X^2\times N*P*(1-P)}{(ME^2*(N-1))+(X^2*P*(1-P))} \quad (1)$$

Where,

n ----the sample size;

X^2 ----the statistical values associated with the desired level of confidence;

N----the population size in each city;

P----the preliminary estimate of the proportion in the population;

ME----the desired margin of error (%).

In order to determine a sample size of n, a 95% confidence level is used (Confidence Interval CI=0.95) in this study; ME is set at 5%. For a degree of freedom of 1, the X^2 value can be found using the chi-square test making the value of X^2 for a 95% confidence interval (CI) equal to 3.84. According to Ref. [41], as the value of P was not known, the maximum value of 0.5 was assumed in this study. Based on the census data [4], the population of each city is listed in Table 2. Therefore, the required sample size calculated using Equation (1) is listed in Table 2.

Table 2: Research situation and sample size

City	Permanent Resident Population (million)	Calculated Sample Size	Planned Sample Size
Chengdu	15.918		
Chongqing	30.484		
Changsha	7.645	384	1500
Hangzhou	9.188		
Shanghai	24.197		

After the sample size for each city is determined, it is necessary to consider location distributions within each city in order to investigate the representative communities of each city. Therefore, the locations of residential communities in each city were coded using a random number generator to obtain the designated locations for survey. It is worth noting that no standards such as postcode orders or location information were applied during screening, which ensured the randomness of residential communities in each city. As a result, 30 sampling sites were identified for each city, and the sample distribution is shown in Figure 2. The red dots in Figure 2 are the survey sites, and the colors of each region border correspond to the number of samples. All urban areas in the five cities have ideal site representativeness, and, thanks to the random sampling, there is no small probability deviation concentrating in a narrow range.

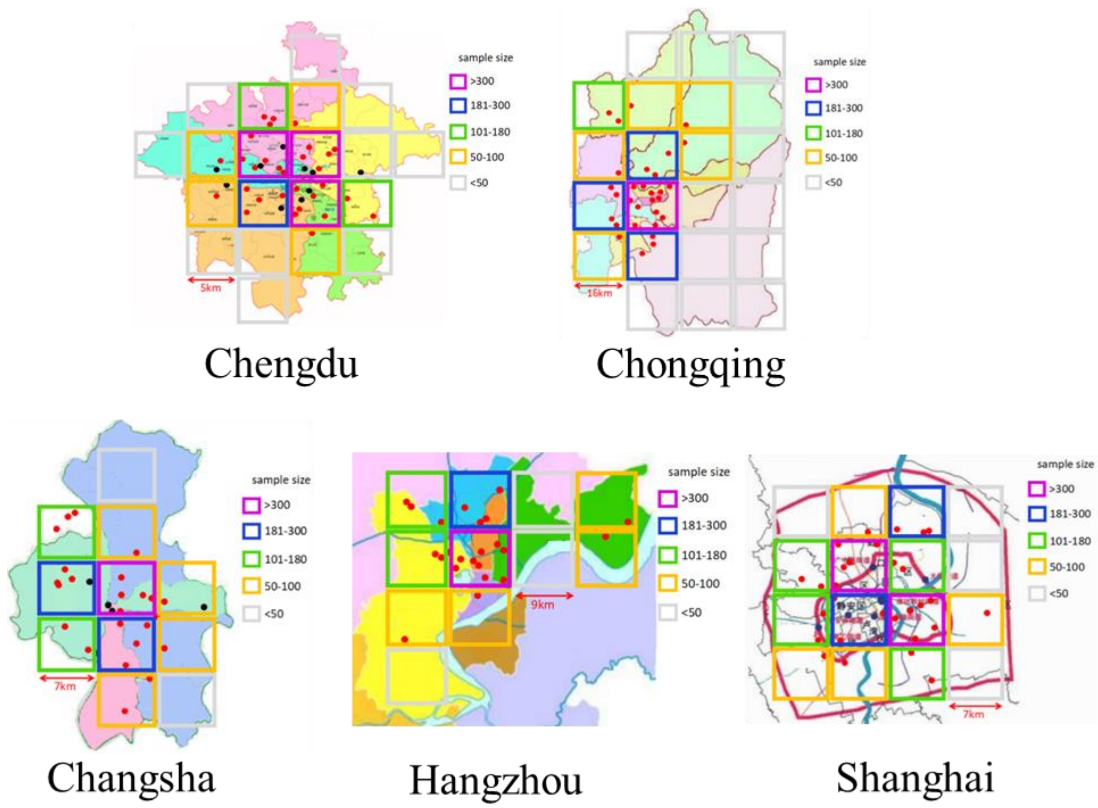

Figure 2: Sample distribution in the main districts of each city

2.3 Questionnaire Design

A rigorous survey is based on research questions, theories, reasonable hypotheses, and well-defined explanations of variables [42]. To meet the purpose of obtaining the data for analysis and the research objectives of this study, the contents of the survey questionnaire have been divided into two parts. The building construction information, family structure of respondents, energy-matter behaviors and habits for winter heating and ventilation have been partly optimized and recorded as the occupancy behavior schedules for the related analysis of building heating energy consumption [43]. Explanations of how each part of the questionnaire was designed to respond to the research questions are presented as follows:

Part 1 mainly includes the basic information on building characteristics such as building construction age and dwelling size, family structure and time at home. According to the year of the upgrading of building energy design codes, the construction age band is classified as ‘before 2001’, ‘2001-2009’, and ‘after 2009’. Five family structures were mainly considered referring to the statistical data from the 2016 China National Bureau of Statistics [4]: (a) single (S); (b) couple (C); (c) couple with a child (CP+C); (d) couple with child and the elderly (CCGP); (e) others - any family structure not listed.

