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Field Evidence of Envelope Renovation Impact on Heating Activation Temperature and Heating-Dependent Temperature Range in Apartments

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Abstract

Various studies on the envelope renovation of existing residential buildings have quantified energy savings effects across various climate conditions and building types yet have also reported discrepancies between predicted and actual energy savings performance. Given that identical technical improvements can yield substantially different actual outcomes depending on occupants' behavioral adaptation patterns, renovation effect evaluation requires a multifaceted approach incorporating occupant behavioral changes. This case study empirically analyzed the effects of envelope renovation on occupants' actual heating operation patterns. Envelope renovation effects applied to a 30-year-old apartment were analyzed by subdividing temperature conditions, with comparative evaluation using a non-renovated adjacent unit within the same building as a reference. While recognizing the inherent limitations of single-case analysis, this study presents a novel methodological framework for capturing subtle behavioral shifts through high-resolution temperature-specific analysis. Change-point models utilizing utility billing data were employed to analyze threshold temperature changes, and daily heating water-consumption estimation algorithms were applied to track heating pattern changes according to outdoor temperature variations. Results showed heating energy reduction despite more severe climate conditions post-renovation, with particularly pronounced savings under mild conditions. The upper limit of temperature ranges showing high heating dependency shifted downward from pre-renovation levels, improving to levels lower than the reference unit's upper limit, demonstrating envelope performance enhancement effects. These results provide quantitative evidence that envelope improvements directly influence occupants' heating decision-making criteria, though broader validation across multiple cases would strengthen these findings. This study quantifies envelope renovation effects not only in terms of energy savings, but also from the perspectives of occupant behavioral changes and comparison with reference units, presenting a novel evaluation methodology for effective energy efficiency improvements in aging buildings.

Keywords: building envelope renovation; occupant heating behavior; change-point model; temperature-dependent analysis; daily energy disaggregation

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1. Introduction

Korea established its 2030 Nationally Determined Contributions (NDC) in October 2021, formulating the 2050 Carbon Neutrality Scenario and the Ministry of Land, Infrastructure and Transport's 2050 Carbon Neutrality Roadmap. Given that the building

sector accounts for approximately 14.4% of national greenhouse gas emissions, enhancing building energy efficiency has emerged as a fundamental strategy for achieving carbon neutrality [1].

These policy goals demand extensive energy performance improvements in the existing building stock. The energy performance of these buildings remains substantially below current standards, a consequence of evolving energy codes that have become increasingly stringent since their original construction [2,3]. Following rapid urbanization, apartments have established a dominant position within Korea's residential building stock. Apartments constitute the primary residential type, accounting for 63% of all housing forms [4], with approximately 40% of domestic apartments constructed before 2000, thereby continuously raising concerns regarding the necessity of energy performance enhancement. The first-generation new towns in Korea, which were predominantly constructed between 1989 and 1996, these structures have now exceeded 30 years since construction, resulting in severely deteriorating building energy efficiency.

Methodologies for evaluating building energy-saving potential encompass forward modeling approaches and inverse modeling approaches [5]. Forward modeling relies on physical building characteristics for predictions but is constrained by its need for comprehensive input data. Conversely, inverse modeling derives representative parameters utilizing measured energy consumption data and meteorological data, offering the practical advantage of employing readily accessible data, such as utility bill information, as inputs. Among these approaches, the change-point model has gained recognition as a methodology particularly suited for performance evaluation based on measured data, as it effectively analyzes the nonlinear relationship between heating energy consumption and outdoor temperature [6,7]. This methodology, presented in the RP-1050 research of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14 [8] characterizes energy consumption patterns according to temperature variations by distinguishing them based on inflection points.

Existing research on envelope renovation in residential buildings has quantified energy-saving effects across diverse climatic conditions and building types. Majcen et al. [9] analyzed social housing data from 300,000 households in the Netherlands, reporting that high-efficiency boiler replacement achieved the greatest energy savings, followed by window improvements. As an innovative approach to external wall insulation technology, Uriarte et al. [10] achieved low thermal transmittance values of 0.28 $W/m^2 \cdot K$ and 0.14 $W/m^2 \cdot K$ in Spain and Sweden, respectively, through Vacuum Insulation Panel (VIP) application, reducing annual heating energy by 35% with only 10 cm thickness. Biswas et al. [11] demonstrated in single-family homes in the U.S. that modified atmosphere insulation application reduced natural gas consumption by 12.5% in buildings with existing insulation and 46.4% in uninsulated buildings.

Regarding renovation effects by building age, Zhang et al. [12] applied the TNM Decree methodology (Hungarian thermal regulation standard for calculating building energy performance) to buildings in Beijing. Their analysis showed heating energy savings of 65.53% for buildings constructed from 1978 to 1985, 55.04% for constructed from 1986 to 1995, and 32.79% for buildings constructed from 1996 to 2005, with these periods representing different construction eras with progressively stricter insulation requirements. In tropical climates, Ohene et al. [13] reduced Energy Use Intensity (EUI) from 136–138 to 68–70 $kWh/m^2 \cdot year$ in Ghanaian residential buildings using only passive strategies such as natural ventilation and shading, achieving 48–50% savings. This represents a dramatic reduction in mechanical cooling dependency. From an economic perspective, Huang et al. [14] derived optimal insulation thickness for envelope components through life-cycle cost analysis, proving that optimization models can reduce insulation material

usage by 0.53–73.59% and initial investment costs by 0.21–64.93% compared to standard threshold methods when achieving identical energy-saving targets. This demonstrates the economic superiority of balanced design considering component-specific heat loss contributions. In low-income housing in Korea, Shin et al. [15] revealed that a limited budget averaging $2314 per household achieved 22.61% annual heating demand reduction, requiring $37.09 per 1 kWh/$m^2$·a reduction, establishing a cost-effectiveness benchmark for energy poverty alleviation programs. As a technological innovation case, Yoon et al. [16] applied double-skin façade (DSF) systems to aging apartments, achieving integrated 44.1% savings in heating, cooling, and lighting energy, with a 15-year payback period considered acceptable from a long-term perspective. Wang et al. [17] demonstrated in zero-energy retrofit validation that external wall reinforcement contributed most significantly, reducing heat pump energy by 22.2% in winter and 33.1% in summer, although windows showed priority in efficiency per unit R-value increase. These studies indicate that optimal renovation strategies vary according to building characteristics, climatic conditions, and economic constraints, with substantial variation in savings rates.

While the technical effects of renovation have clearly been demonstrated, actual energy saving performance often shows considerable deviation from predicted values. This prediction–performance gap is primarily attributed to occupant energy consumption behavior as a key variable. Majcen et al. [18] discovered that theoretical heating consumption calculations overestimate actual consumption in low-performance buildings and underestimate it in high-performance buildings, which they traced to variations in occupancy schedules, thermal comfort preferences, and daily living patterns. Heesen et al. [19] identified that occupant behaviors such as temperature setpoints and ventilation levels differ significantly from fixed calculation values, revealing that gaps between predicted energy ratings and actual household consumption stem from inherent limitations in static modeling approaches. Laskari et al. [20] demonstrated differences between regulatory design temperature (20 °C) and actual occupant setpoints (18.5–22.8 °C), reporting consumption variations up to 106% due to seasonal adjustments. Bae et al. [21] confirmed in Korean smart meter research that occupant behavior shows higher explanatory power than external environment and building characteristics. Actual energy-saving effects are significantly influenced by occupants' thermal adaptation capability and energy conservation awareness levels [22–24]. Occupants with broad thermal comfort acceptance ranges who practice active energy-saving behaviors can achieve or exceed predicted savings, while those with limited adaptation capability and low conservation awareness may demonstrate performance below expectations.

