

Article

Indoor Overheating and Comfort-Oriented Heating Demand Reduction in Residential Buildings Across China's Severe Cold Regions

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Abstract

High indoor temperatures during the heating season increase the indoor–outdoor temperature difference and lead to additional heating demand in residential buildings in severe cold regions. However, the quantitative relationship between measured overheating and the potential for optimizing heating temperatures remains unclear. This study investigated case study dwellings in Ulanhot, Xilinhote, and Hailar using field measurements and EnergyPlus simulations to characterize indoor thermal conditions during the heating season and estimated the reduction in heating demand under comfort-oriented temperature adjustments. The results show that all primary occupied spaces exhibited elevated temperatures to varying degrees. The mean bedroom temperature in Xilinhote was 28.03 °C, and the temperature exceeded 28 °C for 63.89% of the monitored time. In Hailar, the mean temperatures in the living room and bedroom were 27.35 °C and 27.78 °C, respectively, and the corresponding time fractions above 26 °C were 90.21% and 95.57%. Under standardized prototype dwelling conditions, heating demand increased continuously with the setpoint temperature. Increasing the setpoint from 18 °C to 26 °C raised seasonal area-normalized heating demand from 64.14–98.18 to 103.39–143.50 kWh m^{−2} across the three cities. Reducing an overheating setpoint of 26 °C to 20 °C lowered seasonal heating demand by 23.94–28.94%; adjusting the measured temperature reference scenarios to 20 °C produced reductions of 24.49–33.60%. The district heating emission factor scenarios further showed that, when 20 °C temperature optimization was combined with the low-coal emission parameters, seasonal area-normalized operational carbon emissions decreased by 57.22–60.03% relative to the 2020 26 °C baseline. These findings indicate that comfort-oriented heating temperature adjustment can effectively reduce residential heating demand in severe cold regions and provide quantitative support for temperature optimization, refined control, and low-carbon operation in district-heated dwellings.



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Keywords: severe cold regions; indoor overheating; heating demand reduction; carbon emissions; comfort-oriented temperature adjustment

1. Introduction

Global climate change and emission reduction targets have drawn sustained attention to operational energy demand and carbon emissions in the building sector [1,2]. The building stock is large and has a long service life. Heating, cooling, ventilation, lighting, and appliances therefore create persistent operational energy demand. The International

Energy Agency reports that building operations account for approximately 30% of global final energy consumption and 26% of energy-related carbon emissions [3]. When construction activities are also included, buildings and construction accounted for approximately 32% of global energy demand and 34% of carbon dioxide emissions in 2023 [4]. In China, urbanization, growth in residential floor area, and rising expectations for indoor environmental quality have increased pressure on operational energy use. Long-term trends in building-sector emissions also show that controlling residential operational energy remains essential to the low-carbon transition [5]. Building energy efficiency is closely related to carbon performance. Reducing operational energy demand can therefore support emissions mitigation in the building sector [6]. Reducing operational energy use in buildings is therefore both a central research objective and a foundation for low-carbon development. For dwellings dominated by winter heating, it is particularly important to identify the drivers of heating demand and the scope for adjustment.

Among different climate zones, dwellings in severe cold regions generally have high heating demand for extended periods because of low outdoor temperatures and long heating seasons [7–9]. Weather conditions determine the baseline level of building heat loss. Temperature, humidity, and seasonal variation can substantially affect regional heating and cooling demand [10]. Previous studies have linked residential heating energy use in severe cold and cold regions to envelope performance, airtightness, heating system efficiency, energy sources, and occupant heating behavior [11–13]. Heating systems and regional energy structures also influence operational carbon emissions. District heating, fossil fuel heat supply, and system operation can amplify the environmental effects of heating demand [14,15]. Accordingly, previous research has examined envelope improvement, phase-change materials, solar heating, heat pumps, and other low-carbon heating technologies [16–18]. However, building characteristics and equipment efficiency alone cannot fully explain differences in actual operation. In district-heated dwellings, limited occupant control or excessively high operating temperatures may generate additional heating demand even when basic thermal conditions are satisfied [19]. Research therefore needs to look beyond heat-loss reduction and system efficiency. Actual indoor thermal conditions and operating temperatures should also be examined to identify avoidable demand caused by elevated indoor temperatures.

Indoor thermal comfort is another important determinant of residential heating demand. The indoor thermal environment is closely associated with occupant health, quality of life, and residential experience [20,21]. As research has shifted from steady-state assessments toward real residential settings, greater attention has been given to differences in thermal perception, behavioral adjustment, and adaptive responses [22]. Thermal comfort needs are not determined by indoor temperature alone. They are also affected by previous thermal experience, building operation, clothing, window opening, heating adjustment, and individual preferences [23–25]. Field studies in severe cold regions show that residents may adapt through clothing, window opening, spatial choice, and heating adjustment during winter [24,26]. Field evidence and thermal comfort databases further indicate that acceptable temperature ranges vary across climates, building types, and populations [27,28]. Reviews have also identified a trade-off between thermal comfort requirements and building energy use. Excessively high or low comfort setpoints can alter operational energy demand [29]. A single fixed setpoint may therefore fail to represent long-term thermal adaptation in severe-cold-region dwellings. Adaptive thermal comfort theory can do more than determine whether minimum thermal requirements are met. It can also help identify excessive operating temperatures and support comfort-oriented heating scenarios [30].

Building on advances in thermal comfort research, recent studies have examined interactions among comfort requirements, heating setpoints, and building energy use [31,32].

Greater winter comfort expectations generally correspond to higher heating setpoints. These setpoints increase the indoor–outdoor temperature difference and heating demand [33]. Clothing, window opening, heating adjustment, and other occupant behaviors can modify this relationship. They can also produce different demand levels under otherwise similar climatic and building conditions [30]. Outdoor climate determines the baseline load. The response to a setpoint change may therefore vary with climatic severity, heating season length, and load timing [34,35]. Control methods, setpoint recommendations, and operational optimization frameworks increasingly seek to balance comfort and energy use [31,32]. A detailed comparison of representative studies is provided in Table A1. Previous studies have examined indoor thermal comfort, occupant behavior, heating control, district heating operation, and building sector decarbonization in cold climate residential buildings, including international studies from Europe and North America. Field studies have improved the understanding of indoor thermal conditions and adaptive comfort, while simulation and control studies have evaluated heating setpoints, dynamic heating operation, and low-temperature district heating strategies. However, few studies have directly linked measured indoor overheating in occupied dwellings with standardized setpoint scenarios, heating demand reduction potential, and operational carbon emission mitigation. This gap limits the assessment of comfort-oriented temperature adjustment in district-heated dwellings in China’s severe cold regions.

This study addresses these gaps by integrating case-based field measurements, standardized prototype simulation, and operational carbon emission assessment. Measured indoor temperatures from dwellings in Ulanhot, Xilinhote, and Hailar were used to characterize heating-season overheating and establish reference scenarios reflecting actual indoor operating temperatures. A standardized prototype dwelling was then simulated in EnergyPlus under heating setpoints of 18 °C, 20 °C, 22 °C, 24 °C, and 26 °C to isolate the effects of climate and setpoint temperature on heating demand. District heating emission factor scenarios were further applied to assess the potential reduction in operational carbon emissions. The main contribution of this study is the translation of measured overheating conditions into comparable heating setpoint scenarios, the quantification of heating demand reduction under standardized building conditions, and the connection of demand-side temperature optimization with the decarbonization of district heating.

2. Methods

2.1. Research Design and Study Area

This study combined field measurements with simulation to evaluate indoor thermal conditions and heating optimization potential in residential buildings in severe cold regions. First, measured indoor temperatures from dwellings in Ulanhot, Xilinhote, and Hailar were used to characterize heating season conditions, high-temperature exposure, and spatial differences. Second, a standardized prototype dwelling was developed in EnergyPlus. Building geometry, envelope properties, internal gains, infiltration, and operating schedules were held constant. Weather data and heating setpoints were then varied by city to evaluate the effects of climate and heating control on heating demand and the potential for temperature adjustment.