Part 2 mainly focuses on how people heat their homes. Questions include “what are the measures used for heating?”, “how do people operate them?”, and “what are the setting points of the air conditioning?”. Through desktop studies and heating appliance market information, the research team listed commonly-used heating devices such as air conditioning, under-floor heating, radiators, oil radiator heating, portable electric heater, fan heater, electric blankets, hot-water bags, etc. and temperature setting-points, clothing regulations, etc. To note, given that residents may have different behaviors in different types of rooms, the occupant behaviors in the bedroom and living area were investigated separately. These questions are expected to benefit researchers seeking to explore the real heat demands in this region, as well as for policy makers for future heating applications and building energy efficiency.

Many studies have confirmed that long-term occupants living in the HSCW zone have habits of opening windows for fresh air, even in the winter time [44]. This could be one of the most diverse and erratic behaviors due to individual differences and could significantly affect thermal comfort and heating energy consumption [26]. Therefore, a question relating to the window opening gap when heating is in use is included in the questionnaire.

The detailed framework of the questionnaire is shown in Figure 3. An appendix containing the questionnaire is provided for reference. The questionnaire was presented in three sections, in three sections of bedroom, living room and fresh air demands. Note that background information, such as gender, age, occupation, family income range and so on were designed in questionnaires but were exclusively considered in this study, considering the main aims and propose of this study.

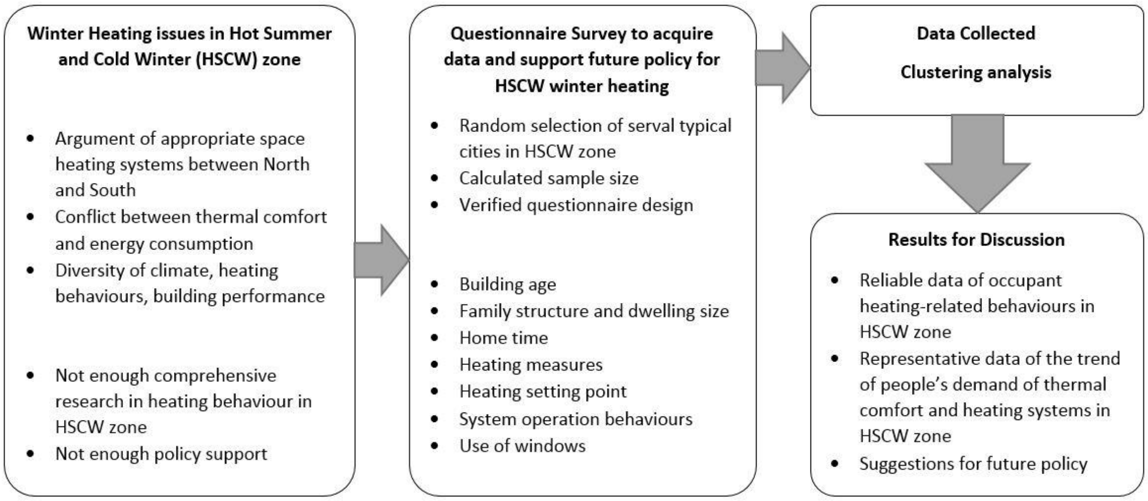

Figure 3: Framework of the questionnaire survey process

2.4 Data screening and statistics

1) Data collection

The surveys were conducted simultaneously in the selected sample locations of the five cities from November 2017 to February 2018. The surveyors paid visits to the selected communities in each city. A total number of 8,764 respondents completed the questionnaire including samples of 1,619 from Chengdu; 2,196 from Chongqing; 1,197 from Changsha; 1,716 from Hangzhou; and 2,036 from Shanghai, by means of face-to-face completion of paper-based forms or by using an electronic version as a social media we-chat app. After screening null or invalid values, the sample size used in analysis was 8471.The survey in each city met the required minimum sampling size which was indicated in Table 2, ensuring the representative and valid analysis in the following results.

2) Validity and reliability analysis

We conducted a questionnaire reliability and validity testing in this study. Reliability analysis and validity analysis are two methods to check the data quality in questionnaire, where the former describes the degree of consistency of data from questionnaires in survey during repeated measurements and the latter evaluates to what degree the results of the designed questions collected by questionnaires could reflect the real situations of occupants' actual heating related behaviors.

For reliability analysis, the Alpha reliability coefficient method, i.e. Cronbach's Alpha, is widely used to examine the inner consistency. The method is suitable for analyzing designed question in questionnaires in this study. The calculation of the Alpha coefficient is as follows [45]:

$$\alpha = \frac{k}{k-1}\left(1-\sum_{i=1}^{k}\frac{s_i^2}{s_p^2}\right) \tag{2}$$

Where,

k---- The number of items for the research objects;

s_i^2 ---- The variance per item;

s_p^2 ---- The total variance of the observed items.

In addition, the validity analysis is mainly adopted to examine whether the designed questions are able to reflect the real situations focused. The higher the values of validity are, the more accurately the results obtained from questionnaires reflect the real features. It is defined as the ratio r_{xy} of variances of effective values and real values, as expressed in Equation (3).

$$r_{XY} = \frac{S_X^2}{S_Y^2} \tag{3}$$

The validity and reliability tests theoretically could be conducted before or after the survey; the complemented survey would be re-conducted if the test was unacceptable. In this study, the tests were conducted after the survey, and Table 3 shows the results of the validity and reliability tests of different questions in the questionnaire. According to Refs. [45, 46], the results are good when the reliability coefficient and validity coefficient are higher than 0.9; and are acceptable when they are above 0.8. Conversely, when the values are lower than 0.7, the questionnaire should be re-designed and the research should be re-conducted in order to ensure scientific rigor. The results in Table 3 shows that for the target questions, the coefficients α were all higher than 0.8, indicating the question designs were good and the questionnaires were acceptable. In addition, Table 3 shows that the values of validity test were both higher than 0.7, suggesting the results obtained from the questionnaire survey could efficiently reveal the heating behaviors of residents in this region. This lays the foundation for the following analysis.