While existing research has clearly established occupant behavior as a critical variable determining building energy performance, most renovation effect evaluation studies merely present monthly or annual total energy consumption reduction rates. Particularly lacking is in-depth analysis of how renovation transforms occupants' energy consumption patterns. Analysis of behavioral patterns, such as the outdoor temperature conditions at which occupants initiate heating or qualitative changes in heating operation methods post-renovation, has been relatively limited.

Comprehensive evaluation of renovation's essential effects requires tracking how occupants' heating behavior patterns change beyond simple total energy savings calculations. Changes in heating initiation threshold temperature particularly serve as a key indicator representing the direct impact of envelope performance improvement on occupant behavior. Furthermore, analyzing differential savings effects under extreme versus mild climatic conditions is essential for understanding energy consumption pattern changes induced by renovation. Given that actual performance can vary significantly depending on occupants'

behavioral adaptation methods despite identical technical improvements, renovation effect evaluation demands a multifaceted approach incorporating occupant behavior changes.

This study empirically analyzed the impact of envelope renovation on actual occupant heating operation patterns in a single unit of an aging apartment building over 30 years old. Unlike existing studies focusing on monthly or annual total energy consumption reduction, this study tracked subtle changes in heating decision-making according to outdoor temperature variations through daily energy consumption estimation. This approach quantitatively captures changes in heating operation patterns, particularly shifts in the threshold temperature for heating activation post-renovation. The demonstration unit demonstrated integrated applications to high-performance windows, high-efficiency entrance doors, and Vacuum Insulation Panel (VIP)-based internal insulation systems, with clear presentation of the rationale for selecting these technical improvements as major components and their performance levels. By integrating utility data-based regression analysis of heating threshold temperatures with indoor temperature-humidity monitoring, this study comprehensively evaluated renovation effects on both energy consumption and residential environment quality. The research presents a novel methodology that quantitatively captures behavioral shifts in occupant heating patterns induced by envelope improvements.

2. Experimental Design and Analytical Methods

2.1. Study Site and Renovation Measures

This study employed a detailed single-case investigation methodology to capture granular changes induced by envelope renovation with high temporal and thermal resolution. The empirical subject of this study is a 131.44 m^2 household unit located in a 30-year-old apartment complex in Seongnam City, Gyeonggi Province, constructed in 1993. The target complex operates under district heating with flow meter measurement, in accordance with pre-2009 construction standards [25], with charges calculated based on heating water consumption [m^3]. The district heating water consumption utilized as an indicator of heating energy consumption in this study presupposes the fundamental structure of the district heating system, which calculates heat quantity based on flow rate and temperature differential. The area encompassing the study unit was developed through a government-led residential land development project in the early 1990s, and the district heating system introduced during this period was designed as a closed-loop circulation structure based on medium-temperature water. The heat transmission pipes maintain supply temperatures up to 120 °C and return temperatures within the 40–65 °C range, while building internal heat exchangers typically operate at supply temperatures of 60–70 °C and return temperatures of 40–46 °C, maintaining a temperature differential of 15–25 °C. Under these conditions, as the temperature differential remains relatively constant, the flow rate itself demonstrates high correlation with energy consumption. Given that the primary objective of this study is to analyze changes before and after renovation rather than provide a precise measurement of total heat quantity, the reliability of the flow-based approach was deemed sufficient, considering the system structure and operational conditions. The renovation was completed in October 2020, and heating energy consumption data were collected through monthly utility bills from January 2018 to February 2022.

For quantitative analysis of indoor temperatures and humidity variations, T&D Corporation's TR-72nw temperature–humidity data loggers were deployed. These instruments feature a temperature accuracy of ±0.5 °C and relative humidity accuracy of ±5%, and were installed in the living room, main bedroom, unheated room, and balcony, respectively. Figure 1 illustrates the measurement setup for both units: the renovated unit (shown on the left) and the non-renovated reference unit within the same building (shown on the right), where measurements were conducted simultaneously. The measurement period extended

from 8 January to 4 April 2021, and both units were occupied by comparable three-member families with similar occupancy patterns.

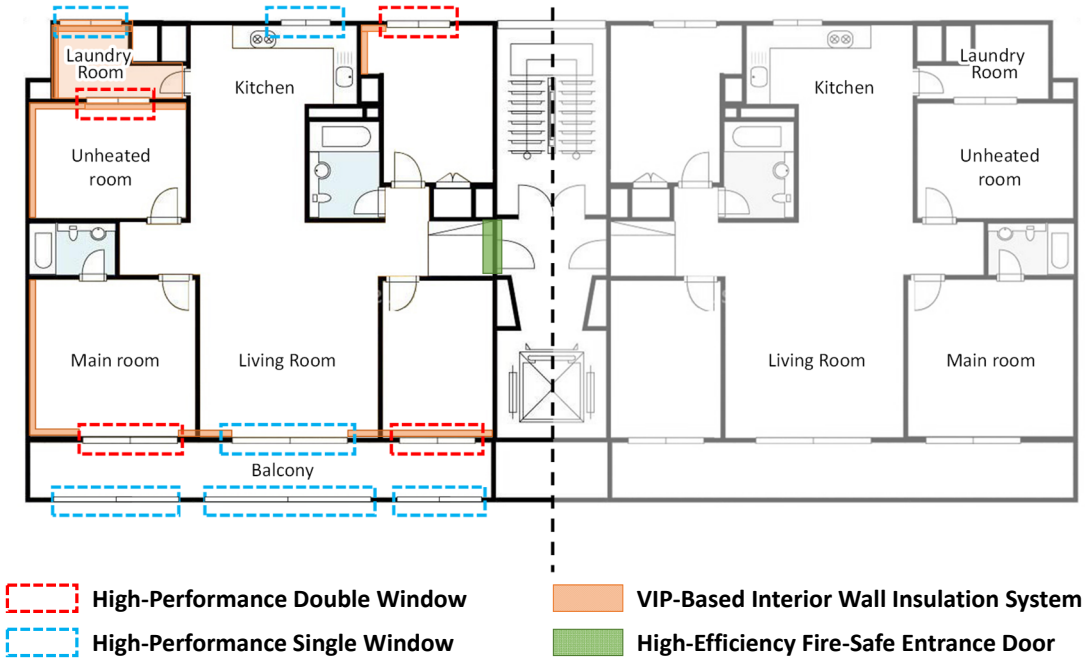


Figure 1. Spatial configuration of the renovated and reference units, indicating the application areas of three improvement measures.