Hailar (49.20° N, 119.70° E), Xilinhote (43.94° N, 116.09° E), and Ulanhot (46.08° N, 122.08° E) have Köppen climate classifications of Dwb, BSk, and Dwa, respectively. Figure 1 shows marked differences in daily maximum and minimum temperatures among the three cities in January 2026. In Hailar, daily maxima ranged from −27 °C to −19 °C, and daily minima from −36 °C to −28 °C. The corresponding ranges were −18 °C to −8 °C and −29 °C to −21 °C in Xilinhote. In Ulanhot, they were −13 °C to −8 °C and −23 °C to −16 °C. These values form a clear gradient of winter climatic severity. The heating season

lasted 212 days in Hailar and Xilinhote and 182 days in Ulanhot. Hailar therefore experiences the lowest temperatures with a long heating season. The three cities represent residential heating conditions in severe-cold subzones 1A, 1B, and 1C, respectively. They were selected to support a comparative analysis across this climatic gradient.

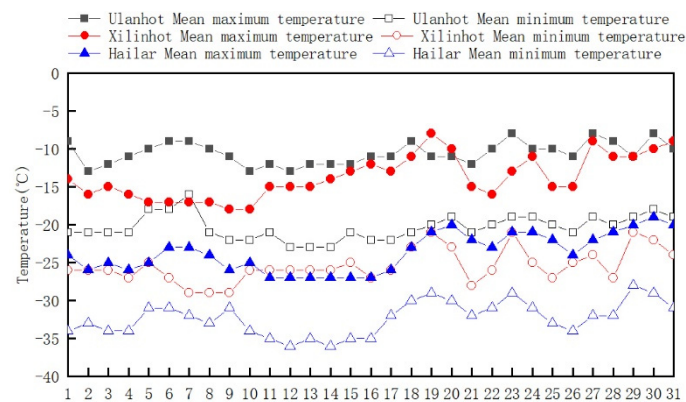


Figure 1. Distribution of daily outdoor temperatures in the three cities in January.

2.2. Case Study Dwellings and Indoor Thermal Environment Measurements

Figure 2 shows the locations of the case study dwellings and their residential communities in Ulanhot, Xilinhote, and Hailar. All three dwellings were located in occupied residential communities and had clear residential functions and stable heating operation. The cases were therefore used as case study dwellings to reflect indoor thermal conditions under routine occupancy during the heating season, rather than as statistically representative samples of the residential building stock in each city.



Figure 2. Study area and case study dwelling locations.

The dwellings were selected because they were located in the target severe-cold subzones, were occupied under routine residential use during the heating season, had stable district heating operation, and allowed continuous monitoring in the main occupied rooms. The basic information of the three monitored dwellings is summarized in Table 1. This information supports the comparison of indoor thermal conditions among the cases.

Continuous indoor thermal environment monitoring was conducted in the three dwellings from 1 January to 31 January 2026. The main parameters were indoor air temperature and relative humidity, measured using the WSZY-1 Temperature and Humidity

Self-Recording Instrument. Sensors were placed in primary occupied spaces, including living rooms and bedrooms, to capture conditions under routine occupancy. Additional sensors were installed in kitchens, bathrooms, or near windows to support analysis of spatial differences. The main analysis focused on living rooms and primary bedrooms. Details of the monitoring setup and instrument specifications are summarized in Table 2.

Table 1. Basic information of the three measured dwellings.

Case	City	Building Use Type	Floor	Rooms	Orientation	Areas (m ²): Floor/Exterior Wall/Window	Heating System
A	Hailar	Residential	3	2 bedrooms, living room, kitchen, bathroom	South–north	78.73 /97.49 /16.86	Centrally controlled
B	Xilinhot	Residential	4	2 bedrooms, living room, kitchen, bathroom	South–north	112.00 /105.92 /24.00	Centrally controlled
C	Ulanhot	Residential	3	2 bedrooms, living room, kitchen, bathroom	South–north	92.30 /73.43 /16.62	Centrally controlled

Table 2. Monitoring setup and instrument specifications.

Item	Description
Monitoring period	1 January to 31 January 2026
Monitored dwellings	Cases A, B, and C
Main monitored spaces	Living rooms and bedrooms
Additional monitored spaces	Kitchens, bathrooms, or near-window locations, depending on room layout
Measured parameters	Indoor air temperature and relative humidity
Instrument	WSZY-1 Temperature and Humidity Self-Recording Instrument
Measuring range	Temperature: −40–100 °C; relative humidity: 0–100% RH
Accuracy	Temperature: ±0.5 °C; relative humidity: ±3% RH
Recording interval	5 min
Data type	Automatically recorded values at 5-min intervals

2.3. Data Processing and Thermal Environment Indicators

The raw monitoring data were processed using a consistent procedure that included outlier identification, removal of invalid records, and sensor classification. Data from primary occupied spaces, such as living rooms and bedrooms, were prioritized to ensure consistent comparisons among cities. Measurements from kitchens, bathrooms, and near-window locations were used only to examine spatial differences. They were not included in the primary city-level comparison.

Minimum and maximum indoor air temperatures were determined from the original 5-min records before temporal averaging, whereas hourly and daily mean values were calculated for temporal trend analysis. This distinction was used to avoid smoothing short-term temperature extrema when reporting the measured temperature range.

For each sensor and city, valid records were used to calculate the mean temperature, observed maximum and minimum values, standard deviation, 5th–95th percentile range, and 24 h hourly mean indoor temperature. The observed maximum and minimum values were taken from the screened valid records, while the 5th–95th percentile range was used to describe the main distribution of measured indoor temperatures and reduce the influence of isolated extreme values. High-temperature exposure was quantified as the percentage of valid measurement time during which indoor air temperature exceeded 24 °C, 26 °C, and

28 °C. These indicators identified elevated indoor temperatures during the heating season. They also informed the subsequent definition of heating temperature scenarios.

2.4. Prototype Dwelling Heating Scenarios and Simulation Outputs

The prototype dwelling was developed using SketchUp, OpenStudio, and EnergyPlus. The three-dimensional geometry was first created in SketchUp. OpenStudio was then used to define thermal zones and specify envelope performance, internal gains, air infiltration, and operating schedules. EnergyPlus dynamically calculated heat transfer and indoor thermal responses using the heat-balance method. An Ideal Loads Air System was used to obtain heating demand under each climate and setpoint scenario. Table 3 summarizes the main model parameters.

Table 3. Main parameters of the prototype dwelling model.

Category	Parameter	Setting
Geometry	Floor area/volume	118.35 m ² /360.74 m ³
	Ceiling height	3.05 m
	Thermal zoning	Seven spaces combined into one thermal zone
Envelope	Space areas	17.52, 55.89, 18.54, 3.72, 3.72, 3.12, and 15.84 m ²
	Exterior wall area	Gross: 71.71 m ² ; net: 55.51 m ²
	Exterior wall U-value	0.340 W/(m ² ·K)
Window	Interior wall/floor/ceiling U-values	1.595/0.986/1.105 W/(m ² ·K)
	Window area by orientation	North: 8.10 m ² ; South: 8.10 m ² ; East/West: 0 m ²
	Window-to-wall ratio	Total: 22.59%; North: 27.26%; South: 23.94%
Air exchange	Window U-value/solar heat-gain coefficient	1.984 W/(m ² ·K)/0.452
	Infiltration	0.000226568 m ³ /(s·m ²), approximately 0.162 h ^{−1}
	Occupant density	30.0 m ² /person
Internal gains	Lighting/equipment power density	4.090/3.875 W/m ²
	Heating system	Ideal Loads Air System
	Simulation timestep and duration	10 min, full year (8760 h)
Weather	Weather file source	CSWD; Hailar example: WMO 505270

The prototype dwelling was used as a standardized reference model rather than as a direct representation of the three measured dwellings. The same geometry, envelope properties, internal gains, infiltration settings, and schedules were used in all city simulations. Only weather files and heating setpoints were varied. This setup allowed the effects of climate conditions and indoor temperature control on heating demand to be compared under consistent model assumptions. A constant infiltration rate was used to keep air-exchange conditions consistent across cities and setpoint scenarios, avoiding additional uncertainty from variable infiltration modeling. Solar heat gains through windows were calculated by EnergyPlus using the weather file solar radiation data together with the window orientation, window area, and solar heat gain coefficient specified in the prototype model.