Table 3: Results of validity and reliability testing

Method	Number of questions(Appendix)	Contents description	Coefficients of Cronbach's Alpha/KMO test
Reliability Analysis	Q1,Q2,Q3	Basic information and background	0.80
	Q8,Q10,Q11	Heating-based behaviors in living room	0.85
	Q4,Q7	Temperature set points in bedroom and living room	0.91
Validity analysis	Q8,Q10,Q11	Heating-based behaviors in living room	0.74
	Q4,Q7	Temperature set points in bedroom and living room	0.88
	Q5,Q6,Q8,Q9,Q10,Q11	Occupants' behaviors during heating in bedroom and living room	0.79

3) Statistical analysis

There are three types of variables from the questionnaire statistics: continuous variables (e.g. AC setting points), dichotomous variables (e.g. ratio of HVAC behaviors), and ordinal multiple variables (e.g. modes of HVAC behaviors), which correspond to different conditions and analytical methods. Descriptive statistics were used first to give a profile of occupant behaviors under different situations. The correlation analysis was used to evaluate the relations among variables and the Kendall's tau-b correlation index was adopted to describe the relations of two classified variables in questionnaires. The ANOVA test was used to examine the differences in occupant behaviors during heating periods among the five cities, and the post-analysis ANOVA was used to compare the differences among different groups (e.g., family structures). The multi-way ANOVA was then conducted to identify the factors that affect the temperature setting points of occupants according to four typical family structures. The cluster analysis was then employed to classify and summarize the households according to the different heating-related behaviors of occupants. All tests conducted were two-sided and any p-values less than 0.05 were considered significant.

3. Results

The current study aimed to provide an overview of knowledge of heating related behaviors of residents at homes in the Yangtze River region; the data from surveys from the five cities were analyzed as a whole in the following analysis, regardless of the slight differences among different cities.

3.1 Basic information from the survey

1) Building age

The census data on building construction age from the Real Estate source for each city has been collected in Table 4. In order to verify whether the building age proportions of this study reflect the cities' real situations, data collected from this survey were compared to the statistical data in Table 4. The most investigated buildings were built from 2001 to 2009 accounting for the highest proportion of 45%. This was followed by buildings constructed before 2001 with a proportion of 36.1%. The proportion of buildings that were built after 2009 was small, about 18.9%. A close comparison shows that the distribution of construction ages of investigated buildings exhibited a good consistency with the census data, and no significant differences of construction ages were found between the statistics and the surveyed results (t test, $p>0.05$). This ensures our survey truly reflects the real building characteristics situation.

Table 4: Proportion of building age of this survey and the census data

	Before 2001	2001-2009	After 2009
Census data	35.5%	44.9%	19.6%
Surveyed buildings	36.1%	45.0%	18.9%

2) Family structure and dwelling size

The analysis of types of family structure and dwelling size can be seen in Table 5. Most investigated families were couples, couples with children (CP+C), and couples with children and the elderly (CCGP), accounting for 27%, 33% and 26% respectively, which reflects well the variety of family types. By analyzing the correlation coefficient r between the family structures and dwelling size, the correlation coefficients in Table 5 exhibit high positive correlations ($p<0.001$). The bigger the family size is, the bigger the coefficient is, indicating that the dwelling had more rooms. Single persons usually take one or two-bedroom dwellings. Two-bedroom and three-bedroom dwellings are the popular types in residential buildings and the most complex three-generation family structure are generally found in three-bedroom dwellings. However, there were still a big proportion (0.49) of type of family living in the two-bedroom dwellings.

Table 5: Correlation coefficient between family structures and dwelling types

Family structures	Number of samples	Dwelling type*			
		One bedroom.	Two bedrooms.	Three bedrooms.	Four bedrooms
Single	1139 (14%)	0.3	0.40	0.27	0.03
Couple	2126 (27%),	0.14	0.56	0.26	0.04
CP+C	2597(33%)	0.03	0.49	0.40	0.08
CCGP	2052 (26%)	0.02	0.32	0.56	0.10

(Note: * the number of bedrooms in the investigated dwellings)

3) Times when residents are at home

The fact whether or not occupants are at home, significantly relates to the usage of household heating. The percentage time spent at home as reported by respondents in each of the four family structures is shown in Figure 4. From the figure we can see that for the family structure with children and the elderly (CCGP), 80% of respondents reported the home time as daytime from 7:00 to 18:00; this proportion was around 50% for couples and couples with a child (CP+C). By contrast, single persons had the lowest home time during daytime with around 20-30%. These results reasonably reflect the activity characteristics in residential buildings, which are believed to affect the heating modes and behaviors at home. Wang *et al.* [8] found that retired couple/single households consume on average 47% more energy than those with no retired members. This may be explained by a longer heating duration needed by the households with retired members. Combined with Figure 4, families that include the elderly had a higher home time - 80% - during daytime. This may contribute to higher heating demands and energy consumption compared to other family structures where occupants leave home for work during the daytime. Therefore, in future, it would be worthwhile considering occupancy as a most important factor for building energy efficiency design standards, energy efficiency policy-making, and predicting energy consumption in the HSCW zone.