Building energy performance is critically influenced by components in direct contact with outdoor conditions, with heat loss through windows accounting for the largest proportion [26]. The target unit exhibited severe performance degradation requiring comprehensive improvements. While the exterior walls necessitated insulation reinforcement [27], interior insulation was considered due to structural limitations inherent to apartment buildings [15]. The laundry room and unheated room experienced severe condensation leading to secondary issues, including mold formation. The entrance door showed degraded airtightness performance due to deterioration and required urgent improvement as a significant thermal bridge location [28,29].

Although the subject unit complied with the Energy-Saving Design Standards for Buildings [30] at the time of construction in 1993, substantial performance gaps exist when compared to current standards. Figure 1 presents three principal envelope improvement strategies implemented to address these performance disparities. Systematic enhancement of envelope performance was achieved through the installation of high-performance window systems, replacement of entrance doors with doors featuring both enhanced thermal performance and fire safety specifications, and application of interior insulation systems utilizing vacuum insulation panels.

Table 1 presents the changes in thermal transmittance (U-value) for each improvement element shown in Figure 1. Comparing the initial U-values based on design standards at the time of construction with the performance achieved after the renovation, all components were enhanced to levels meeting current standards.

The high-performance window system achieved an approximately 81% performance enhancement from the existing U-value of 4.300 W/(m^2·K) to 0.780–0.800 W/(m^2·K). While maintaining the existing spatial configuration, aluminum–PVC composite frames and Low-E coated double glazing were applied, achieving thermal transmittance values of 0.800 W/(m^2·K) for double windows and 0.783 W/(m^2·K) for single windows according

to thermal transmittance testing per KS F 2278 [31]. Additionally, airtightness testing conducted according to KS F 2292 [32] confirmed performance below 1.0 $m^3/(h \cdot m^2)$.

Table 1. Envelope Insulation Performance Benchmarks: Existing, Legal Reference, and Renovation of Envelope.

			Unit: $W/(m^2 \cdot K)$
Envelope Component	**Existing Performance**	**Legal Reference Standard**	**Renovation Result**
Exterior Wall	0.500	0.170	0.125
Exterior Window (Double)	3.200	1.000	0.783
Interior Window (Single)	6.600	1.900	0.800
Unit Entrance Door	2.700	1.800	0.795

The entrance doors that improved the U-value by 70% from 2.700 $W/(m^2 \cdot K)$ to 0.795 $W/(m^2 \cdot K)$ through a composite structure of vacuum insulation panels and multi-layer mineral wool. The improved entrance doors not only enhanced thermal performance but also satisfied the most stringent regional criteria in condensation resistance testing according to KS F 2295 [33], while achieving 90 min of flame resistance and 65 min of thermal insulation per KS F 2268-1 [34] standards, thereby simultaneously fulfilling fire door requirements.

The existing wall structure, comprising 120 mm concrete and 70 mm glass wool with a U-value of 0.407 $W/(m^2 \cdot K)$, met the then-applicable standard of 0.50 $W/(m^2 \cdot K)$ but fell considerably short of the current 0.15 $W/(m^2 \cdot K)$ requirement. Interior insulation using 15 mm vacuum insulation panels with thermal conductivities of 0.002 $W/(m \cdot K)$ reduced the U-value to 0.125 $W/(m^2 \cdot K)$, achieving both a 69% performance enhancement and compliance with contemporary standards. Given that vacuum insulation panels cannot be cut on-site, modular installation strategies were employed to minimize thermal bridging at panel joints.

2.2. ASHRAE Model and Daily Consumption Estimation

To evaluate the actual heating energy savings resulting from envelope performance improvements, regression analysis using the change-point model from ASHRAE Guideline 14 [8] was conducted. Actual heating water consumption data-based on monthly utility bills were utilized, while meteorological data were collected from weather stations located within 18 km of the demonstration site. Hourly outdoor temperature data were converted to monthly or daily averages to align with the billing periods for heating energy consumption. The model can be expressed as follows:

$$E_{tot} = E_{nonOA} + HS(T_{CP} - T_{OA})^{+} \quad (1)$$

Here, E_{tot} represents monthly heating energy consumption [m^3], E_{nonOA} denotes baseline energy consumption independent of outdoor temperature [m^3]. The coefficient HS indicates the slope, T_{CP} represents the change-point temperature (°C) at which the heating system begins responding linearly to outdoor conditions, and T signifies the monthly mean outdoor temperature (°C). The notation $(\ )^{+}$ indicates that only positive values within the parentheses are used; negative values are treated as zero. Following model construction,

goodness-of-fit was evaluated using the coefficient of determination (R^2) and coefficient of variation in the root mean square error (CV-RMSE):

$$R^2 = \frac{\sum_i (y_i - \overline{y})^2 - \sum_i (y_i - \hat{y}_i)^2}{\sum_i (y_i - \overline{y})^2} \tag{2}$$

$$CV - RMSE = \frac{\sqrt{\frac{\sum_i (y_i - \hat{y}_i)^2}{n-p}}}{\overline{y}} \times 100\% \tag{3}$$

where y_i represents actual monthly heating energy consumption, $\hat{y}_i$ denotes model-predicted consumption, $\overline{y}$ indicates mean actual consumption, n is the number of data points, and n represents the number of parameters. Model adequacy thresholds were established according to ASHRAE guidelines: $R^2 \geq 70\%$ and CV-RMSE $\leq 30\%$. However, considering the high variability in residential heating consumption due to occupant behavior and hot water usage, the CV-RMSE tolerance was extended by 10%, setting the maximum acceptable limit at 40% [35].

Furthermore, this study applied a disaggregation approach to decompose monthly billing-based heating water consumption data to daily resolution for precise analysis of heating energy consumption characteristics responding to outdoor temperature variations. This enabled quantitative analysis of actual heating operation patterns and spatial thermal efficiency characteristics responsive to daily outdoor temperature conditions.

The disaggregation technique employs daily differences between outdoor temperature (T_d) and the change-point temperature (T_{CP}) as weighting factors to distribute the monthly total district heating water consumption (Q_m) across individual days. This approach parallels the mathematical structure of the Variable-Base Degree-Day (VBDD) method proposed in existing literature [8]. Our implementation directly applies outdoor temperature deviations below the change-point temperature as daily weights, creating a distribution method that precisely preserves monthly total consumption.

The methodology is formalized as follows:

$$Q_d = \frac{w(T_d)}{\sum_{d=1}^{D} w(T_d)} \times Q_m \tag{4}$$

$$w(T_d) = \begin{cases} T_{CP} - T_d, & if\ T_d < T_{CP} \\ 0, & otherwise \end{cases} \tag{5}$$

where Q_d represents estimated daily heating water consumption (m^3/day) and Q_m indicates actual monthly consumption per billing statement (m^3/month). T_d is the daily mean outdoor temperature (°C), and T_{CP} is the change-point temperature (°C) derived through change-point regression modeling. $w(T_d)$ represents the outdoor temperature-based weight, with D denoting the total days in the month. Since this method assigns positive weights only to days when outdoor temperature falls below the change-point temperature, it quantitatively captures periods when heating was likely operational. By differentially weighting according to outdoor temperature and normalizing by the sum, monthly total consumption can be disaggregated to daily resolution while preserving the original total.