Weather data for Ulanhot, Xilinhote, and Hailar were used in separate simulations. Heating system operation was scheduled according to the heating season in each city. Standardized setpoints of 18 °C, 20 °C, 22 °C, 24 °C, and 26 °C were evaluated. Additional scenarios matched the mean measured indoor temperatures: 24.84 °C for Ulanhot, 27.40 °C for Xilinhote, and 27.57 °C for Hailar. Together, these scenarios represented a range of heating control conditions, from basic requirements to observed overheating conditions.

Within each city, only the heating setpoint was changed across temperature scenarios. Building geometry, envelope properties, internal gains, infiltration, weather data, and operating schedules remained unchanged. The outputs included hourly indoor air temperature, hourly heating load, monthly heating demand, total seasonal heating demand, heating demand per unit floor area, and mean daily heating demand per unit area. Hourly outputs

were used to examine short-term dynamic responses in indoor temperature and heating load. Daily outputs were used to evaluate day-to-day variability and outdoor-temperature response, whereas monthly or seasonal indicators were used only as cumulative or statistical summaries for heating demand and reduction potential comparisons. Therefore, aggregated monthly and seasonal indicators were not interpreted as instantaneous or short-term dynamic values. The daily area-normalized indicator reduced the effect of different heating season lengths on intercity comparisons. Relative differences between each temperature scenario and its baseline were then used to evaluate the potential reduction in heating demand.

2.5. Emission Factor Scenarios and Accounting Method

To assess how changes in heat supply emission intensity affect operational carbon emissions during the residential heating season, this study introduced district heating decarbonization scenarios as sensitivity parameters. Liu et al. [36] developed high-coal, medium-coal, and low-coal scenarios for 2030 considering district heating technology substitution and carbon lock-in associated with coal-fired combined heat and power. Following their scenario logic and corresponding emission intensities, this study used 112 kg CO₂/GJ in 2020 as the baseline and 95, 84, and 63 kg CO₂/GJ in 2030 to represent slower, moderate, and faster district-heating decarbonization, respectively. These values were used only as exogenous sensitivity parameters to represent the possible range of carbon emission outcomes under different levels of heat supply decarbonization. They do not represent the actual or projected heat source structures of the three cities. The uncertainty of these future emission factors mainly arises from the pace of heat source substitution, the coal share in combined heat and power, renewable and waste heat integration, and district heating network efficiency. The same emission factors were applied to all three cities to control the heat supply assumptions and highlight differences in heating demand caused by climate conditions and heating setpoints.

Emissions from purchased heat were calculated by multiplying activity data by an emission factor. The GHG Protocol includes purchased steam, heat, and cooling in indirect energy emission accounting and states that regional average emission factors should reflect the heating fuel mix and conversion efficiency. Because the EnergyPlus output District_Heating_Water_kWh already represents the amount of district heat purchased by the building, seasonal operational carbon emissions per unit floor area were calculated as follows without applying an additional heating system efficiency conversion:

$$C_A = \frac{E_h}{A} \times 0.0036 \times EF$$

where C_A is the seasonal operational carbon emission per unit floor area (kg CO₂/m²), E_h is the purchased district heating energy (kWh), A is the floor area (m²), 0.0036 converts kWh to GJ, and EF is the district heating emission intensity (kg CO₂/GJ). Industrial waste heat, large heat pumps, renewable heat sources, and improvements in network efficiency are important directions for decarbonizing district heating. In this study, different emission intensities were used as unified supply side scenario parameters to support supplementary discussion of how heat supply decarbonization affects estimates of operational carbon emissions. Compared with studies that mainly focus on the evolution of district heating technology portfolios and infrastructure, this analysis emphasizes the building demand side, namely changes in heating demand under different severe-cold climate conditions and heating setpoints. Introducing heat supply emission intensity scenarios further allows the relative influence and potential combined effects of demand-side temperature optimization and supply-side emission factor reduction on carbon emission reduction to be discussed.

3. Result

3.1. Measured Indoor Thermal Environment in the Three Cities

Figure 3 summarizes the measured indoor thermal conditions in the primary occupied spaces during the heating season. Figure 3a shows the mean temperatures, 5th–95th percentile ranges, observed minimum and maximum values, and the checked high extreme value in living rooms and bedrooms. Figure 3b quantifies the percentage of valid measurement time above 24 °C, 26 °C, and 28 °C. All three dwellings exhibited elevated temperatures to varying degrees. These conditions differed not only in mean temperature but also in variability and the duration of high-temperature exposure.

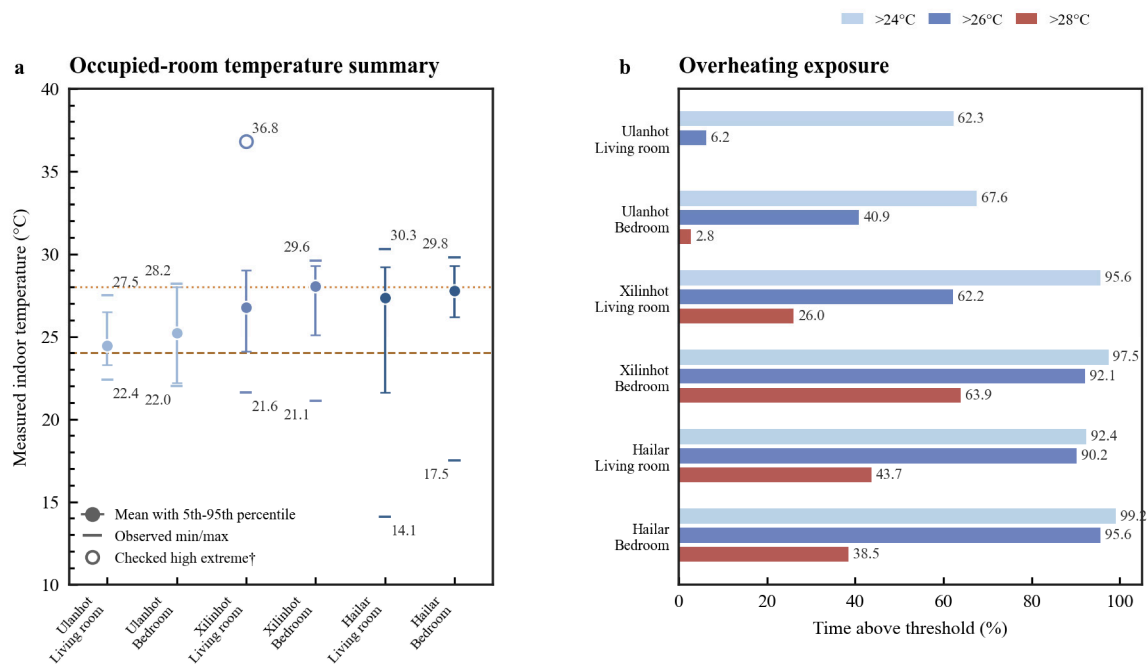


Figure 3. Measured indoor thermal conditions and overheating exposure in the primary occupied spaces of the three case-study dwellings. (a) Occupied-room temperature summary, including mean values, 5th–95th percentile ranges, and observed minimum and maximum values. (b) Time above 24 °C, 26 °C, and 28 °C.