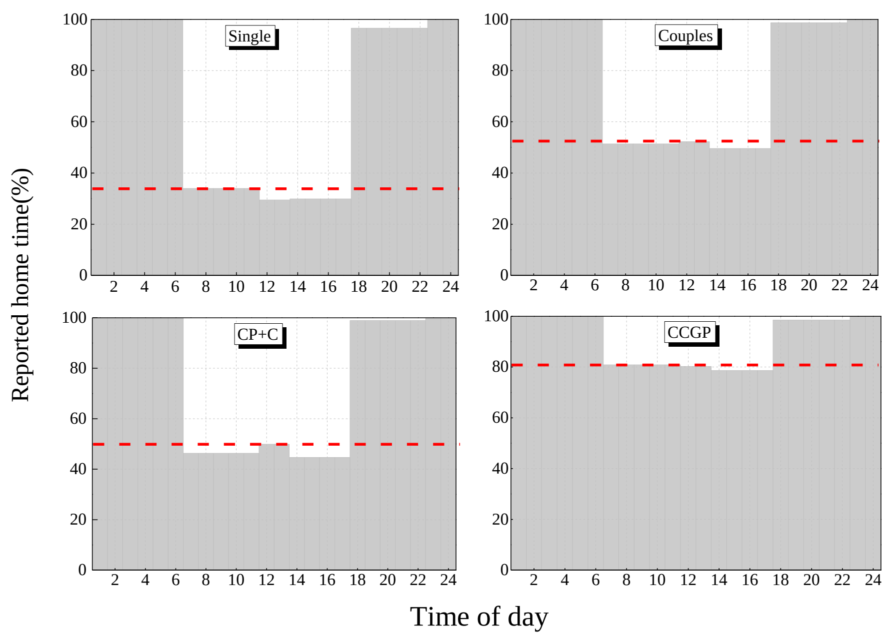

Figure 4: Percentage of the reported home time

3.2 Heating behaviors

1) Heating measures

From this survey, 63% of respondents reported heating their bedroom and 43% their living room, as shown in Figure 5. From the figure, we can see that the air conditioner (AC), or air source heat pump (ASHP) were the most used for heating in winter. The proportions using AC in bedrooms and living rooms were 63% and 58% respectively. This is in agreement with Ref. [25] and with AC being the most commonly used heating device in this region. In addition, Figure 5 further confirms that residents from the HSCW climate zone do not heat their homes for 24-hours, unlike those in northern zones. There is still a quite large proportion of residents that do not heat their home at all (37% in the bedroom and 57% in the living room, respectively), as seen in Figure 5.

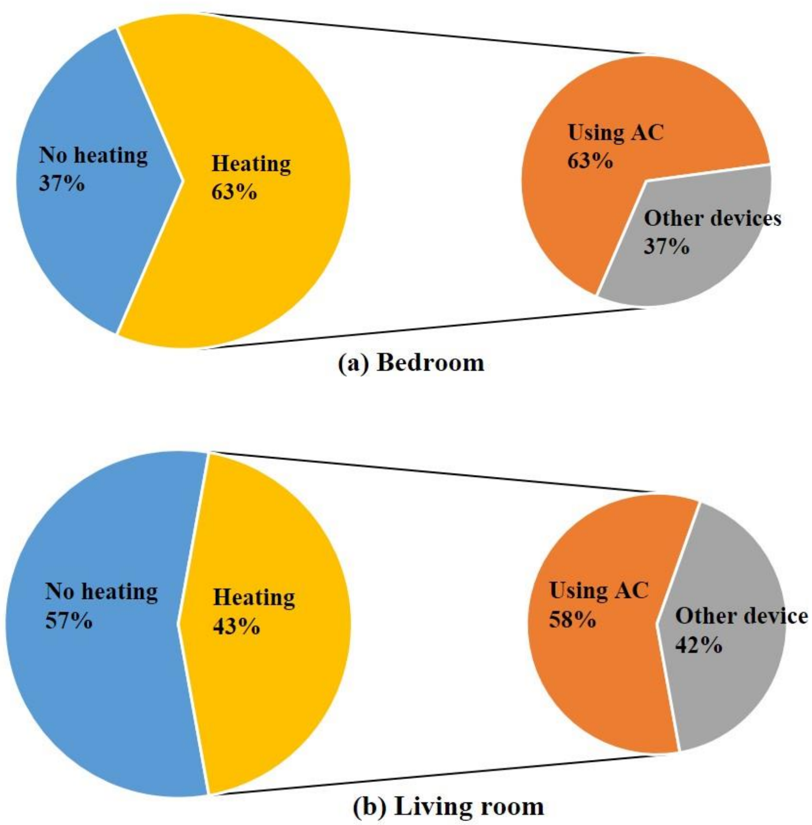

Figure 5: Proportions of heating/no heating in the bedroom and living room

During the survey, a variety of heating measures were investigated. Apart from AC, Table 6 lists the heating devices used by respondents and the corresponding proportions. A variety of heating devices including under-floor heating, oil heaters, radiators, portable electric heaters (infrared heaters, fan heaters, electric blankets) were found in households. However, compared to the AC usage, all these devices accounted for a relatively lower proportion ranging from 1%-14%. Therefore, it is reasonable to infer that, in the long run and with technological development, AC will become the dominant form of heating.

Table 6: Heating devices applied in households in winter

Heating patterns	Bedroom		Living room	
	Cases	Proportion	Cases	Proportion
Air conditioning (AC)	4258	63%%	2424	58%
Underfloor heating	207	3%	154	4%
Oil heating radiant	379	6%	267	6%
Radiator	188	3%	150	4%
Infrared heater	370	5%	607	14%
Fan heater	264	4%	209	5%
Electric blanket	860	13%	43	1%
Other	211	3%	360	9%

2) Heating setting-point for AC

The temperature setting-points significantly affect the heating energy consumption. Figure 6 shows the distribution of temperature settings during heating reported by respondents. The sizes of the bubbles represent the sample capacity for reporting each temperature setting point and they are marked in different colors to distinguish four typical family structures. It can be seen that, regardless of family structures, the majority of occupants chose to set the AC temperature within the range 24-28^{o}C, with higher proportions and bigger bubble sizes.