The approach employed here differs methodologically from the Day-Adjusted Model (DAM) proposed in ASHRAE Guideline 14 [8]. DAM divides monthly energy consumption by the number of days in that month and uses daily averages for regression analysis. While this captures the aggregate influence of climate variables, it struggles to reflect temporal responsiveness to daily outdoor temperature variations. In contrast, our research estab-

lishes weights based on daily differences between outdoor and change-point temperatures, decomposing monthly consumption to daily units, thereby more precisely capturing actual heating response characteristics to changing climate conditions.

This method represents a quantitative estimation technique based on outdoor temperature, utilizing monthly billing data as its foundation. The district heating billing structure in the study area provides only aggregated consumption data encompassing both space heating and domestic hot water usage; consequently, the proposed disaggregation methodology was implemented on the composite consumption values without component-level separation. Additionally, since heating load is assumed zero above the change-point temperature, actual consumption in that range—baseline load from hot water usage—is not reflected in daily estimates. Therefore, daily estimation results from this study focus on identifying relative trends in heating patterns responding to outdoor temperature changes while preserving monthly totals, rather than providing absolute predictive values. Future acquisition of high-resolution metering data distinguishing hot water from heating consumption would enable validation and refinement of the disaggregation technique presented here.

3. Results and Discussion

This chapter systematically analyzes the complex effects of building envelope renovation on indoor thermal environment and heating energy consumption patterns. Based on measured data from renovated and reference units, the impacts of envelope performance enhancement on indoor temperature–humidity conditions and heating energy efficiency are evaluated. Section 3.1.1 quantifies thermal environment improvements by space through comparative analysis of indoor temperature and humidity measurements across outdoor temperature ranges, while Section 3.1.2 analyzes the effects of envelope improvements on fundamental thermal performance and heating efficiency through regression analysis between indoor–outdoor temperature differences and heating water consumption. Section 3.2 analyzes renovation's influence on occupant heating behavior changes through change-point model and daily estimated consumption analysis. Section 3.2.1 tracks how occupants' heating initiation timing changed through envelope performance improvements by analyzing shifts in change-point temperature. Section 3.2.2 analyzes shifts in heating dependency ranges through outdoor temperature-based analysis, demonstrating how renovation altered the boundaries of temperature zones where heating is required.

3.1. Thermal Performance Enhancement Through Building Envelope Renovation

3.1.1. Spatial Temperature Stability and Humidity Control

This section quantifies the direct improvement effects of envelope renovation on the temperature and humidity in each space. Temperature and humidity were simultaneously measured in the Main room, Living room, Unheated room, and Balcony to evaluate thermal environmental changes by space. The reference unit, a non-renovated adjacent unit within the same building, served as a control group, enabling isolation and evaluation of pure effects from envelope performance improvements under identical outdoor conditions.

During the measurement period from 8 January to 4 April 2021, data from 17 January to 31 March 2021 were utilized for final analysis after removing outliers. Analysis results showed outdoor temperatures ranging from −7.9 °C to 15.0 °C, with a mean of 5.1 °C. For analytical clarity, outdoor temperature (T_O) was categorized into four ranges: Severe Cold ($T_O \leq -5$ °C), Cold (-5 °C $< T_O \leq 0$ °C), Mild (0 °C $< T_O \leq 10$ °C), and Moderate (10 °C $< T_O$), to evaluate indoor thermal environment improvements under each condition. During the analyzing period, Severe Cold conditions occurred on 3 days, Cold conditions

on 12 days, Mild conditions on 48 days, and Moderate conditions on 11 days, with most measurement days falling within the 0–10 °C Mild condition range.

As shown in Table 2, the renovated unit maintained higher indoor temperatures than the reference unit across all spaces and outdoor temperature conditions. The main room demonstrated the largest improvement, achieving a 7.1 °C temperature increase under Severe Cold conditions ($T_O \leq -5$ °C) and 6.7 °C enhancement under Cold conditions (-5 °C $< T_O \leq 0$ °C). The improvement effect progressively diminished with rising outdoor temperatures, showing differences of 5.5 °C under Mild conditions (0 °C $< T_O \leq 10$ °C) and 4.9 °C under Moderate conditions (10 °C $< T_O$).

Table 2. Indoor temperature variations across different spaces and outdoor temperature (T_O) ranges for reference and renovated units.

Space	Unit	Severe Cold ($T_O \leq -5$ °C)	Cold (-5 °C $< T_O \leq 0$ °C)	Mild (0 °C $< T_O \leq 10$ °C)	Moderate (10 °C $< T_O$)
Main room	Reference	18.7 ± 0.9	18.9 ± 0.5	19.1 ± 0.7	19.0 ± 0.6
	Renovated	25.8 ± 0.6	25.6 ± 0.6	24.6 ± 0.8	23.9 ± 0.8
	Improvement	+7.1 °C	+6.7 °C	+5.5 °C	+4.9 °C
Living room	Reference	19.5 ± 0.9	19.9 ± 0.7	19.9 ± 0.7	19.6 ± 0.6
	Renovated	22.7 ± 0.9	23.0 ± 0.7	22.8 ± 0.7	22.5 ± 0.5
	Improvement	+3.2 °C	+3.1 °C	+2.9 °C	+2.9 °C
Unheated room	Reference	15.4 ± 2.1	15.5 ± 1.1	17.0 ± 1.1	17.1 ± 1.3
	Renovated	18.2 ± 1.0	17.7 ± 0.7	18.8 ± 1.0	19.4 ± 0.6
	Improvement	+2.7 °C	+2.2 °C	+1.8 °C	+2.4 °C
Balcony	Reference	8.8 ± 0.9	10.7 ± 1.7	14.9 ± 1.8	16.9 ± 1.2
	Renovated	9.5 ± 1.2	11.1 ± 1.5	15.4 ± 2.0	17.7 ± 1.3
	Improvement	+0.7 °C	+0.4 °C	+0.5 °C	+0.7 °C

The renovated unit's main room average temperatures ranged from 23.9 to 25.8 °C, mostly exceeding the 24 °C upper comfort limit for residential buildings in winter established by Ji et al. [36]. In comparison, the reference unit's temperatures remained within 18.7 to 19.1 °C, indicating that the renovated unit maintained substantially higher indoor temperatures.

The living room exhibited relatively consistent improvements across all outdoor temperature conditions. Temperature increases of 3.2 °C and 3.1 °C were observed under Severe Cold and Cold conditions, respectively, with sustained improvements of 2.9 °C maintained under both Mild and Moderate conditions. The smaller improvement magnitude in the living room compared to the main room is attributed to ongoing heat exchange through its open structure connecting to the balcony and entrance.

The unheated room, despite receiving no direct heating supply, showed consistent temperature improvements across all outdoor temperature conditions. Under Severe Cold conditions, while the reference unit's unheated room maintained an average of 15.4 °C, the renovated unit recorded 18.2 °C, maintaining 2.7 °C higher temperatures without heating. This is significant as the renovated unit achieved the 18 °C winter indoor comfort lower limit [37] without direct heating equipment intervention. Temperature increases of 2.2 °C and 1.8 °C were confirmed under Cold and Mild conditions, respectively, with the effect increasing again to 2.4 °C under Moderate conditions.