Ulanhot exhibited relatively moderate overheating. Mean temperatures were 24.46 °C in the living room and 25.22 °C in the bedroom. Both spaces had mean temperatures at or above 24 °C, but their exposure above 26 °C differed markedly. The living room exceeded 26 °C for only 6.25% of the monitored time, compared with 40.86% in the bedroom. Overheating in this dwelling was therefore localized and intermittent rather than persistent throughout the entire dwelling. Xilinhot showed a general upward shift in indoor temperature. The mean bedroom temperature reached 28.03 °C, and the temperature exceeded 28 °C for 63.89% of the monitored time. The high extreme value in the Xilinhot living room was checked against the original record and is marked separately in Figure 3a. Therefore, the interpretation focuses mainly on the mean values, 5th–95th percentile ranges, and threshold exceedance percentages rather than on this single extreme value. This high-temperature state was sustained rather than caused by a few extreme peaks. This result suggests sustained overheating in the bedroom, which may be related to elevated heat supply, limited room-level regulation, envelope characteristics, or occupant behavior.

The Hailar dwelling showed more stable and widespread high-temperature exposure. Mean temperatures were 27.35 °C in the living room and 27.78 °C in the bedroom. Temperatures exceeded 26 °C for 90.21% and 95.57% of the monitored time, respectively. The primary occupied spaces therefore remained within a high-temperature range during most

of the monitoring period. Unlike the localized overheating in Ulanhot and the pronounced bedroom overheating in Xilinhote, Hailar showed more persistent and spatially consistent overheating. Despite its colder climate, the dwelling did not operate at a lower indoor temperature. Instead, it maintained a high indoor thermal level.

Figure 3a,b show that indoor temperatures did not simply decrease as outdoor climatic severity increased. The primary occupied spaces in Xilinhote and Hailar experienced high proportions of high-temperature exposure. This pattern suggests excessive heat supply or elevated temperature settings during actual operation. Exposure was particularly pronounced above the 26 °C and 28 °C thresholds in the Xilinhote bedroom and the main spaces in Hailar. These dwellings therefore have substantial potential for heating temperature optimization. The measurements reveal heating season overheating in severe-cold-region dwellings. They also provide an empirical basis for the setpoint scenarios and the subsequent assessment of heating demand reduction.

3.2. Seasonal Distribution of Heating Demand and Response to Indoor Setpoints

To compare heating demand across climates, a uniform setpoint of 22 °C was first used as a standardized condition. This approach removed the effect of differences in actual indoor temperature. All three cities showed a pronounced seasonal concentration of heating demand (Figure 4). Monthly demand increased from the beginning of the heating season, peaked in January, and declined as outdoor temperatures rose. Hailar maintained the highest demand throughout the heating season, reaching 27.5 kWh m⁻² in January. The January peaks were 23.1 kWh m⁻² in Xilinhote and 19.8 kWh m⁻² in Ulanhot. October and April contributed relatively little to seasonal demand. Heating loads were therefore concentrated in the coldest period from December to February.

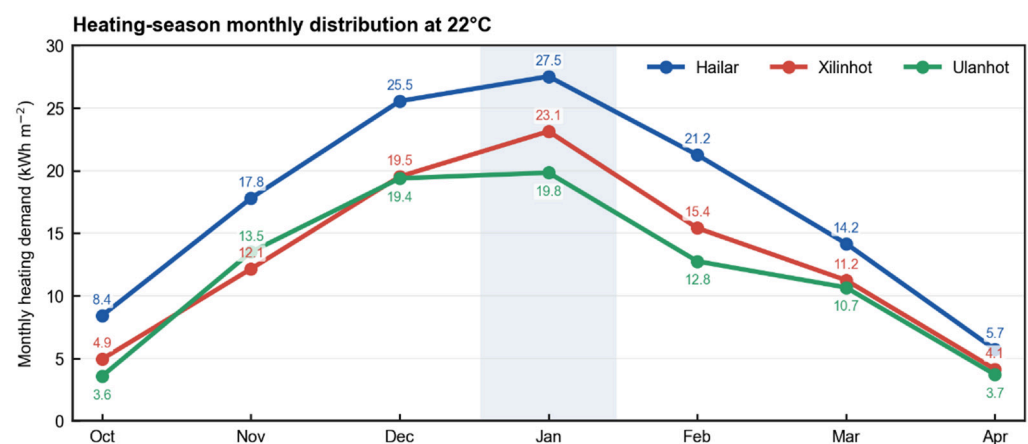


Figure 4. Seasonal distribution of heating demand in the three cities at a 22 °C setpoint.

The intercity differences show that heating demand depends on both heating season length and winter climatic severity. Hailar had lower outdoor temperatures and a longer heating season. Its total seasonal demand and peak month demand were therefore higher than those of the other cities. Xilinhote and Ulanhot had similar heating season lengths, but January demand was substantially higher in Xilinhote. Outdoor climatic severity thus remained an important determinant when heating season lengths were similar.

Area-normalized heating demand increased with the indoor setpoint in all three cities, while the city ranking remained unchanged (Figure 5). Increasing the setpoint from 18 °C to 26 °C raised seasonal demand from 98.18 to 143.50 kWh m⁻² in Hailar. Demand rose from 69.95 to 112.53 kWh m⁻² in Xilinhote and from 64.14 to 103.39 kWh m⁻² in Ulanhot. In the measured temperature reference scenarios, demand reached 152.74, 120.44, and 97.53 kWh m⁻², respectively. The mean measured temperatures in Hailar and Xilinhote

exceeded 26 °C, so their demand was greater than under the standardized 26 °C condition. The measured temperature in Ulanhot was slightly above 24 °C, and its demand fell between the 24 °C and 26 °C scenarios.

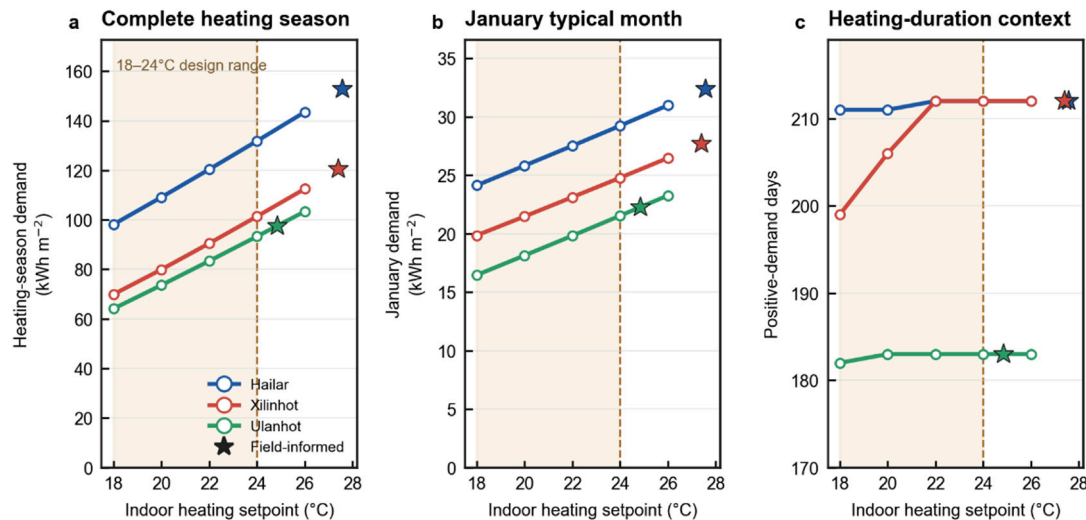


Figure 5. Heating demand response to indoor setpoints at different temporal scales: (a) complete heating-season demand; (b) January heating demand; and (c) heating-duration context, expressed as the number of positive-demand days.

