Keeping warm in Northern China: Do rural households benefit from clean heating policy?

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Abstract. Northern rural China experiences large heating demand during winter. To address carbon emissions and air pollution, the Chinese government has developed clean heating policies seeking to switch from traditional biomass to modern energy in this region. However, to what extent these policies register with rural households' living experiences is little researched. This study investigates households' practices to keep warm during winter and the indoor thermal environment in a village in northern China. Qualitative and quantitative data were gathered in a field study conducted in January 2022, the coldest month in a year. The data demonstrate that despite the possibility to connect to the village gas infrastructure and the general availability of electric heaters, solid-fuel stoves remain by large the most adopted heating method by households. Even so, households cannot afford to heat their homes to the government-prescribed 14°C benchmark for indoor temperatures. To cope with the cold, residents complement limited space heating by warming their bodies through clothes and hot drinking. These results indicate a gap between political expectations and rural households' practices regarding winter heating. This study can also act as a reference to other countries that are working on energy transition affecting low-income groups.

Keywords. Rural households, Cold regions, Indoor thermal comfort, Clean heating, Energy vulnerability

1. Introduction

Heating during winter is essential in northern China due to low temperatures and long winters (Zhi et al., 2017). In northern rural areas, most houses are not equipped with central heating (Duan et al., 2014). The Kang, stove, firewall, and radiator are common heating methods, with coal and biomass being used as primary energy sources for space heating (Zhu et al., 2020). This results in air pollution, health issues and excessive carbon emissions (Zhang et al., 2021). An average building energy consumption in northern rural China is 27.4 kgce/(m^{2}a) – where kgce stands for kilogram of standard coal (GB/T 2589-2020) – which is double of what is used in southern China (Juan & Weijun, 2018).

To reduce carbon emissions and mitigate air pollution, the Chinese government has been working on its clean heating policies. The most significant has been the Clean Heating Plan for Northern China in Winter (2017 – 2021) (NDRC, 2017). The plan envisages a shift towards clean heating energy sources including natural gas, biomass, electricity, clean coal, industrial waste energy, nuclear energy, and other renewable and sustainable energy.

The implementation of this plan has been buttressed by studies which have been mainly conducted from policy and technical perspectives, such as concerning: potential contribution of clean heating policies to mitigating air pollution (Li et al., 2021); evaluation of the implementation effectiveness of clean heating policies (Xie et al., 2022); novel clean heating techniques for clean heating in rural households in Northern China (Deng et al., 2021); evaluation of capital and operating costs for households using different heating options, such as air-source heat pumps with fan coils, electric resistance heaters with thermal storage, natural gas heaters and clean coal briquettes with improved stoves (Liu & Mauzerall, 2020).

A small body of research has studied the clean heating policies from the rural residents' perspective: household acceptance of clean heating (Liu et al., 2022) and their satisfaction with the clean heating program (Liu et al., 2021). Xie et al. (2022) point out that northern rural households have financial difficulty in paying energy bills regarding space heating during winter, demonstrating that this accentuates energy poverty among households with low income. However, little research can be found regarding rural households' heating behavior under these clean heating policies. To what extent do rural households benefit from these policies?

To answer this question, this study has investigated changes in energy infrastructures, rural households' heating activities and thermal comfort thresholds in a rural village during January 2022. By adopting mixed methods, this study documented the energy infrastructure used in this community, housing conditions and occupant demographics, energy types and devices regarding household space heating. It also investigated the indoor thermal environment in rural homes under different space heating regimes, measures adopted by the households to keep warm at different times of the day, and residents' indoor thermal sensation.

This study shows that rural households are indeed experiencing a transition from traditional biomass energy to electricity and natural gas for space heating in winter, but the uptake of clean heating energy is still low, most likely as a result of affordability issues. The reality on the ground also reveals multiple energy vulnerabilities in this community. This study thus contributes to a better understanding of rural households' heating practices from a social and technical perspective, evaluates clean heating policies and provides insights into the factors that contribute to the adoption of clean energy.