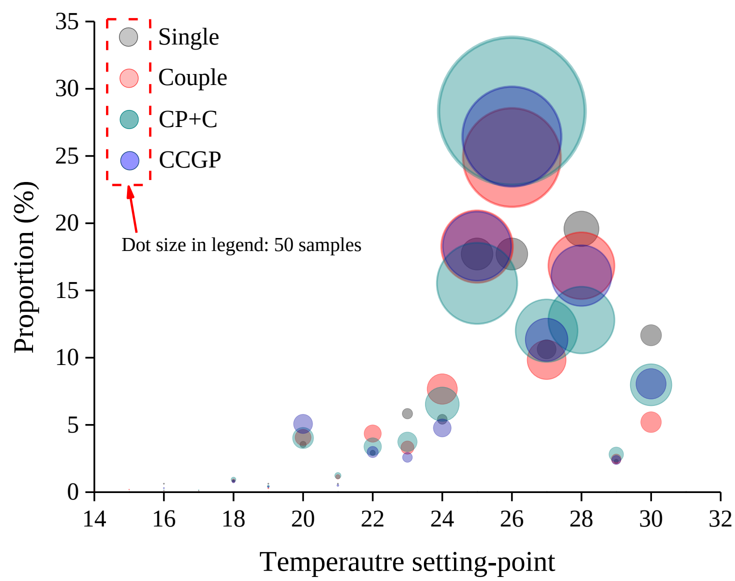

Figure 6: Temperature setting point distribution with different family structures

Figure 7 shows the distribution of temperature setting-points by different family structures. We can clearly see that the mean temperature setting-points in both bedrooms and living rooms are overwhelmingly high, in the range 25-28^{o}C. Though the mean temperature setting points for each of the four family structures are close, the statistical results shows that the factor of family structure has significant effect on the temperature setting-points (ANOVA, $p<0.05$). Similar trends were found for living rooms. This setting-point temperatures are much higher than those in northern China [39]. Compared to a study from the UK [47], this figure seems unacceptably high. This phenomenon can be explained as being based on the ‘part-time-part-space’ heating style, the room temperature for an unheated room is usually very low (e.g. low indoor temperatures of around 12^{o}C for unheated space in the HSCW area [25]). However, occupants expect a speedy temperature increase when they enter into unheated rooms, which brings us to the next question about how people operate the heating devices.

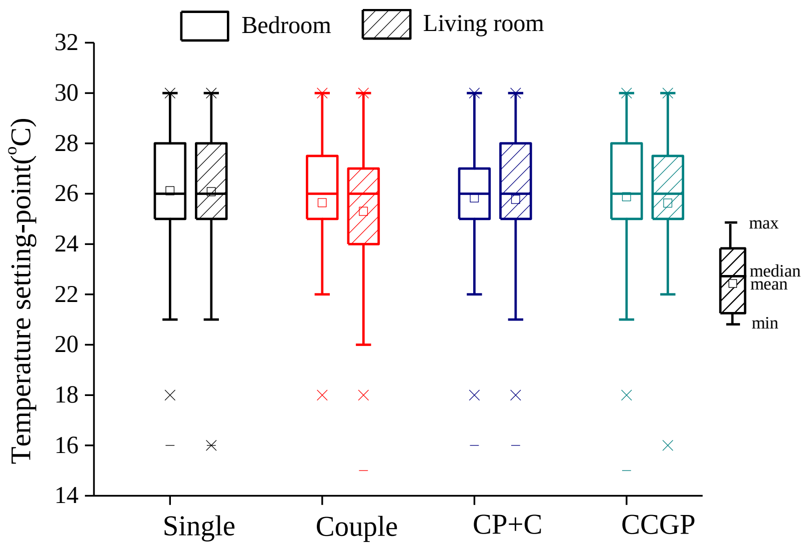

Figure 7: Temperature setting-points in different room types with different family structures

3) AC operation behaviors

In order to further understand how the urban residents operate AC for heating, Q6 and Q11 specifically ask this question for bedrooms and living rooms. From the survey, 1,989 respondents reported their AC operation modes as seen in Table 7. For bedroom, three similar modes were almost equally used when occupants slept. That is, nearly 34% of respondents chose to set a constant temperature all night; 37% of respondents set a timing mode whilst 29% of respondents used the sleep mode integrated into the AC, indicating occupants' different individual preferences for using AC modes.

Table 7: Operation modes when AC on

Room types	Q6-AC using modes	Cases/proportion
Living room	Set a constant temperature	1989/80%
	Set a high temperature at start and turn down when the room get warm	490/20%
Bedroom	Set a constant temperature all night	1010/34%
	Set a timing mode	1086/37%

Use the sleep mode embedded in the AC	860/29%

Note: The sleep mode is an operation algorithm embedded in the AC by manufacturers. The maximum operation time is 8 hours in order to save energy

We further explored the temperature setting-points responding to each mode of use and a statistical test was conducted to examine whether the AC modes used by occupants affect the temperature setting points. We counted the distribution of temperature setting-points under each mode of using AC; the results are shown in Table 8. From the table, we can see that for living rooms, when respondents reported they set a high temperature first and then turned it down when the room became warmer, the majority set a temperature higher than 26^{o}C (65%). This was similarly remarkable when respondents reported setting a constant temperature in living rooms. The ANOVA test shows a significant difference in living rooms (ANOVA, $p<0.05$), suggesting that the setting temperature in the living room was significantly affected by occupants' modes of using AC. This was consistent with Table 7 which suggests that most occupants set constant temperatures when AC was on.

For bedrooms, the trends of temperature setting points under each mode of use were similar to those for living rooms. Regardless of the mode of using AC, a large number of occupants chose to set a temperature of over 26^{o}C, and the proportion was higher than 60%, even up to 67% when the mode of use was to set a constant temperature all night. 60% of respondents chose to set a temperature setting-point over 26^{o}C. Such results explain why the setting points in Figures 6 and 7 were so high.