The January results were consistent with those for the complete heating season. Across the 18–26 °C setpoint range, January demand was 24.14–30.98 kWh m⁻² in Hailar, 19.86–26.48 kWh m⁻² in Xilinhot, and 16.47–23.27 kWh m⁻² in Ulanhot. The measured-temperature reference scenarios yielded 32.36, 27.67, and 22.27 kWh m⁻², respectively. Heating demand in all three cities was therefore strongly affected by the indoor setpoint. Observed overheating further increased demand. Adjusting elevated operating temperatures to a reasonable range is consequently an important strategy for reducing residential heating demand in severe cold regions.

3.3. Temporal Characteristics of Heating Load and Response to Outdoor Temperature

At the uniform 22 °C setpoint, the mean hourly heating load profiles for January showed clear diurnal patterns (Figure 6a). Loads were higher at night and in the early morning and lower in the afternoon in all three cities. Heating demand therefore remained sensitive to daily outdoor-temperature variation and building heat loss. Hailar had the highest hourly load throughout the day. Its load remained approximately 5.0–5.3 kWh in the early morning and decreased to only about 3.3 kWh in the afternoon. This profile reflects persistently high demand under a severe cold climate. Xilinhot had an intermediate load, with a profile similar in shape but lower than that of Hailar. Ulanhot had the lowest load and the largest afternoon decrease, reaching approximately 1.3 kWh. Its daytime load reduction was therefore greater.

The coefficients of variation of daily heating demand in January were 0.085 in Hailar, 0.178 in Xilinhot, and 0.105 in Ulanhot. This indicator describes daily variability relative to the mean demand. Hailar had the highest total load but relatively stable daily demand. Xilinhot showed the greatest day-to-day variability, while Ulanhot was intermediate.

Daily heating demand in January was strongly and negatively correlated with mean daily outdoor temperature (Figure 6b). The correlation coefficients were −0.984, −0.969, and −0.905 in Hailar, Xilinhot, and Ulanhot, respectively. All correlations were statistically significant ($p < 0.001$). Based on Fisher’s z transformation, the approximate 95% confidence intervals were −0.993 to −0.968 for Hailar, −0.985 to −0.936 for Xilinhot, and −0.954 to

−0.810 for Ulanhot. The slopes of the linear fits were −2.853, −2.521, and −2.927 kWh day^{−1} °C^{−1}. Thus, a 1 °C increase in mean daily outdoor temperature reduced daily heating demand by approximately 2.5–2.9 kWh. Ulanhot had the largest absolute slope and was the most sensitive to outdoor temperature variation. Hailar had a similar slope, but its demand remained high because January temperatures were consistently lower.

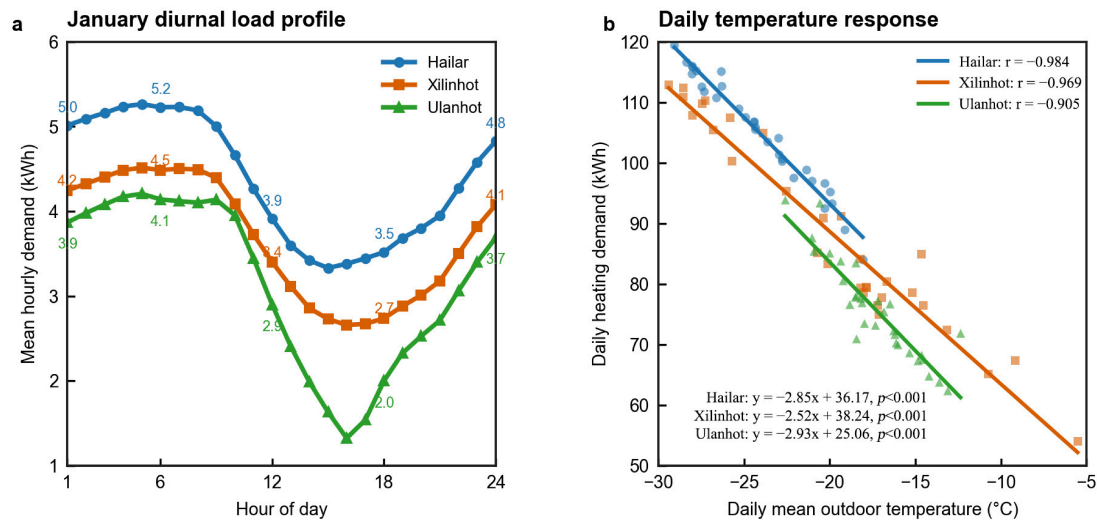


Figure 6. January load profiles and outdoor temperature responses under the uniform 22 °C setpoint. (a) January diurnal load profile, showing the mean hourly heating demand over a typical day. (b) Daily temperature response, showing the relationship between daily heating demand and daily mean outdoor temperature.

To further illustrate the temporal variation of the simulation results, Figure 7 presents the simulated hourly outdoor temperature, indoor air temperature, and heating demand in January under the 22 °C heating setpoint. The indoor temperature remained close to the setpoint because the Ideal Loads Air System supplied heating to maintain the control temperature. Hourly heating demand increased during colder outdoor periods and decreased when outdoor temperature rose. Hailar generally showed the highest hourly heating demand, followed by Xilinhote and Ulanhot, reflecting the influence of climate severity under the same prototype dwelling assumptions.

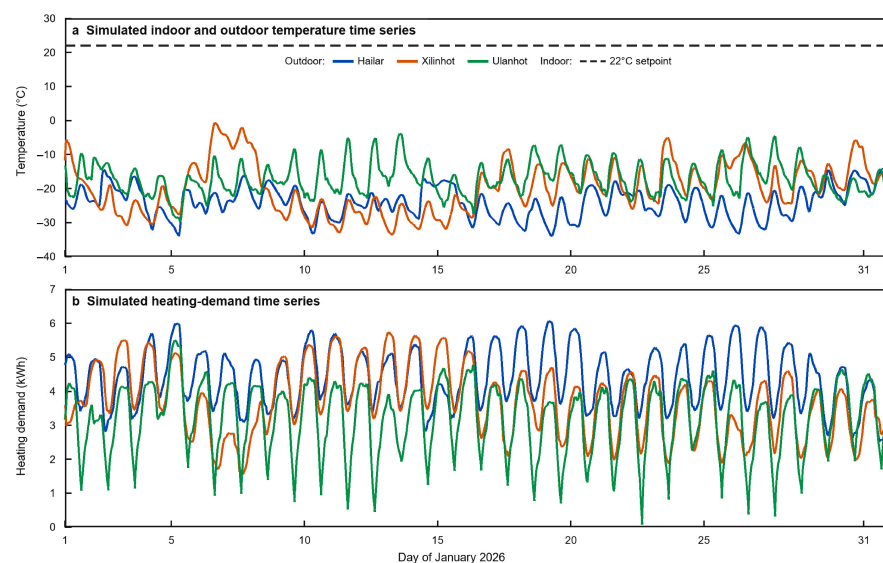


Figure 7. Simulated January hourly temperature and heating demand profiles at the 22 °C setpoint. (a) Simulated indoor and outdoor temperature time series. (b) Simulated heating-demand time series.

At the 22 °C setpoint, the 95th percentiles of non-zero heating load over the heating season were 5.33, 4.52, and 4.19 kWh in Hailar, Xilinhote, and Ulanhote, respectively. The corresponding January hourly peaks were 6.07, 5.74, and 5.49 kWh. The 95th percentile represents high load operating intensity while limiting the influence of isolated start-up peaks.

3.4. Potential Reduction in Heating Demand Under Comfort-Oriented Temperature Adjustment

The standardized analysis used 26 °C as the overheating baseline and 20 °C as the comfort-oriented target (Figure 8). Reducing the setpoint from 26 °C to 20 °C lowered seasonal heating demand by 23.94% in Hailar, 28.94% in Xilinhote, and 28.77% in Ulanhote. Temperature optimization could therefore reduce seasonal demand by approximately one quarter. The corresponding January reductions were 16.65%, 18.90%, and 22.05%. These values were lower than the seasonal reductions. The high baseline load during the coldest month therefore reduced the relative savings potential.