2. Methods

2.1 Research region and climate

The study was undertaken in a village in northern China, a rural community with approximately 200 households, in Liquan County, Shaanxi Province, which experiences high seasonal temperature fluctuations. Summer continues from May to August with temperatures averaging a daily high of 27°C and a low of 15°C, while winter begins in November and ends in February with average daily temperature varying from 3°C to 13°C. According to the design standard provided by the MOHURD (2013), this village is part of the 'Cold' Zone where the design indoor temperatures for living rooms and bedrooms in winter are 14°C. This figure was used as a benchmark in this study to assess results.

2.2 Household questionnaire survey, observations and unstructured interviews

A questionnaire survey was conducted with a sample of 64 households out of the total 137 households who were registered to reside in this community all year round, from September to November 2021. Participants were selected through probability sampling. The survey was carried out by the lead author who interviewed one adult household member at a time on behalf of the entire household. The information included participants' demographics, household size, property age, occupancy and space heating usage during winter with a focus on heating period, heating devices and fuel type. Besides, personal observations and unstructured interviews were conducted with participants and other villagers to contextualize information from the questionnaire and assess housing conditions as well as everyday energy infrastructures.

2.3 Thermal comfort survey combined with indoor environmental monitoring

A thermal comfort survey combined with indoor environmental monitoring began on the 28th December 2021 and ended on the 30th January 2022 with a randomly selected subsample of 30 houses. This survey used questionnaires to identify measures and tactics adopted by the household to stay warm, respondents' activity levels and thermal comfort perception by asking participants 'How do you feel at this moment?' offering answers using the ASHRAE's seven-point Likert scale (ASHRAE, 2013). Along with this survey, indoor air temperature and relative humidity were collected with two HOBO MX1101 data loggers and one high-accuracy and quick response 2020 High-accuracy TL-500 handheld temperature and humidity meter.

Measurements together with the thermal comfort survey were undertaken in the main room (master room and living room) of six different homes every week. Thirty different homes were monitored in total, in groups of 6 with the monitoring happening in five consecutive weeks. In each week, data from six households was collected, one by one, at three times during different periods of the day (morning, afternoon and evening) for six consecutive days. Indoor sensors were placed 1m away from the heating source and close to the center of the main room.

2.4 Outdoor environmental monitoring and Heating Degree Hours

Simultaneously with the indoor environmental monitoring, outdoor environmental monitoring was carried out using a HOBO MX2301 data logger to collect outdoor air temperature and relative humidity with 30 mins intervals. The sensor was placed in a household's courtyard at the center of the village and was shaded against the sun.

Since the indoor environmental monitoring was conducted during five consecutive weeks, Heating Degree Hours (HDH), an indicator showing the effect of outside air temperature on building energy demand, was applied as a benchmark to investigate the comparability of each week monitored.

$$HDH = \frac{\sum(T_b - T_n)}{2} \quad (1)$$

HDH was calculated by Equation 1 using 48 temperature data points per day. T_b is the base temperature, which is set as 14°C, according to (Chen et al., 2021; MOHURD, 2013). T_n is the half-hourly outdoor temperature (n=1, 2, 3 … 48) of each monitoring day. Only positive temperature differences were taken, while the negative ones were set to null.

3. Results

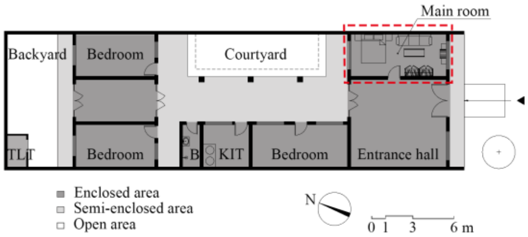
3.1 Housing and occupants' features

Dwellings in this village are single-story or two-story terraced houses with private courtyards and/or backyards built from 1980 but with 61% of them dating from the past two decades. Houses were designed and constructed by local builders and households on the rural homestead land. They are similar in outlook and have a brick masonry structure with prefabricated concrete and/or wooden framed roof. Due to the absence of sewerage, the toilet is either a dry toilet room built in the backyard and separated from other living areas or a flush toilet room with a seepage well underneath the courtyard to deal with wastewater.