The balcony, due to its semi-outdoor space characteristics [38], showed the smallest improvement magnitude, yet consistent improvements were confirmed across all outdoor temperature conditions. Temperature increases of 0.7 °C under Severe Cold, 0.4 °C under Cold, 0.5 °C under Mild, and 0.7 °C under Moderate conditions were recorded, demonstrating that envelope performance improvement effects extend even to semi-outdoor spaces, albeit to a limited extent.

Table 3 shows that the renovated unit maintained higher absolute humidity than the reference unit across all measured spaces throughout the outdoor temperature ranges.

Table 3. Absolute humidity [g/kg] comparison by outdoor temperature (T_O) range and space.

Space	Unit	Severe Cold ($T_O \leq -5$ °C)	Cold (-5 °C $< T_O \leq 0$ °C)	Mild (0 °C $< T_O \leq 10$ °C)	Moderate (10 °C $< T_O$)
Main room	Reference	2.90 ± 0.75	3.52 ± 0.90	4.97 ± 1.04	5.56 ± 1.02
	Renovated	4.00 ± 0.92	4.81 ± 1.26	6.24 ± 1.26	6.80 ± 1.04
	Improvement	+1.1 g/kg	+1.29 g/kg	+1.27 g/kg	+1.24 g/kg
Living room	Reference	2.66 ± 0.70	3.29 ± 0.94	4.82 ± 1.07	5.55 ± 1.03
	Renovated	2.96 ± 0.91	3.58 ± 1.03	5.13 ± 1.22	5.80 ± 1.13
	Improvement	+0.3 g/kg	+0.29 g/kg	+0.31 g/kg	+0.25 g/kg
Unheated room	Reference	2.25 ± 0.65	2.67 ± 0.75	3.72 ± 0.96	4.36 ± 0.90
	Renovated	2.55 ± 0.78	2.93 ± 0.83	3.97 ± 1.01	4.62 ± 0.96
	Improvement	+0.3 g/kg	+0.26 g/kg	+0.25 g/kg	+0.26 g/kg
Balcony	Reference	1.07 ± 0.45	1.47 ± 0.57	2.45 ± 0.78	2.97 ± 0.85
	Renovated	1.35 ± 0.54	1.76 ± 0.63	2.72 ± 0.84	3.21 ± 0.88
	Improvement	+0.28 g/kg	+0.29 g/kg	+0.27 g/kg	+0.24 g/kg

In the main room under Severe Cold conditions, the reference unit showed an average absolute humidity of 2.90 g/kg, while the renovated unit recorded 4.00 g/kg, representing a difference of 1.10 g/kg. Under Mild conditions, this difference further increased, with the renovated unit at 6.24 g/kg compared to the reference unit's 4.97 g/kg, showing a gap of 1.27 g/kg.

Similar patterns were observed in the living room, and notably, the unheated room and balcony also maintained consistently higher absolute humidity levels in the renovated unit across all outdoor temperature ranges. This suggests that envelope performance improvements affect humidity environments not only in heated spaces but also in unheated spaces.

The observed increase in absolute humidity is closely associated with improved airtightness resulting from envelope renovation. Taki et al. [26] reported that building deterioration over time leads to decreased airtightness, resulting in uncontrolled infiltration by introducing external heat and moisture loads into indoor spaces, causing qualitative degradation of living environments. Enhanced airtightness suppresses unintended exchange between indoor air and external environments. Moisture generated from occupants' daily activities such as cooking, bathing, and respiration [39] remains in airtight spaces for extended periods, contributing to indoor humidity levels.

Envelope renovation achieved temperature increases of 2–7 °C across all spaces, with greater improvement effects under extreme climate conditions. Temperature standard deviation decreased by 25–37% in living spaces, indicating improved indoor temperature stability against outdoor temperature fluctuations. Absolute humidity increased by 0.4–1.6 g/m^3 (10–30%) across all spaces, reflecting the effect of reduced infiltration due to

improved envelope airtightness, where water vapor generated from occupant activities is retained indoors rather than escaping outside.

However, limitations exist in attributing these thermal environment improvements solely to envelope performance enhancement. While this study established the reference unit as a comparison group for indoor thermal environments before and after renovation, the renovated and reference units are separate households with different occupants, making it impossible to exclude the possibility of differing thermal comfort preferences and heating operation habits. The renovated unit's tendency to maintain higher indoor temperatures than the reference unit under identical outdoor conditions may result from combined effects of envelope performance improvements and occupants' preference for higher indoor temperatures. Therefore, additional quantitative analysis examining the relationship between heating water consumption and indoor–outdoor temperature differences is necessary to isolate pure envelope improvement effects from observed thermal environment differences.

3.1.2. Regression Analysis of Indoor–Outdoor Temperature Differential and Heating Consumption

To clearly distinguish whether the indoor temperature differences identified in Section 3.1.1 resulted from increased heating water consumption or from envelope performance improvements, heating water consumption from 17 January to 31 March 2021 was analyzed by outdoor temperature ranges.

Table 4 presents average daily heating water consumption by outdoor temperature range, calculated using the daily consumption estimation method specified in Section 2.2 to derive daily heating water estimates from utility bill data. Daily mean outdoor temperatures from 17 January to 31 March 2021 were classified into four ranges.

Table 4. Daily heating water consumption patterns across outdoor temperature ranges for Reference and Renovated units.

Outdoor Temperature Range	Reference Unit [m^3/Day]	Renovated Unit [m^3/Day]	Difference
Severe Cold ($T_O \leq -5$ °C)	5.89 ± 0.73	7.92 ± 0.97	+34.60%
Cold (−5 °C < $T_O \leq 0$ °C)	4.56 ± 0.42	6.41 ± 1.12	+40.58%
Mild (0 °C < $T_O \leq 10$ °C)	2.22 ± 0.70	2.52 ± 1.30	+13.83%
Moderate (10 °C < T_O)	0.60 ± 0.34	0.06 ± 0.11	−89.52%

Under Severe Cold conditions ($T_O \leq -5$ °C), the renovated unit's average daily consumption was 7.92 ± 0.97 m^3/day, 34.6% higher than the reference unit's 5.89 ± 0.73 m^3/day. Under Cold conditions (−5 °C < $T_O \leq 0$ °C), this difference increased to 40.6%, with consumption of 6.41 ± 1.12 m^3/day and 4.56 ± 0.42 m^3/day respectively.

Both units showed decreased heating water consumption with rising outdoor temperatures. Under Mild conditions (0 °C < $T_O \leq 10$ °C), the renovated unit recorded 2.52 ± 1.30 m^3/day while the reference unit recorded 2.22 ± 0.70 m^3/day. Under Moderate conditions (10 °C < T_O), consumption decreased to 0.06 ± 0.11 m^3/day and 0.60 ± 0.34 m^3/day respectively. The consumption reduction rate from Severe Cold to Moderate reached 99.2% for the renovated unit and 89.8% for the reference unit.

The renovated unit with improved envelope performance paradoxically consumed more heating water than the reference unit under Severe Cold, Cold, and Mild conditions. This pattern allows for different interpretation when considered alongside the indoor temperature data from Section 3.1.1. As shown in Table 2, the renovated unit maintained indoor temperatures 4–7 °C higher than the reference unit under all outdoor conditions, particularly in the main room under Severe Cold conditions, where the reference unit maintained

18.7 °C and the renovated unit achieved 25.8 °C, operating heating to exceed the recommended winter comfort temperature upper limit [36]. Therefore, the higher heating water consumption is interpreted as occupants' choice to maintain higher indoor temperatures.