Table 8: AC mode of use and the corresponding temperature setting points

Room types	AC using modes	Temperature settings(°C)	Cases	Proportion (%)
Living room.	Set a high temperature at start and turn down when the room gets warm.	<18	1	0%
		18≤Tset < 24	83	20%
		24≤Tset < 26	60	15%
		≥26	272	65%
	Set a constant temperature.	<18	16	1%
		18≤Tset < 24	296	17%
		24≤Tset < 26	378	22%
		≥26	1053	60%
Bedroom.	Set a constant temperature all night.	<18	3	0%
		18≤Tset < 24	91	10%
		24≤Tset < 26	216	23%
		≥26	642	67%
	Set a timing mode.	<18	7	1%
		18≤Tset < 24	135	14%
		24≤Tset < 26	225	23%
		≥26	605	62%
	Use the sleep mode embedded in the AC.	<18	2	0%
		18≤Tset < 24	100	13%
		24≤Tset < 26	181	24%
		≥26	475	63%

4) Use of window for fresh air

Many scholars have conducted research on occupant window-opening behavior and found that people living in the HSCW climate zone have a habit of opening windows, even in winter [10, 31, 44]. The main driving force of this habit is inferred to be a high demand for fresh air. In this study, Q5 and Q9 explore whether people open windows when they use heating. The results are shown in Table 9. We can clearly see that although the AC was used for heating, around half of occupants chose to open windows with a small gap, 49% for the bedroom and 57% for the living room respectively.

Table 9: Window open/close in bedroom and living room when using AC

Window operating modes	Bedroom	Living room
Closed totally.	49%	40%
Open with a small gap.	49%	57%
Open with a big gap.	2%	3%

From Figures 6-7 and Table 8, occupants preferred to set high temperatures when using AC for heating; while Table 9 reveals that occupants tended to open windows during heating use. Therefore, such occupant behavior is believed to relate to the heating efficiency in rooms, which may affect the occupants' temperature setting points for AC. As a result, we analyzed the relationship between the temperature setting-points (Q4/Q7) and the operation of windows by occupants (Q5/Q9), as shown in Table 10.

It can be seen that, whether for bedroom or living room, when the setting temperature increases, both the proportions for windows open and closed increased. In particular, when AC was set higher than 26^{0}C, the proportion of windows being closed was the highest, accounting for 65% and 62%. However, there were still high proportions of occupants who chose to open windows with a small gap, 59% and 61% respectively. By contrast, 59% of respondents reported a big gap for window opening in bedrooms, and 36% in the living room. The statistical results show that the temperature setting-points were significantly affected by the window operations in bedrooms (ANOVA, $p<0.05$); while no significant difference was found between temperature setting-points and window operations in living rooms (ANOVA, $p>0.05$). This further verified that occupants in this region have a significant habit of leaving windows open with a gap - small or large - for fresh air when heating was applied.

Table 10: Relationships between temperature settings of AC and window open/closed

Room types	Temperature settings	Close totally	Open with a small gap	Open with a large gap
Bedroom	<18	1%	1%	0%
	18≤Tset < 24	11%	16%	12%
	24≤Tset < 26	23%	24%	29%
	≥26	65%	59%	59%
	Total cases	2079	1889	51
Living room	<18	1%	1%	0
	18≤Tset < 24	16%	19%	12%
	24≤Tset < 26	21%	19%	52%
	≥26	62%	61%	36%
	Total cases	1055	1142	25

3.3 Cluster analysis of occupants' heating-related behaviors

In this study, we have confirmed that there are a variety of behaviors relating to winter heating which makes identifying household characteristics in terms of winter heating behavior complex. In order to generalize the characteristics of heating-related behaviors in different households, the cluster analysis method has been applied. This is a method widely employed in field studies to subdivide a set of observations into subsets, where the same clusters are highly similar, meantime, different clusters have low similarity [48]. The two-step clustering analysis takes advantage of using both discrete and continuous variables as inputs and of building clusters with the optimal variables and proportions, hence its use in this analysis.

At the first stage, the 'exhaustive search' method is used to select the feature factors that enable the characteristics of occupant behavior related to heating to be represented. Then, during clustering analysis, keeping a 'goodness of fit' and retaining input factors and behaviors were two principles adopted to debug the model. Building a debug model which aims at keeping to these principles forms the second stage. We adopted the logarithmic likelihood method to evaluate the distances between different clusters and the number of clusters referring to the Schwarz Bayes Criterion (BIC Bayesian information criterion). Therefore, the different clusters with different factors were calculated. Accordingly, seven heating-related factors were screened in three clusters, which enabled the features in different clusters to be characterized.

Table 11 shows the results of cluster analysis. From Table 11, Cluster 1 was likely to be the working mode, as in this group occupants only or mainly used AC in the evening. This group was matched to behavior modes with shorter 'AC on' times (only evening). In addition, occupants in this group tended to keep windows closed in the living room and bedroom when using AC. This indicated that occupants in Cluster 1 have frugal heating-use behaviors. By contrast, Cluster 2 and Cluster 3 show a behavior pattern of being at home all day and having higher proportions of periods when windows are open when using AC, which is different from Cluster 1. The difference between Cluster 2 and Cluster 3 is that people in Cluster 3 depended heavily on AC, and use AC as long as they are in the living room. Besides, occupants in Cluster 3 keep the AC on in bedroom throughout the night until next day, indicating a more luxurious behavior when using AC for household heating. Overall, the cluster analysis in Table 11 identifies seven significant factors affecting heating in rooms and generalizes the behaviors in different groups, which gives us a holistic insight into occupants' heating-related behaviors and a general profile of clustering occupants' behavior characteristics.

Table 11: Results of cluster analysis when using AC for heating

No *	Variables included in model	Levels /proportion**		
		Cluster 1	Cluster 2	Cluster 3
1	AC use in living room	Only use when feeling cold/100%	Only use when feeling cold/100%	Use as long as room occupied/100%
2	Heating with/without window opening in bedroom****	AC without window opening/100%	AC with window opening/100%	AC with window opening/51.5%
3	Heating with/without window opening in living room****	AC without window opening gap/74.6%	AC with window opening gap/81.3%	AC with window opening gap/58.8%
4	Use modes of AC before sleep	Keep on till next day/38.1%	Set time off/42.4%	Keep on until next day/45.4%
5	AC temperature set points in bedroom /°C***	26	26	26
6	Presence at home	Evening only/41.4%	All day/42.8%	All day/43.3%
7	AC temperature set points in living room/°C***	26	26	25
Overall proportion/cases		46%/575	39%/493	15%/194

*: the order indicates the importance of factors varying from high to low during modeling;
**: the proportion means how many cases that are in agreement with the feature of such behavior in this cluster;
***: it is the average value of the investigated cases, instead of the proportion;
****: there are three choices responding to occupant window-opening behaviors. However, for clustering, the two choices where respondents reported opening a window with a small gap and with a big gap were combined as a window opening gap.