A rural home usually has an enclosed, semi-enclosed and open area or courtyard (Figure 1). The semi-enclosed area acts as a walkway giving access to daily activities and additional bedrooms alongside a courtyard exposed to the outdoor environment. The enclosed area features a large entrance hall with the main room adjacent to it. The hall has multi-functions, such as parking agricultural vehicles or cars, packing, storing apples, corn or other agricultural products or holding family gatherings. The main room, of which the average size based on the survey is around 89m³ (3.3×6.9m area with 3.9m height), is normally where space heating happens during winter and therefore was selected to place the sensors.

Figure 1

A typical building layout



All surveyed houses are owner-occupied with an average household size of 3.4 people; 47% of them have 2 people. Most occupants (83%) are economically active. Almost all of them have family farming, but only half work solely in the agricultural sector (including apple, pear, cherry, jujube, wheat, corn, and landscape trees, of which apple farming takes the largest proportion). According to these respondents, agricultural activity can no longer bring sufficient income. The other half of households have full-time or part-time jobs in nearby areas while operating their farms.

3.2 Energy infrastructure for heating during winter

Electricity transmission lines, natural gas pipelines and smart electricity meters were all observed in this village. Each house has potential access to the main natural gas pipeline that was installed by the government in 2020 under the clean heating policies. Besides, the analysis revealed that the government offers gas boilers and different types of electric heaters together with discounts on energy bills (gas and electricity) through a subsidized clean heating scheme (Liquan Government Office, 2019) to encourage households to use natural gas or electricity for heating in winter. However, most houses (55 out of 64) were still not connected to the existing natural gas infrastructure due to the relatively high capital costs involving service to connect to the pipelines and relevant devices. In addition, not all households got electric heating systems through this attractive scheme.

Results from the questionnaire showed that electricity, natural gas, liquefied petroleum gas (LPG), coal, wood and solar energy were used to support household daily activities, such as cooking, lighting, etc. Space heating was provided by electricity, natural gas, coal and wood (that is free to collect from households' agricultural lands). Among all types of heating devices in homes, electric heating systems, including the air conditioning split system, convector heater and graphene electric heater, claimed to be used by 64% of the local households, followed by solid fuel stoves and Kangs (29%), a traditional heating method combined with a bed used in northern China, whilst the natural gas heater was the least voted heating method (8%).

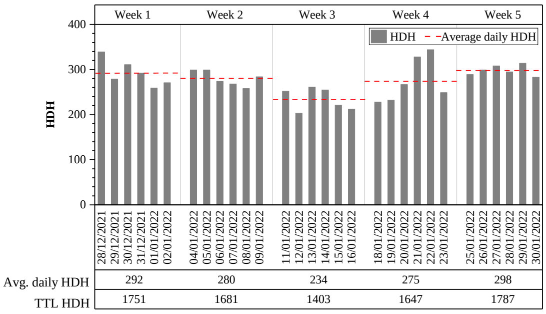
3.4 Outdoor environment setting the rationale for data analysis

During the monitoring period, the outdoor temperature varied from -4°C to +10°C with an average value of 3°C, and the outdoor relative humidity was in the range of 24% to 93%, averaging out at 61%. These conditions differed from statistical daily averages either showing a particularly cold period or insufficient data related to rural climates.

The total HDH of each week monitored, daily HDH and average values are presented in Figure 2, showing the smallest overall differences in average daily HDH between monitoring weeks 1 and 5 (1%), and weeks 2 and 4 (1%). As a result, these outdoor weather conditions were combined to group results for main rooms surveyed into three clusters, so the analysis of data coming from the monitoring phase could be undertaken considering differences in outdoor weather conditions. Cluster A included the 12 main rooms monitored in weeks 1 and 5. Cluster B included a set of 12 main rooms monitored in weeks 2 and 4, whereas cluster C included the 6 main rooms monitored in week 3. On average, the outdoor temperature and relative humidity of Clusters A, B and C were subsequently 1.9°C and 65%, 2.8°C and 67%, and 4.6°C and 40%.

Figure 2

Heating Degree Hours of each day in the five weeks monitored



3.5 Indoor temperature variations vs. main room heating regimes

Figure 3 displays indoor temperature ranges of main rooms under different space heating conditions, which were No heating (N), Stove heating with solid fuel (S), Clean heating with electricity (C - E) and Clean heating with natural gas (C - G) with their percentages of occurrences in the mornings, afternoons and evenings.