According to Du et al. [24], residential building occupants directly bear energy costs and thus clearly recognize the direct relationship between their heating behavior and energy expenses, forming conservative attitudes toward energy usage patterns. From this perspective, the reference unit is interpreted as showing heating operation suppression behavior under extreme cold considering economic burden, despite limitations in maintaining comfortable indoor temperatures due to continuous heat loss through the unimproved envelope. In contrast, the renovated unit performed active heating maintaining high indoor temperatures even under extreme cold. As outdoor temperatures rose, both units reduced heating operation frequency, with the renovated unit with enhanced envelope performance operating almost no heating under Moderate conditions. These results indicate that the improved envelope effectively blocks heat loss, enabling maintenance of occupants' preferred indoor temperatures for extended periods with only intermittent heating.

The importance of independent variable selection in heating energy prediction models has been demonstrated in numerous studies. Lee et al. [37] reported that indoor temperature comprehensively reflects building thermal performance, showing high predictive capability, while Ji et al. [36] confirmed indoor temperature as a primary factor in predicting occupants' thermal sensation. However, Bae et al. [21] reported that outdoor temperature alone explains only 24.8% of heating energy variation, increasing to 41.2% when occupant behavior variables are included. Gill et al. [40] and Schweiker and Shukuya [41] also emphasized that occupant behavior accounts for 51–90% of heating energy variation.

The deteriorated envelope characteristics of the subject building, completed in 1991, are particularly susceptible to outdoor temperature influences. Lee et al. [37] revealed that indoor–outdoor temperature differences in deteriorated low-income housing reach up to 8.2 °C in winter, while Ji et al. [36] reported that heating energy accounts for 65–90% of total energy consumption in buildings with poor envelope performance.

These previous research findings suggest that neither indoor temperature nor outdoor temperature alone can adequately explain heating energy consumption, indicating the need for an approach that reflects occupant behavioral patterns. Therefore, this study adopted indoor–outdoor temperature difference (ΔT) as the independent variable for regression analysis, as it comprehensively captures envelope insulation performance, heating input, external influences, and occupant preferences.

The analytical model is defined as follows, where H represents heating water consumption:

$$\Delta T = a + b \times H \tag{6}$$

Here, the intercept (a) represents the baseline temperature difference maintained solely by envelope performance without heating operation, while the slope (b) indicates the temperature difference increase rate per unit of heating water consumption (°C/m^3). The coefficient of determination (R^2) was utilized as an indicator of how well heating water consumption explains indoor–outdoor temperature difference variations.

Table 5 presents regression analysis results for the relationship between indoor–outdoor temperature difference and heating water consumption by space. H represents the daily heating water consumption (m^3/day) mentioned in Table 4, applied uniformly across all spaces. Therefore, the focus was on identifying relative performance change patterns before and after renovation rather than absolute efficiency.

Table 5. Regression analysis of indoor–outdoor temperature difference versus heating water consumption relationship by space type.

Space	Unit	Intercept (a) [°C]	Slope (b) [°C/m^3]	R^2
Main room	Reference	4.98	3.38	0.853
	Renovated	12.15	2.35	0.882
Living room	Reference	5.48	3.49	0.848
	Renovated	10.63	2.21	0.888
Unheated room	Reference	3.48	3.06	0.827
	Renovated	7.45	1.90	0.836
Balcony	Reference	4.35	1.83	0.597
	Renovated	6.08	1.14	0.600

The R^2 values in Table 5 maintaining high levels of 0.827–0.888 for main, living, and unheated rooms demonstrate statistically significant linear relationships between heating water consumption and indoor–outdoor temperature differences. Particularly, the renovated unit's R^2 values for main and living rooms were 0.882 and 0.888, respectively, higher than the reference unit's 0.853 and 0.848. This suggests that thermal responses of the heating system became more predictable and stable after envelope performance improvements. However, the balcony showed lower R^2 values around 0.6 compared to other spaces, attributed to its characteristic of direct exposure to outdoor conditions.

As shown in Table 5, the renovated unit's intercept values were higher than the reference units across all spaces. The main room increased 2.4-fold from 4.98 °C to 12.15 °C, while the living room increased 1.9-fold from 5.48 °C to 10.63 °C. The unheated room, despite lacking direct heating, also showed a 2.1-fold increase from 3.48 °C to 7.45 °C. The elevated intercept values in the renovated unit indicate an increased tendency to maintain indoor–outdoor temperature differences even without heating water supply, suggesting overall insulation performance improvement through envelope renovation.

The slope coefficients demonstrate thermal responsiveness to heating energy input. The reference unit's main room and living room showed high slopes of 3.38 °C/m^3 and 3.49 °C/m^3 respectively, indicating rapid indoor–outdoor temperature difference increases per unit heating water consumption. In contrast, the renovated unit recorded lower slopes of 2.35 °C/m^3 and 2.21 °C/m^3 in the same spaces. Additionally, the unheated room's slope decreased by 38% from 3.06 °C/m^3 in the reference unit to 1.90 °C/m^3 in the renovated unit, demonstrating effective heat retention in adjacent spaces.

The relationship between intercept and slope coefficients clearly reveals differences in envelope performance and heating operation methods between the two units. The reference unit's low intercept and high slope indicate small indoor–outdoor temperature differences without heating and sharp responses when heating water is supplied. This suggests occupants operate heating intermittently only when necessary. Conversely, the renovated unit's high intercept and gradual slope indicate that indoor–outdoor temperature differences maintain above certain levels even without heating, with relatively moderate indoor temperature rise responses to heating operation. This shows that the improved envelope effectively blocks heat loss, consequently enabling occupants to maintain relatively high indoor temperatures with moderate heating operation. These findings align with occupant behavior change mechanisms presented by Laskari et al. [20]. Users with higher thermostat settings (20.7–22.8 °C) and longer operation times (16–24 h) showed relatively stable heating patterns, while those with lower settings (18.5–20 °C) and shorter

operation times (6–9 h) exhibited intermittent patterns activating heating systems multiple times daily.

3.2. Quantification of Occupant Heating Behavior Changes Through Energy Analysis

3.2.1. Critical Heating Temperature Shift Analysis

To quantify the effects of building envelope renovation on changes in heating initiation timing, change-point model analysis was performed on heating water consumption for the renovated unit before and after renovation, as well as for the reference unit. The analysis utilized monthly billing-based heating water consumption and outdoor temperature data.

Pre-renovation data covered 33 months from January 2018 to September 2020, reflecting the renovated unit's heating operation patterns before renovation. Post-renovation data covered 16 months from November 2020 to February 2022, with October 2020 excluded from analysis, as this was during renovation construction, to clearly evaluate envelope performance improvement effects. The reference unit, an adjacent household within the same complex, corresponds to the comparison group established in Section 3.1. The analysis of reference unit utilized heating water consumption billing data for the period from January 2018 to September 2021.