4. Discussion

4.1 Appropriate heating modes and policies in the HSCW zone

As discussed in the introduction and literature review, the appropriate space heating approach for the HSCW climate zone has been widely argued for a long time. From the statistics and standards, the settings between these two heating modes could be very unbalanced. In Northern China in the Severe Cold and Cold zones, the central heating system provides continuous space heating hot water from stations to radiators for every room, with a very luxurious 24/7 mode during the entire heating period, and the set point temperature is at least 18°C. However, in the HSCW zone, as seen in this survey study, AC is used as the means for winter space heating and is usually available in bedrooms and living rooms, with a part-time mode when the room is occupied, for a shorter cold weather period. Furthermore, although the setting-point temperature for AC could be higher than 26°C, it is discussed that studies [24] have still shown the average indoor temperature in reality is only around 15°C for the heated rooms due to the complex factors of equipment efficiency, poor thermal insulation, infiltration, and window-opening habits. Therefore, the potential energy demand in future for better thermal comfort is enormous to achieve the comfort level in the range 18°C to 28°C [3, 49].

Comparatively, statistics and data showed that the average heating energy consumption for urban heating in northern China was 15.1kgce/m^2 in 2016 [39]. For the HSCW zone, current heating energy intensity is proven to be 3.6kWh/m^2 [24]. However, it is predicable that the average indoor temperature in HSCW winter will be improved to a better condition at 18°C, and it is questionable about what would happen to the overall heating energy consumption in the HSCW zone if the entire heating system was to be rebuilt as a central heating system.

This unstoppable demand for indoor thermal comfort improvement could be an extremely ambitious challenge for national policies on energy conservation [47]. Although the current heating energy use intensity is low as 3.6 kWh/m^2, the current heating method in the HSCW zone - the ‘part-time and part space’ method - could provide a smoother path towards increasing the energy load given people’s requirements for improved thermal comfort [48]. Accordingly, focusing on increasing insulation performance and the energy efficiency of equipment based on this method is a widely-proven [50, 51] and better approach to reducing energy waste and carbon emissions rather than changing the whole heating system in this region. Jiang *et al.* [52] once discussed and studied that to achieve the energy conservation and environmental protection objectives set by the national government, the energy benchmark for summer cooling and winter heating in the HSCW zone should be limited within 20kWh/m^2. As the HSCW zone also has enormous energy demand for summer cooling [9], there is not too much left for the space heating energy increase. If completely copying the northern central heating system to the HSCW zone, the sudden increase in energy consumption could be extremely massive; which is unacceptable. As a result, this study believes that the very 'luxurious' central heating system should not be applied to the HSCW zone, instead, improving the current separate heating system is a smarter choice that fits into China's national development policy. Building design and refurbishment as well as operation management is recommended to refer to the spatial and temporal elements of the end-users' heating demand.

4.2 Outlook of future studies

The current study mainly focused on the behaviors and measures taken by occupants at homes to improve and adapt to the indoor thermal environments in winter, providing a general profile of heating situations in residential buildings in this region. The diverse demographic factors (eg., age, numbers), building characteristics (e.g., construction ages, insulation, air infiltration), socio-economic factors (e.g. family incomes), are exclusively considered in our analysis. In fact, they are various driving factors underlying the occurrence of a certain heating behavior of occupants. For example, the family structure plays dominant role affecting the heating behaviors that as a whole, the behaviors of one resident would be affected by family members. Family incomes was also a key determining the use patterns and intensity of heating [48]. Moreover, since the heating patterns and devices vary in homes, the factors and motivations changed over time, thus influencing the heating behaviors and future energy use intentions in this region [31]. Given that the large-scale survey mainly focuses on observation of the phenomena, we have conducted more in-depth focus group interviews and surveys in small samples, aiming to exploring the motivations, preferences, ect., and explaining the reasons behind theses heating related behaviors. In addition, considering that occupant heating-related regulations may be affected by the temporal-special usage patterns, demographic factors as well as their impacts on energy consumption, the use behaviors for AC by residents, including temperature setting, modes, durations, indoor and outdoor temperatures have been monitoring in several demonstration households of this region; the data results, however, are our undergoing research works, which would be presented in future.

Research on holistic solutions for winter heating specifically suitable for this region should not only consider performance improvements in the building passive technologies and energy devices and systems, but also consider the operation strategies (people's usage behaviors) and real comfort demands, in order to efficiently use energy for winter heating. Heating energy modeling is important for the energy prediction at the domestic stock level. The findings of this study of occupant behavior patterns for different clustered groups have been incorporated into the modeling in our present research work and provided more realistic boundary settings in models, to optimize the solutions for passive technologies for new buildings and existing buildings and balance the multiple objectives of thermal comfort and energy consumption quota. This is believed to allow predictions of different energy demands and the possible energy-saving potential during heating periods in this region.

The current study pays attentions to residents' related features affecting heating in winter. Notably, the building envelope characteristics indeed play dominant roles on heating choices and energy outcomes. For example, the thermal performance and air tightness of existing buildings are poor in this region, and the insulation levels in terms of U-value that suits the region are expected to be clear. The solutions to solve the air infiltration arising from the habit of leaving windows open to allow a gap for fresh air should be a research focus. Sensor technologies can be applied to provide occupants with information on internal air temperature, humidity, and CO_2 concentration which will help achieve appropriate operation. Fresh air supply devices should be compulsory when air-tightness is implemented. Energy policy codes for energy-efficient design specifically for this region should be updated based on in-depth studies.