26°C to 20°C: Multidimensional benefits and seasonal reduction

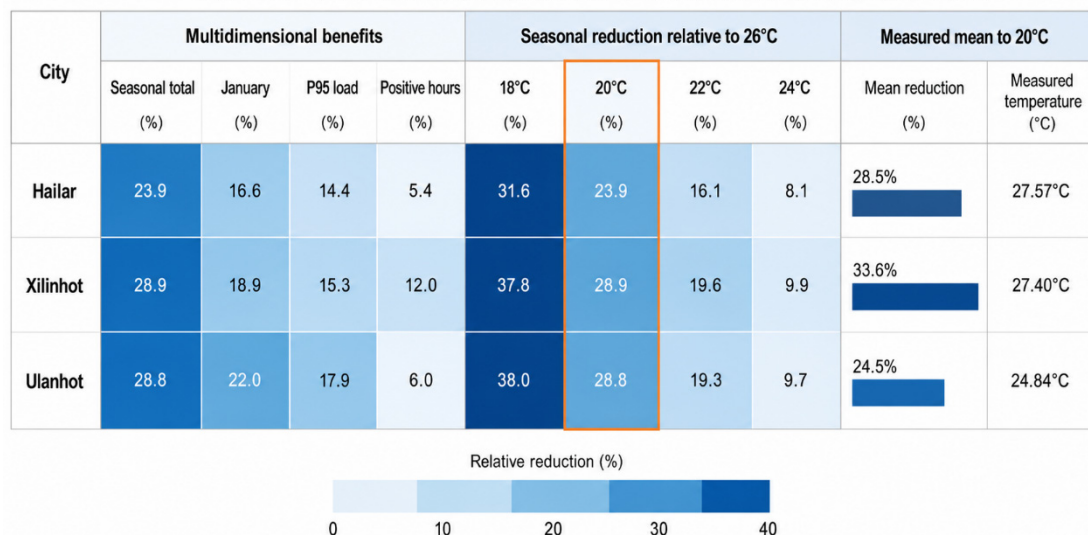


Figure 8. Potential reduction in heating demand under comfort-oriented temperature adjustment.

Temperature adjustment also reduced peak loads and operating hours. The 95th percentiles of non-zero seasonal heating load decreased by 14.37% in Hailar, 15.31% in Xilinhote, and 17.88% in Ulanhote. Non-zero load hours decreased by 5.38%, 12.03%, and 6.05%, respectively. Temperature optimization can therefore reduce cumulative demand, high-load intensity, and heating duration. Xilinhote showed the greatest reduction in operating hours. Demand reduction increased continuously as the target setpoint decreased. Across target temperatures from 24 °C to 18 °C, the reduction expanded from approximately 8–10% to 32–38%. Compared with lower setpoints, 20 °C provided a favorable balance between basic heating requirements and demand reduction.

The measured-temperature reference scenarios represented the observed overheating level in each case study dwelling. Adjusting these scenarios to 20 °C reduced heating demand by 28.54% in Hailar, 33.60% in Xilinhote, and 24.49% in Ulanhote. Intercity differences mainly reflected the initial operating temperature and the available adjustment range. Xilinhote had the highest measured mean temperature and therefore showed the greatest relative reduction. Overall, adjusting overheating conditions to 20 °C substantially reduced seasonal heating demand. Comfort-oriented indoor temperature control is therefore an important optimization strategy for dwellings in severe cold regions. These results represent relative demand reduction potential under standardized prototype dwelling conditions.

They should not be interpreted as absolute energy use estimates for specific dwellings or cities.

3.5. Operational Carbon Emission Results

Under the 2020 district heating emission intensity, seasonal operational carbon emissions per unit floor area in the 26 °C overheating scenario were 57.86, 45.37, and 41.69 kg CO₂/m² in Hailar, Xilinhot, and Ulanhot, respectively (Figure 9). Reducing the heating setpoint to 20 °C decreased the corresponding emissions to 44.01, 32.24, and 29.70 kg CO₂/m², representing reductions of 23.94%, 28.94%, and 28.77%, respectively. Because the emission factor was constant within the same heat supply pathway, these reductions were entirely driven by lower purchased heat demand. This result indicates that temperature optimization can produce a stable demand-side emission reduction effect under different severe-cold climatic conditions.

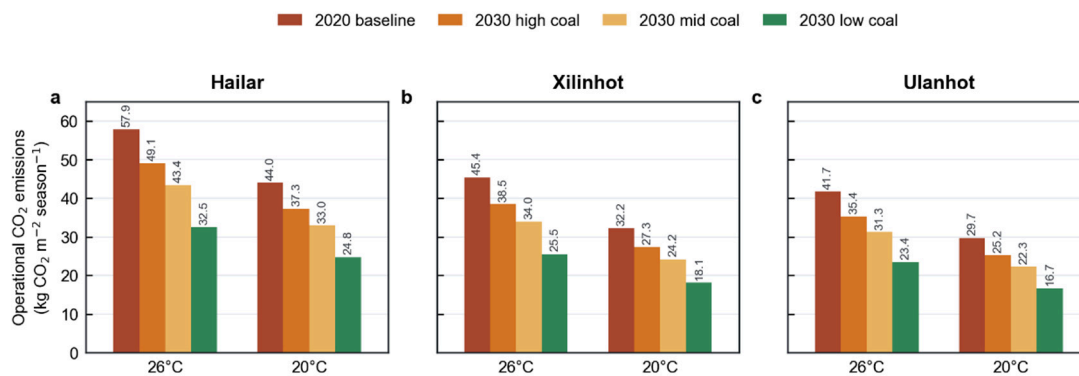


Figure 9. Operational carbon emissions under heating setpoint and district heating emission factor scenarios. (a) Hailar. (b) Xilinhot. (c) Ulanhot.

Lower heat supply emission intensity further amplified the above emission reductions. Under the 20 °C scenario, the 2030 high-coal, medium-coal, and low-coal parameters produced per-area emissions of 37.33, 33.01, and 24.75 kg CO₂/m² in Hailar; 27.35, 24.18, and 18.14 kg CO₂/m² in Xilinhot; and 25.19, 22.27, and 16.70 kg CO₂/m² in Ulanhot. Relative to the 2020 baseline at the same temperature, the low-coal parameter reduced emissions by 43.75% in all three cities. When 20 °C temperature optimization and the low-coal parameter acted together, the combined reductions relative to the 2020 26 °C baseline reached 57.22%, 60.03%, and 59.93% in Hailar, Xilinhot, and Ulanhot, respectively. This finding shows that demand-side temperature control and supply-side decarbonization have a clear combined mitigation effect. However, because heating demand and other operating conditions were held constant in the analysis, the 2030 results should be interpreted as emission-factor sensitivity results rather than predictions of future heating demand, heat-source structure, or carbon emissions.

4. Discussion and Limitations

4.1. Spatial Heterogeneity, Potential Adaptive Behavior, and Implications for Heating Optimization

Room-level measurements show that heating season overheating was not spatially uniform within the dwellings. Based on the January data, the mean within-dwelling temperature differences were 3.95 °C in Ulanhot, 2.72 °C in Xilinhot, and 3.09 °C in Hailar. Marked thermal differences can therefore occur among rooms or local sensor positions within the same dwelling. Mean living room and bedroom temperatures describe overall conditions in the primary occupied spaces. However, they cannot fully represent actual thermal exposure across different rooms and local areas. The observed high temperatures,

local extreme values, and room-to-room differences may be affected by the combined effects of district heating operation, building characteristics, and occupant behavior. The monitored dwellings used water-based district heating, and heat supply was mainly regulated at the building or community level rather than by precise room-level control. Therefore, supplied heat may not always match the actual heat demand of individual rooms. Room orientation, exterior wall exposure, window area, envelope performance, solar gains, and local ventilation conditions can further affect indoor temperature levels. Occupant behaviors, such as window opening or radiator valve adjustment, may also contribute to short-term temperature fluctuations, although these behaviors were not directly monitored. These factors help explain why persistent overheating, local extreme values, and spatial temperature differences occurred during the heating season.