Table 6 comprehensively presents change-point model analysis results for the three cases. All three constructed models showed high goodness-of-fit, with coefficients of determination (R^2) of 0.96 for pre-renovation, 0.95 for post-renovation, and 0.92 for the reference unit, all demonstrating excellent explanatory power exceeding 90%. CV-RMSE values were 23.7%, 21.9%, and 36.7%, respectively, meeting the 40% threshold for residential buildings [35]. The reference unit's relatively high CV-RMSE of 36.7% is interpreted as reflecting heating pattern variability during the approximately four-year analysis period and irregular heat loss characteristics of the deteriorated envelope. Figure 2 presents monthly heating water consumption and monthly mean outdoor temperatures for pre- and post-renovation and the reference unit, visually showing seasonal heating pattern changes and particularly confirming an overall decreasing trend in winter heating water consumption.

Table 6. Comparison of change-point model parameters for pre-renovation, post-renovation, and reference units.

Category	Change-Point Temperature (T_{CP}) [°C]	Baseline Consumption (E_{nonOA}) [m³]	Slope Coefficient (*HS*) [m³/°C]	R^2	CV-RMSE [%]
Pre-renovation	16.4	156.5	−6.92	0.96	23.7
Post-renovation	11.0	129.2	−6.07	0.95	21.9
Reference unit	13.9	115.7	−5.24	0.92	36.7

The pre-renovation change-point temperature (T_{CP}) was 16.4 °C, indicating a pattern where substantial heating commenced when outdoor temperatures fell below 16.4 °C. The baseline consumption (E_{nonOA}) of 156.5 m³ reflects hot water demand and basic heating needs maintained even above the change-point temperature, while the slope coefficient (HS) of −6.92 m³/°C indicates the sensitivity of 6.92 m³ additional heating water consumption per 1 °C decrease in outdoor temperature.

The relationship between building envelope performance and change-point temperature has been confirmed in previous studies. Staffell et al. [42] explained that change-point temperature is determined by building physical characteristics and occupant behavioral patterns. Building insulation performance, airtightness, and window area particularly

influence indoor temperature, consequently serving as primary factors determining heating initiation temperature.

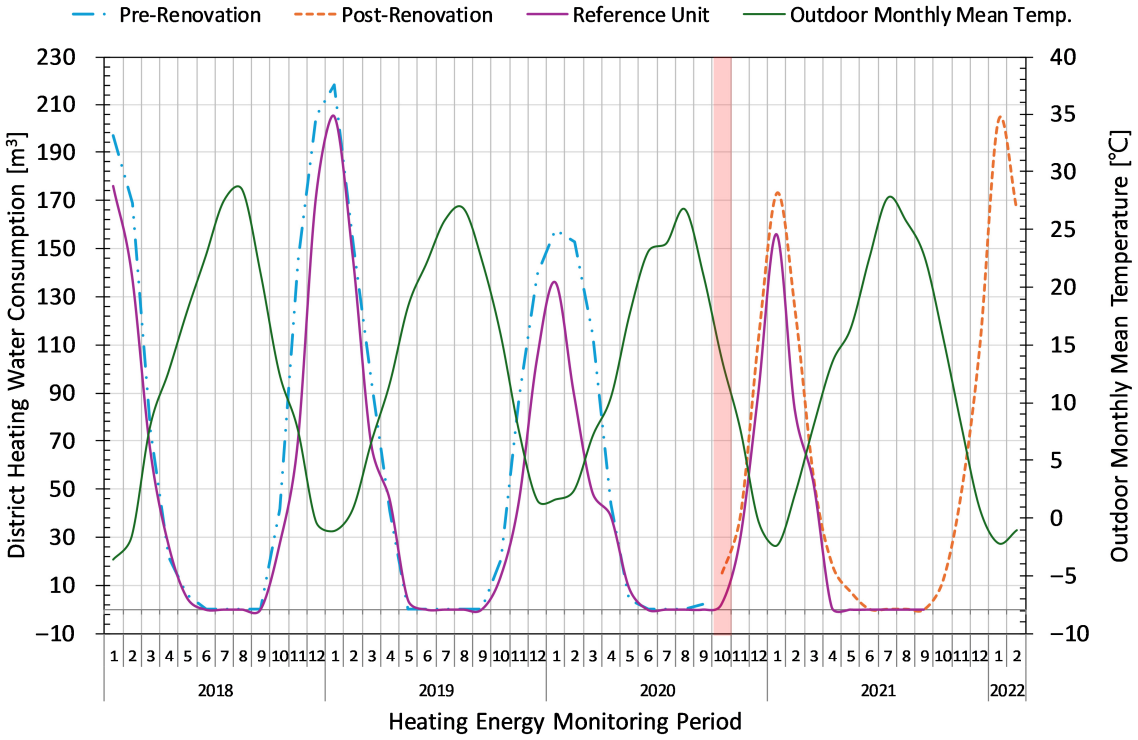


Figure 2. Comparison of monthly heating water consumption for the renovated unit (pre- and post-renovation) and the reference unit alongside outdoor mean temperature.

In the post-renovation period with envelope renovation applied, the change-point temperature shifted substantially downward by 5.4 °C to 11.0 °C. This indicates that envelope performance improvements enabled occupants to maintain preferred indoor temperatures without heating until lower outdoor temperatures. Baseline consumption decreased by 17.4% to 129.2 m^3, confirming basic heating load reduction due to improved airtightness and decreased heat loss. The slope coefficient moderated to −6.07 m^3/°C, representing a 12.3% reduction in heating demand increase rate relative to outdoor temperature changes.

The reference unit's change-point temperature of 13.9 °C is 2.5 °C lower than pre-renovation but 2.9 °C higher than post-renovation. This demonstrates that while reference unit occupants adopt conservative heating strategies due to economic burden, envelope performance limitations prevent them from delaying heating initiation as much as the post-renovation case. The reference unit's baseline consumption of 115.7 m^3 is the lowest among the three cases, reflecting the conservative heating pattern maintaining average indoor temperatures of 18–19 °C as confirmed in Section 3.1.1. The slope coefficient of −5.24 m^3/°C is also the most gradual, indicating low sensitivity to outdoor temperature changes, but this is interpreted as resulting from passive operation methods restraining active heating.

Figure 3 presents a comparison of the correlation between monthly mean outdoor temperature and heating water consumption. Pre-renovation forms a change-point at 16.4 °C with a steep slope, while post-renovation shows the lowest change-point at 11.0 °C with a moderate slope. The differences among the three cases are particularly evident in the 10–15 °C outdoor temperature range, where pre-renovation already shows high heating water consumption while post-renovation maintains minimal usage before initiating substantial heating below 11 °C, a pattern that is visually confirmed. The reference unit

shows an intermediate change-point at 13.9 °C with the most gradual slope, maintaining the lowest consumption across all temperature ranges.