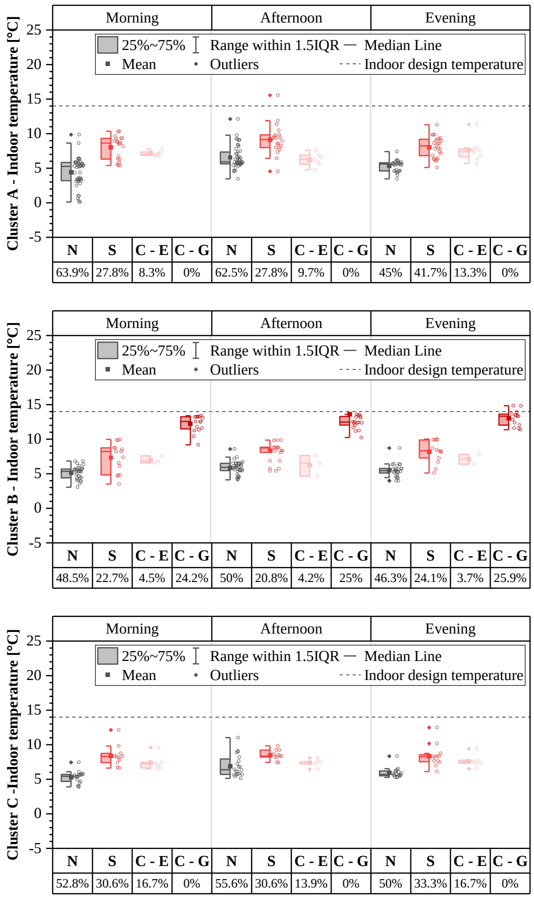
In Cluster A, the coldest period, around 63% of the main rooms monitored were not heated during daytime, but this was reduced by 19% at night. The adoption rate of stoves was the same in the mornings and afternoons but increased by 14% in the evenings, while that of electric heating systems rose by 5% from the mornings to the evenings.

In Cluster B around 48% of the main rooms monitored were not heated with a slightly increased figure for this regime in the afternoons, followed by a decrease of it in the evenings. The adoption rate of stoves decreased by 2% in the afternoons and then increased by 4% in the evenings. Electric heating system usage had a small decrease towards the evening (1%) whereas natural gas heating systems usage had a slight increase towards this period (2%).

In Cluster C, the warmest period, around 53% of the main rooms monitored were not heated during daytime, increasing by 3% in the afternoons but decreasing by 6% in the evenings. The adoption rate of stoves was the same in the mornings and afternoons but increased by 2% in the evenings, whereas that of electric heating systems was the same in the mornings and evenings but decreased by 3% in the afternoons.

Figure 3

Distribution of indoor air temperatures of main rooms under four space heating regimes in each cluster



Comparing different space heating regimes showed that, on average, around 53% of main rooms were not heated across the three clusters. Interestingly, cluster A, the coldest period, had the largest proportion of non-heated rooms during daytime. The reason for this is unclear. One hypothesis is that people could not afford to heat the main room for an extended period of cold wave, but this would need to be confirmed by a further analysis. Overall, households who participated in this monitoring predominantly heated their main room by using solid fuels, and only a few of them, coincidentally all monitored in Cluster B, were using natural gas.

On average, indoor temperatures of main rooms not heated were 8°C away from the benchmark (14°C), whereas those of main rooms heated with solid fuels, electricity and natural gas were respectively 6°C, 7°C and 1°C away from it. This shows that natural gas heaters seem to be the most successful heating method to meet the requirement of the design standard, despite being used by a small number of households.

Table 1

Indoor temperature variations of main rooms under four space heating regimes in each cluster recorded at all times

Type	Cluster A	Cluster B	Cluster C
N	9°C	4°C	7°C
S	7°C	7°C	4°C
C-E	3°C	3°C	3°C
C-G	N/A	6°C	N/A

In general, the widest temperature range was found among non-heated main rooms monitored in Cluster A, whereas temperature variations of main rooms monitored in the three clusters were the same when electric heating systems were used (Table 1).