The auxiliary sensors provided further evidence of local thermal disturbances in occupied dwellings. In Hailar, the mean temperature difference between the living room and near-window sensors was 12.53 °C. Differences of at least 10 °C occurred in 61.0% of the records. The normalized frequency of living room temperature decreases of at least 2 °C within 10 min was 1.28 events d⁻¹ in Hailar. This value exceeded 0.67 events d⁻¹ in Xilinhot and 0.00 events d⁻¹ in Ulanhot. These patterns may reflect cold air exchange near windows, cold radiant effects, or other transient thermal disturbances. They do not constitute direct observations of window-opening behavior. However, they can serve as proxy evidence of potential behavioral effects and local heat dissipation.

These findings have important implications for heating optimization. The simulations quantified relative demand reduction potential under a standardized prototype dwelling and controlled setpoints. The measurements show that actual dwellings also experience room-level temperature differences and local thermal disturbances. Heating optimization in severe cold regions should therefore extend beyond uniform setpoint reduction. Room-level control, occupancy detection, window-opening detection, and occupant comfort feedback should be integrated into adaptive heating strategies that better reflect actual residential use. For district heating operators, these results suggest the need to identify overheated dwellings and improve heat supply regulation using building-level or room-level temperature feedback. For local governments, continuous temperature monitoring, refined heating control guidance, and support for low-carbon heat sources could help reduce avoidable heating demand while maintaining indoor comfort.

4.2. Study Limitations and Future Work

This study has several limitations. First, the measurements were obtained from one case study dwelling in each of three cities. January data were used consistently to improve temporal comparability, but the sample size remained limited. The measurements were therefore used to provide case-based evidence of observed overheating, spatial heterogeneity, and potential behavioral signals. They should not be interpreted as a statistical ranking of residential thermal conditions across the three cities.

Second, the simulations used a standardized prototype dwelling to isolate the effects of climate and heating setpoint. This approach supported consistent comparisons but did not calibrate the model to the envelope, actual ventilation rate, solar shading, occupant schedules, or dynamic heating system control of each dwelling. The results should therefore be interpreted as relative changes in heating demand and reduction potential under standardized model conditions. They are not absolute energy predictions for individual dwellings or cities.

Window position, radiator valve opening, occupancy, indoor CO₂ concentration, and real-time thermal comfort votes were not monitored. Short-term temperature changes and differences among sensor locations could therefore be used only as proxies for spatial

heterogeneity and potential transient disturbances (Figure 10). Future research should include more dwellings and integrate behavioral sensing, occupant comfort feedback, and dynamic building simulation. Such data would enable a more direct assessment of how adaptive behavior affects indoor conditions and heating demand reduction.

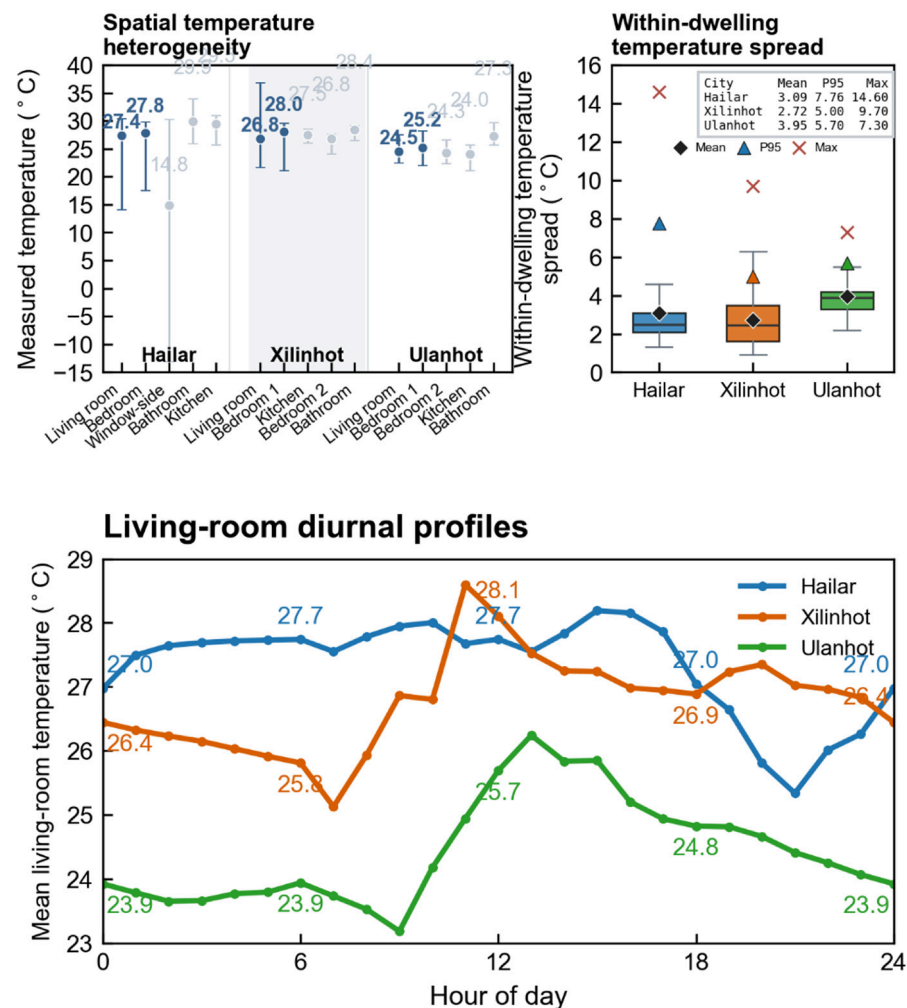


Figure 10. Spatial temperature heterogeneity and daily living room temperature variation in the three case study dwellings.

Future work should extend monitoring to additional winter months and multiple heating seasons to examine interannual variability and improve the robustness of the observed overheating patterns and heating demand reduction estimates. Additional sensitivity analyses should also consider different occupancy schedules, ventilation rates, internal gains, and heating control strategies. This study focused on operational emissions from district heating and did not include embodied carbon emissions related to building materials or heating infrastructure. To support a more comprehensive thermal comfort assessment, future studies should further include occupant surveys, thermal comfort questionnaires, adaptive comfort analysis, relative humidity analysis, CO₂ concentration, air velocity, and mean radiant temperature measurements. These data would help evaluate occupant satisfaction, vulnerable populations, and thermal comfort acceptability more comprehensively. The findings are most applicable to district-heated dwellings in China's severe cold regions, and their transferability to other cold climates should be examined with local building standards, envelope performance, heating system types, and occupant control conditions.

5. Conclusions

This study combined field measurements from case study dwellings in three cities with simulations of a standardized prototype dwelling. It analyzed heating season indoor thermal conditions, heating demand responses, demand reduction potential under comfort-oriented temperature adjustment, and the associated operational carbon emission effects in residential buildings in China's severe cold regions. The main conclusions are as follows.

(1) The primary occupied spaces in all three dwellings showed elevated heating season temperatures to varying degrees. Ulanhot exhibited localized and intermittent overheating, whereas the Xilinhote bedroom and the main spaces in Hailar showed higher proportions of persistent high-temperature exposure. The case study results suggest that actual heating temperatures in similar district-heated dwellings may have scope for optimization.

(2) Under standardized prototype dwelling conditions, heating demand increased continuously with the indoor setpoint in all three cities. Overall demand was highest in Hailar, followed by Xilinhote and Ulanhot. January was a high-demand period in all three cities and can serve as a representative winter peak load window.