5. Conclusions

This study developed a holist method to conduct a large-scale field survey on winter heating in domestic homes in the hot summer and cold winter climate zone in the Yangtze River region. The method is rigorous in terms of determination of location, community area, sampling size, and questionnaire design. A set of valid 8,471 sets of questionnaires were collected from the five capital/municipality cities namely, Chengdu, Chongqing, Changsha, Hangzhou, and Shanghai, covering the upper, middle and downstream regions of the Yangtze River. The distribution of the sample size of building construction ages is consistent with that of the China National Bureau of Statistics, which confirms the representativeness of this survey. The main outcomes from the survey can be summarized as follows:

(1) There is a high correlation between the size of the family structure and the size of dwelling; the more family members, the bigger the dwelling;

(2) The winter heating for homes does not reach full capacity. Only 63% reported heating the bedroom and 43% reported heating living rooms.

(3) Air conditioners (called AC) is the major device that is popularly used for winter heating in the hot summer and cold winter climate zone, indeed AC accounts for 63% of bedroom and 58% of living room heating. The remaining uses include a large variety of devices e.g. under-floor heating, oil heaters, radiators, electric heaters, etc., but the proportions are relatively low, about 1% (electric blanket) to14% (infrared heater).

(4) Urban residents in this region heat their home in ways that are highly dependent on their occupancy of space. This means the heating usage is intermittent as a kind of 'part-time-part-space', which is completely different to the heating mode involving a central heating system with continuing operation in northern China.

(5) The temperature setting-point of AC is around 26^{o}C, with statistically significant differences among different family structures. This does not mean the room temperatures reach 26 ^{o}C. The high temperature setting is mainly due to the AC usage

patterns: 80% of occupants set a constant temperature in the living room but tended to set a timing mode (37%) or use the sleep mode (29%) in the bedroom.

(6) People living in this region have a strong demand for fresh air, with nearly half of occupants opening the windows to provide a gap in winter when using heating. The proportions of window close/open increase with increasing temperature setting points when the AC is operating, indicating a coupled interaction of heating-related behaviors by occupants.

(7) The two-step clustering analysis classifies three clusters of heating-related behaviors using seven significant factors: occupants in Cluster 1 only or mainly used AC in the evening, matching to a shorter time when the AC is on and keeping windows closed when using AC, which indicated a frugal heating use behavior. Cluster 2 and Cluster 3 have higher proportions of window opening when using AC and people in Cluster 3 depended heavily on AC, using it as long as they are in the living room and keeping the AC on during the whole night, which indicates a more luxurious behavior for AC household heating.

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Questionnaire contents

Part 1: Questions of Basic information of respondents and buildings

Questions of Basic building information

Q1: Family structure (single choice):

○ Single

○ Couple

○ Couple with a Child

○ Couple with Child and the elderly

○ Others ________________ *

Q2: Home time (multiple choice):

☐ Morning (7:00-12:00)

☐ Noon (12:00-14:00)

☐ Afternoon (14:00-18:00)

☐ Evening (18:00-7:00)

Q3: Dwelling structure (single choice):

○ One bedroom

○ Two bedrooms

○ Three bedrooms

○ Four bedrooms

○ Others ____________ *

Part 2: Questions of Heating behaviors

(*the following behaviors were limited to weekdays)

Section 1. Questions for Bedroom

Q4: Whether or not you heat your bedroom? *【if not, please skip】*

○ Not at all

○ If Yes, please tick the box that is relevant to your heating measures:

☐ Air conditioning, temperature, with setting-point _______ °C*

☐ Underfloor heating, with

temperature setting-point_______ °C when room occupied*;

temperature setting-point_______ °C when nobody at home*;

(If you turn off underfloor heating when nobody is in the bedroom please write "0") (multiple choice)

☐ Oil heater

☐ Heating radiator

☐ Infrared heating

☐ Fan heater

☐ Electric blanket

☐ Other ________________ *

Q5: What is the status of door or window in your bedroom when heating is in operation? (single choice)

○ Closed

○ Open with a small gap

○ Open with a big gap

Q6: How do you set the air-conditioning operation mode? (single choice)

○ Sleep mode

○ Keep on until next day

○ Setting time shutdown_______ (how many hours) *

○ Don’t operate air conditioning

○ Other ____________ *

Section 2. Questions for Living Room *(*contains the *study)*

Q7: Do you heat your living room? *【if not, please skip】*

○ Not at all

○ Yes; Please tick the box that is relevant to your heating measures:

☐ air conditioning, setting-point was_______ ^{o}C*

☐ underfloor heating,

temperature set point _______^{o}C when room occupied*

temperature set point _______^{o}C when nobody at home*

(If you turn off underfloor heating when nobody is in the living room please write "0")
(multiple choice)

☐ Oil heater

☐ Heating radiator

☐ Infrared heating

☐ Fan heater

☐ Electric blanket

☐ Other ________________ *

Q8: Your family members' clothing adjustment behaviors: (single choice)

○ Adding clothes to reduce heating dependence

○ Relying on heating rather than clothing adjustment

Q9: The usual status of doors or windows in your living room when occupier heating is ‘On’: (single choice)

○ Closed

○ Open with a small gap

○ Open with a big gap

Q10: Occasions of air condition usage in the living room: (single choice)

(If heating mode doesn’t include air conditioning, this question can be skipped)

○ Use air conditioning as long as occasion room occupied

○ Use air conditioning when feeling cold

Q11: Habits of air condition usage in the living room: (single choice)

(If heating mode doesn’t include air conditioning, this question can be skipped)

○ Set a high temperature for rapid warming, then lower it when room heats up

○ Set constant temperature

○ Other__________________ *

Section 3. Questions for Fresh Air

Q12: The usual status of doors or windows in your bedroom when no heating: (single choice)

○ Closed

○ Open with a small gap

○ Open with a big gap

Q13: Your family members' habits of window operation: (single choice)

☐ Ventilation based on the weather

☐ Ventilation based on indoor air quality

☐ Ventilation based on daily habits