Table 2

Average indoor relative humidity of main rooms under four space heating regimes in each cluster at all times

Type	Cluster A	Cluster B	Cluster C
N	60%	57%	46%
S	61%	54%	51%
C-E	67%	51%	60%
C-G	N/A	41%	N/A

The average indoor relative humidity (RH) ranged from 41% to 67% across all monitored main rooms, with the lowest RH found in main rooms having natural gas heaters (Table 2). Further analysis is needed to understand how each of these different systems were operated in relation to how their operation affected indoor temperature fluctuations.

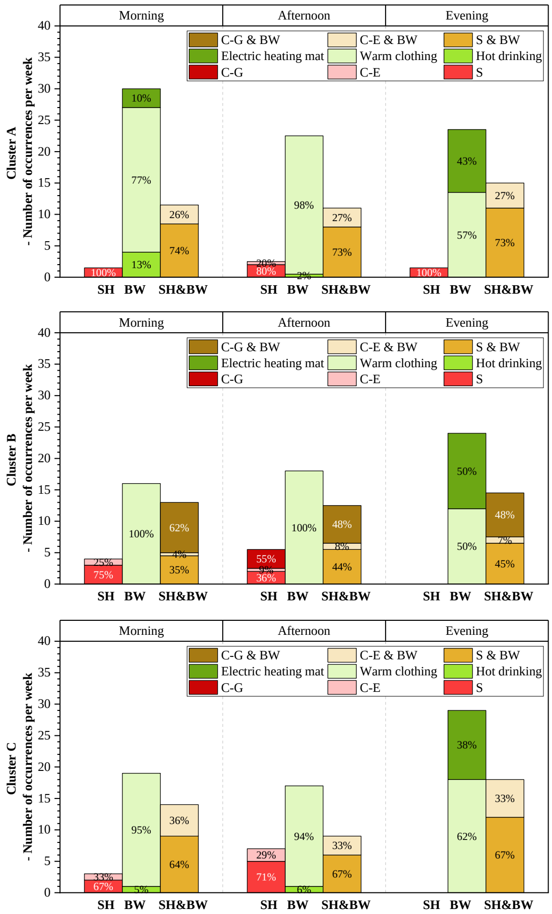
3.6 Measures adopted by the households to keep warm

Apart from the space heating measures (SH) shown in section 3.5, the thermal comfort survey also found rural households heavily rely on heating their bodies to keep warm during winter, primarily through warm clothing, with insulation levels between 1.61clo and 2.59clo (ASHRAE, 2004), hot drinking, and using electric heating mats. These body warming measures (BW) were adopted by rural households alone or together with SH.

Figure 4 shows SH and BW used alone and together during different times of the day in each cluster. The adoption rate of BW alone in all clusters was on average 63% whereas the combined SH&BW was on average 37%.

Figure 4

The usage of Space-heating and Body-warming methods at different times in each cluster



The most frequently used BW measure was warm clothing, followed by electric heating mats for bedding and hot drinking, such as tea, water and soup. Warm clothing was put on all day, while the electric heating mat was normally used at night but also used in the mornings during the coldest period (Cluster A). Rural residents usually had hot drinking in the daytime, showing a preference for the mornings.

The combined usage of SH and BW was around 35% in each cluster on average. Households tended to use SH and one body warming measure in most cases, especially in the warmest period (Cluster C). However, this was not sufficient on colder days when they combined up to three body warming measures (cluster A). Moreover, rural households usually had hot drinks when using solid fuel stoves or natural gas heaters, but they insulated their bodies with warm clothes when electric heating systems were used. This finding is in accordance with section 3.5, which shows among main rooms with space heating, those heated by electric heating systems reached the lowest average indoor temperature.