(3) January heating load showed a stable diurnal structure and was strongly and negatively correlated with mean daily outdoor temperature. At the uniform 22 °C setpoint, the correlation coefficients between daily January heating demand and mean daily outdoor temperature were −0.984, −0.969, and −0.905 in Hailar, Xilinhote, and Ulanhot, respectively. Outdoor temperature variation is therefore an important driver of heating load fluctuations during severe-cold months.

(4) Comfort-oriented temperature adjustment can substantially reduce seasonal heating demand. Reducing the 26 °C overheating condition to 20 °C lowered seasonal heating demand by 23.94–28.94% across the three cities. Adjusting the measured temperature reference scenarios to 20 °C produced relative reductions of 24.49–33.60%. Adjusting elevated operating temperatures to a reasonable comfort-oriented setpoint is therefore an effective strategy for reducing heating demand in severe-cold-region dwellings.

(5) The operational carbon emission scenario analysis indicates that demand-side temperature optimization and heat supply decarbonization can produce combined emission reductions. Under the 2020 district heating emission intensity, reducing the 26 °C overheating condition to 20 °C lowered area-normalized operational carbon emissions by 23.94–28.94% across the three cities. When 20 °C temperature optimization was combined with the low-carbon emission parameter, seasonal area-normalized operational carbon emissions decreased by 57.22–60.03% relative to the 2020 26 °C baseline.

(6) Proxy indicators of spatial heterogeneity and thermal disturbances suggest that room-level temperature differences and occupant adaptive behavior may affect actual dwelling operation. Future heating optimization should further integrate room-level control, occupancy status, window-opening detection, and occupant comfort feedback to develop strategies that better reflect actual residential use.

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Appendix A. Appendix

Table A1. Comparison of representative studies on indoor thermal conditions, heating demand, and carbon emission mitigation in cold-climate residential and district-heated buildings.

Reference	Region/Climate	Building Type and Sample/Model	Method	Main Focus	Heating Demand/Carbon Analysis	Relevance To This Study and Remaining Gap
[7]	Severe-cold region of China	Residential buildings	Data analytics	Heating energy consumption characteristics	Heating energy included; carbon not the main focus	Provides heating energy evidence, while the link between measured overheating and comfort-oriented setpoint adjustment remains less explored.
[24]	Severe-cold area, China	Two residential case studies	Field investigation and thermal comfort analysis	Thermal adaptation and comfort	Energy /carbon not the main focus	Focused on comfort adaptation rather than simulated heating demand reduction.
[26]	Northeast severe-cold regions, China	Rural residential houses	Field investigation	Winter thermal comfort	Energy /carbon not the main focus	Provides field evidence on winter comfort, while demand and emission reductions from overheating mitigation remain less explored.
[19]	Severe-cold areas	Residential buildings	Occupant behavior and energy-saving analysis	Occupant behavior, energy-saving measures, thermal comfort	Energy-saving measures included; carbon not the main focus	Addresses occupant behavior and comfort, while the translation of measured overheating into standardized setpoint scenarios remains limited.
[31]	General building context	Heating control model	Setpoint recommendation/optimization	Thermal comfort and energy consumption	Energy included; carbon not the main focus	Provides a useful reference for heating setpoint optimization, while its context differs from district-heated dwellings in China's severe cold regions.
[33]	Residential heating context	Households	Quantitative analysis	Thermal comfort requirements and household heating energy	Heating energy included	Links comfort requirements with heating energy, while measured overheating and operational carbon emissions are not fully integrated.
[37]	Northern China	District-heated buildings	Local thermal-comfort-based method	Room-temperature setting for district heating	Related to heating operation; carbon not the main focus	Provides useful setpoint guidance, while integrated analysis of case measurements, prototype simulation, and carbon scenarios remains limited.
[38]	Cold regions	Residential buildings under different heating charging modes	Field investigation/behavioral analysis	Occupant control behavior and thermal comfort	Energy implications discussed; carbon not the main focus	Supports behavioral interpretation but does not quantify operational carbon-reduction potential.

Table A1. Cont.

Reference	Region/Climate	Building Type and Sample/Model	Method	Main Focus	Heating Demand/Carbon Analysis	Relevance To This Study and Remaining Gap
[39]	District-heated residential buildings	Residential building model	Calibrated heating load prediction model	Model calibration and heating load prediction	Heating load included	Highlights the value of calibration; does not address measured overheating and carbon mitigation.
[36]	China's urban district-heating systems	District heating supply systems	Scenario analysis	Heat source diversification and carbon lock-in	Supply-side carbon emissions included	Provides supply-side decarbonization evidence, while building-side temperature optimization is outside its main scope.
[40]	China and India	Residential building sector	Carbon intensity and decomposition analysis	Residential building operational decarbonization	Operational carbon emissions included	Sector-level analysis; not linked to measured indoor temperature or heating setpoint adjustment.
[41]	Northern rural China	Residential heating	Carbon mitigation assessment	Sustainable heating and carbon reduction potential	Carbon mitigation included	Policy/scenario focus; limited evidence on indoor overheating in occupied dwellings.
[42]	Chinese district heating systems	District-heated buildings	Multi-dimensional indoor-temperature analysis	Indoor temperature across heating periods and building efficiency levels	Indoor temperature included; carbon not the main focus	Highly relevant to indoor temperature, but does not quantify demand and carbon reduction through prototype setpoint scenarios.
[43]	European cold climate/district heating context	Old apartment building with district heating	Measurement and simulation	Dynamic heating control, indoor air temperature, and power reduction	Energy and indoor temperature included	Strong international reference, but not focused on Chinese severe cold cities or overheating-derived setpoint scenarios.
[44]	Nordic/European heating context	Buildings with hydronic heating systems	Indoor temperature-based feedback control	Heating control using indoor temperature measurements	Heating operation included	Relevant to indoor-temperature-based control but does not quantify comfort-oriented carbon emission reduction.
[45]	European district-heating systems	District heating networks and connected buildings	Review/control strategy analysis	Demand-side management and innovative control in district heating	Energy-saving potential discussed	System-level control focus; limited dwelling-level measured thermal evidence.
[46]	Denmark/European cold climate	Existing Danish buildings connected to district heating	Technical economic assessment	Low-temperature district-heating readiness	Heating system efficiency and energy implications included	Focuses on low-temperature district-heating preparation rather than measured indoor overheating.
[47]	Cold climate, North America	Occupied all-electric single-family house	Field demonstration and predictive heating control	Predictive heating control using weather and occupancy information	Heating energy reduction quantified	Focuses on heat-pump-based residential heating, not district-heated dwellings or carbon scenarios.
This study	Severe-cold regions of China: Ulanhot, Xilinhote, and Hailar	Three case-study dwellings and a standardized prototype dwelling	Field measurement and EnergyPlus simulation	Indoor overheating, comfort-oriented setpoint adjustment, heating demand reduction, and operational carbon emissions	Heating demand and operational carbon emissions quantified	Integrates case-based field measurements, standardized prototype simulation, and operational carbon emission assessment; results indicate relative reduction potential under standardized model conditions.

Table A2. Example statistical characteristics of heating season indoor temperatures in the main rooms of the three case study dwellings.

City	Room	Mean Temperature (°C)	Maximum Temperature (°C)	Minimum Temperature (°C)	Standard Deviation (°C)	>24 °C (%)	>26 °C (%)	>28 °C (%)
Ulanhot	Living room	24.46	27.5	22.4	0.97	62.27	6.25	0
Ulanhot	Bedroom	25.22	28.2	22	1.92	67.59	40.86	2.78
Xilinhote	Living room	26.76	36.8	21.6	1.64	95.6	62.15	26.04
Xilinhote	Bedroom	28.03	29.6	21.1	1.35	97.45	92.13	63.89
Hailar	Living room	27.35	30.3	14.1	2.19	92.4	90.21	43.66
Hailar	Bedroom	27.78	29.8	17.5	1.07	99.18	95.57	38.54

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