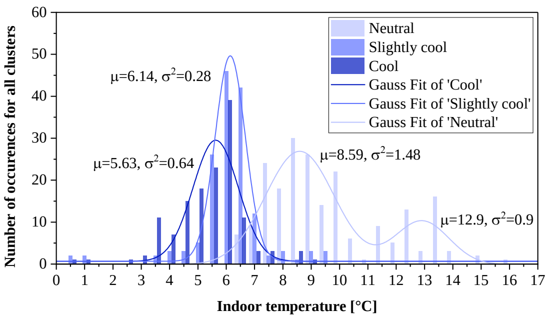
3.7 Occupants' thermal sensation

All the thermal sensation votes were in the range of -2 to 0 (Cool to Neutral), and no one voted -3 (Cold), or 1 to 3 (Slightly warm to Hot). The distribution of indoor temperatures shown in Figure 5 demonstrates this community is quite resilient to low temperatures, as people stated to feel 'Neutral' (41.7%), 'Slightly cool' (30.8%) and 'Cool' (27.6%) when queried about it.

Rural households claimed to feel 'Cool' when the indoor temperature fell between 4.8°C and 6.4°C, and they responded 'Slightly cool' when the indoor temperature increased to values between 5.6°C and 6.7°C. They felt 'Neutral' when the indoor temperatures were between 7.4°C and 9.8°C with a mean value of 8.6°C as well as between 12°C and 13.9°C with a mean value of 12.9°C. Combining the findings from section 3.5 with Figure 5, it is possible to see that mean values of 12.9°C were achieved in houses with natural gas heaters, where people stated they were always feeling 'neutral'. Mean values of 8.6°C reached in houses heated with solid fuels did not always achieve the same levels of comfort.

Figure 5

Distribution of indoor temperatures voted as 'Cool', 'Slightly cool' and 'Neutral'



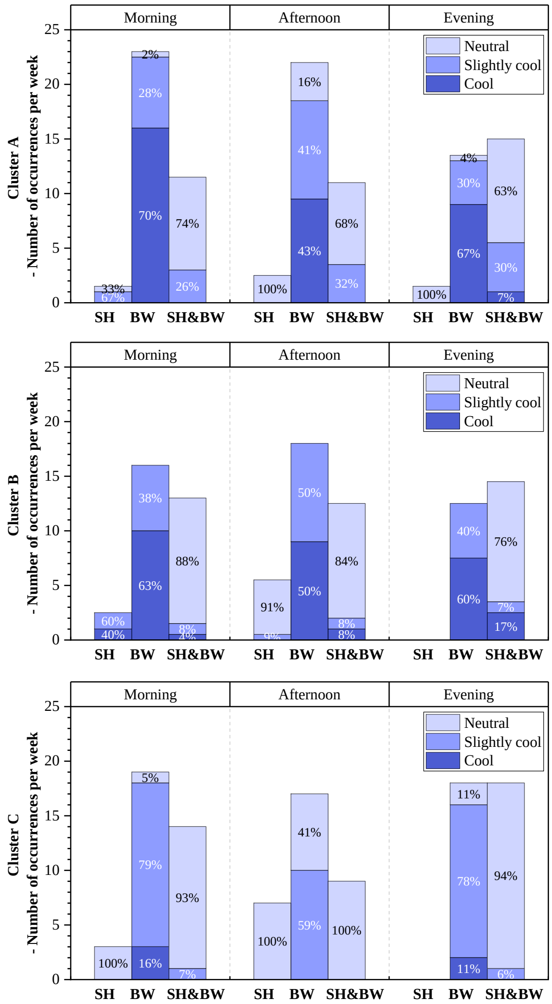
When combing thermal sensation with measures adopted to keep warm, Figure 6 shows that residents felt 'Cool' more often when using BW alone in all clusters, predominantly in the mornings. In contrast, by using SH alone or in combination with BW (SH&BW), occupants felt 'Neutral' more often in all clusters, especially in Cluster C.

Figure 6 shows that thermal sensation was also related to external temperatures, as the number of responses stating 'cool' using BW alone decreased from the colder to the warmer period (from cluster A to C). This is potentially explained by the housing layout, which forces occupants constantly to be exposed to outdoor temperatures when they need to access different parts of their house. Besides, by using BW alone, they felt 'Cool' more often in the mornings and 'Neutral' more often in the afternoons. This could potentially be explained by the increase in outdoor air temperatures in the afternoons, as well as the acceleration of bodily activities.

BW measures alone worked up to a point but could not cater for very low external temperatures. Further analysis is needed to establish proper thresholds for temperatures below which BW alone was not enough as well as to establish better connections between external temperatures and thermal sensation, especially considering houses with open layouts.

Figure 6

Thermal sensation votes at different times in each cluster



4. Discussion

Although a sponsored scheme was provided under the clean heating policies, including access to natural gas and a combo of gas boilers or electric heaters together with discounts for energy bills, there was still a low level of uptake for these heating systems in this village. The questionnaires showed that over half of the households had a heating preference for electric heaters, which is consistent with existing studies. Wang et al. (2019) and Liu et al. (2022) found that electric heating is the most popular heating method among rural households through questionnaires. However, rural households' actual heating practices during winter told another story. The solid fuel (coal and wood) stove was still the dominant method for space heating, while the electric heating system was the least used, and natural gas heaters were used by a small number of households for space heating. Rural residents mainly warmed their bodies at different times of the day without turning any space heating on, despite this tactic failing to meet their comfort demands.

This study only investigated household thermal perception without evaluating it through thermal preference, thermal comfort of thermal acceptance. Combinations of body warming and space heating measures were found, however, to be most successful at night. With these combinations, rural households could cope with indoor air temperatures of 9°C, much lower than the indoor temperature benchmark adopted in China (14°C). However, the benchmark refers to the usage of space heating alone, meaning that 9°C is not an indicative of indoor desirable temperature for comfort but a tolerable temperature when space heating is used together with body warming measures. In any case, this population shows a high tolerance for cold environments and consistently dresses in warm clothes. This can also be explained by their occupation and housing typology.

Most rural residents work in outdoor farming for most of their daytime, enabling them to get used to cold weather. Therefore, their thermal perception is likely to be highly influenced by the outdoor environment. This is also reflected by their daily interaction with the outdoor environment at home. As a result of the building layout, rural residents have to move in and out of the main room to carry out different household activities. This exposes them constantly to temperature differences between indoors and outdoors, as well as heated and unheated rooms, which they state preferring to avoid.

These hybrid heating practices, predominance in adopting body warming measures and low uptake of clean heating systems, even when having the equipment installed, show that rural households in this community experience low expectations of thermal comfort which could be influenced by income (Han et al., 2009). Section 3.1 shows most households operate family farms that could bring them little income, especially when they are older and the household size is reduced. Among households that did not heat the space, half worked exclusively in agriculture, and those who could afford space heating still did not heat the whole house but the main room only. In addition, households that used solid fuel stoves for heating usually mixed coal and wood to reduce coal costs, and many households could not afford the capital investment to connect their houses with natural gas infrastructure, despite having it coming to their front door.

5. Conclusion

This study demonstrates that household behavior and lifestyle regarding space heating do not necessarily match policy expectations. The need to reduce the usage of solid fuel stoves was confirmed by the findings as this was the preferred space heating mode used by this community to keep warm in winter. However, space heating demands of the main rooms were mostly not met.

Households could not afford to heat their homes to reach the 14°C temperature benchmark. They relied on warming their bodies through clothes, hot drinking and electric heating mats, and combinations of these measures with limited space heating to cope with colder periods. They are likely to have a high tolerance to the cold environment, so that whenever it was physiologically possible, space heating remained off. Decreasing energy consumption would accentuate inequalities and energy poverty among these low-income groups, while further putting their health at serious risks.

The policy seems to be generally going in the right direction in terms of promoting the usage of natural gas heaters that proved to achieve indoor temperatures near the benchmark and provided an always 'neutral' thermal sensation vote. However, more is needed for this type of heating system to be adopted as a reality on the ground. The cost of installation remained a barrier as well as potentially the cost of gas bills. More studies are needed to determine rural households' affordability to gas switch and usage.

The policy seems, however, not to be successful in terms of promoting the use of electric heating systems. Most households had these systems already installed, meaning they could afford the replacement of heating equipment. However, they were likely experiencing difficulty in paying electricity bills. The potential of these systems to increase indoor temperatures up to the benchmark was unclear. These systems might be undersized, not properly operated or not affordable to operate. Further research is needed to gauge the efficiency of the different electric heating systems in indoor thermal sensation and room temperatures already in place in this community.

6. Acknowledgements

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