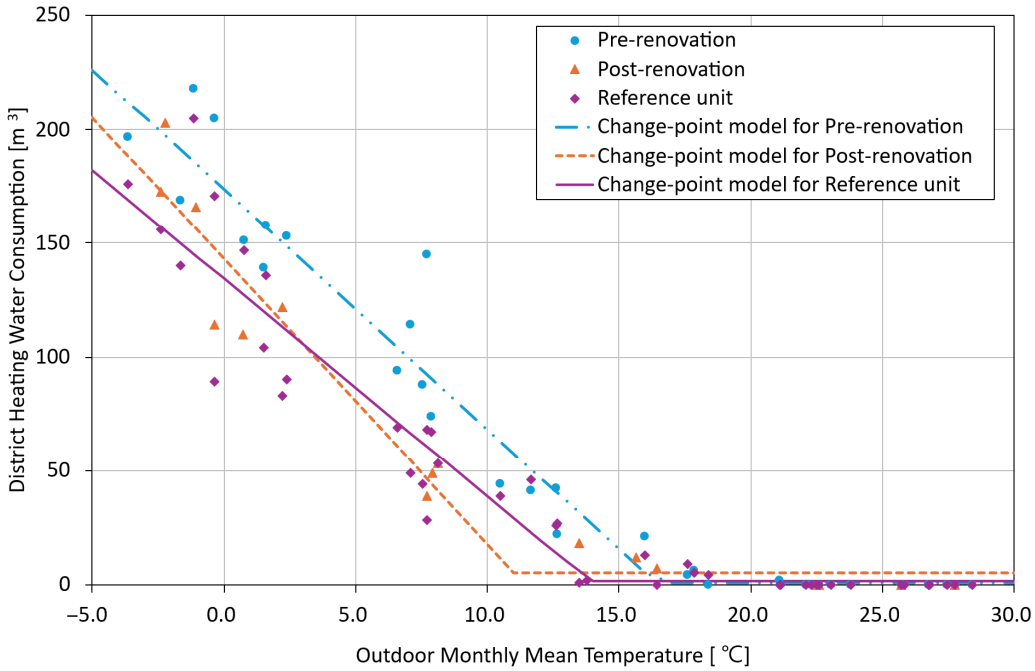


Figure 3. Correlation analysis of monthly mean outdoor temperature and district heating water consumption with change-point models: comparison of pre-renovation, post-renovation, and reference units.

These change-point analysis results quantitatively demonstrate that envelope renovation not only reduced total energy consumption but also altered heating initiation temperature and heating intensity control patterns. The 5.4 °C downward shift in change-point temperature indicates that occupants actually experienced the effects of envelope performance improvements and reflected this in their heating decisions.

3.2.2. Temperature-Segmented Analysis of Energy Reduction Patterns

Section 3.2.1 confirmed through change-point model analysis that the heating threshold temperature shifted downward by 4.7 °C from 15.4 °C to 10.7 °C. This section specifically identifies changes in occupant heating behavioral patterns through heating water consumption changes by outdoor temperature range and shifts in temperature ranges with high heating dependency. The daily heating water consumption estimation algorithm presented in Section 2.2 was applied to derive consumption patterns per 1 °C outdoor temperature interval. However, this estimation method inherently assumes heating consumption is zero beyond the change-point temperature, which may not fully reproduce occupants' actual intermittent heating behavior.

The analysis periods were set as 486 days pre-renovation (1 November 2018–29 February 2020) and 485 days post-renovation (1 November 2020–28 February 2022). Despite more severe climate conditions post-renovation, with minimum temperatures dropping from −9.9 °C to −14.4 °C and days below −5 °C increasing more than 2.5-fold from 13 to 33 days, total heating water consumption decreased by 347.0 m^3 from 1413.0 m^3 to 1066.0 m^3, achieving a 24.6% reduction rate. While average outdoor temperature remained similar at 10.7 °C versus 10.4 °C, these savings under substantially increased frequency and intensity of extreme cold clearly demonstrate the practical effects of envelope performance improvements.

Classifying outdoor temperature into four ranges—Severe Cold ($T_O \leq -5$ °C), Cold (-5 °C < $T_O \leq 0$ °C), Mild (0 °C < $T_O \leq 10$ °C) and Moderate ($T_O > 10$ °C)—and analyzing average daily consumption revealed differentiated reduction patterns by temperature range. In the Severe Cold range, average daily consumption decreased 12.5% from 8.8 m^3/day to 7.7 m^3/day, while in the Cold range it decreased 11.9% from 6.7 m^3/day to 5.9 m^3/day, showing stable reduction rates around 12% under extreme conditions. These reductions were achieved despite the renovated unit maintaining substantially elevated indoor temperatures even under extreme cold conditions, as analyzed in Section 3.1.1. This demonstrates that energy savings were achieved not through conservative heating practices, but rather that envelope improvements enabled simultaneous realization of both energy reduction and enhanced thermal comfort.

Conversely, markedly higher reduction effects appeared under mild climate conditions. In the Mild range, average daily consumption decreased 35.7% from 4.2 m^3/day to 2.7 m^3/day, while in the Moderate range it decreased 66.7% from 0.3 m^3/day to 0.1 m^3/day. The Mild range particularly represents the most frequent days during the heating period, and achieving high reduction rates despite decreasing from 176 to 151 days suggests the importance of intermediate-season heating efficiency improvements. High reduction rates under mild conditions indicate that periods when occupants can maintain comfortable indoor environments without relying on heating operation have been substantially extended.

Figure 4 illustrates the distribution of cumulative heating water consumption by outdoor temperature. Pre-renovation shows a pattern of sharp increase from -10 °C to -3 °C, followed by gradual decrease to 7 °C, then plateauing above 8 °C. Post-renovation exhibits a modified pattern starting from -14 °C with an overall gentler slope, reaching a peak at -5 °C before gradually declining. Notably, the 50% cumulative consumption point shifted downward by 3 °C from 2 °C pre-renovation to -1 °C post-renovation, indicating changes in heating dependency following envelope performance improvements. The steep slope in the post-renovation below -5 °C range is attributed to extreme climate conditions, with intermediate-season reduction effects offsetting this increase to achieve overall cumulative reduction.

Table 7 presents average daily heating water consumption by outdoor temperature range, calculated by dividing total consumption at each temperature by the number of days at that temperature. During the pre-renovation analysis period, no extreme low temperatures below -10 °C were observed, leaving these ranges blank, whereas post-renovation recorded severe cold down to -14 °C.

To quantitatively evaluate changes in temperature ranges with high heating dependencies, daily heating water consumption of 4.0 m^3 or above was established as the high-dependency criterion. This threshold represents the 75th percentile in the distribution of individual daily heating water consumption, rounded from the post-renovation 75th percentile value (3.85 m^3/day) to ensure consistency in before–after comparisons.

This percentile-based approach is a commonly utilized methodology in energy consumption pattern analysis. Staffell et al. [42] employed 90th and 10th percentiles to distinguish high/low heating days for identifying extreme climate conditions, methodologically consistent with this study's 75th percentile criterion. Particularly, Heesen et al. [19] discovered that the 25th percentile represents a major inflection point in consumption behavior when analyzing actual heating energy consumption across energy efficiency ratings in German buildings.

Pre-renovation analysis of the renovated unit revealed high dependency of 4.0 m^3/day or above in the range from the observed minimum temperature of -10 °C to 6 °C. Days exhibiting actual high dependency numbered 187, accounting for 38.5% of the total, with an average consumption of 5.9 m^3/day and average outdoor temperature of 0.6 °C.

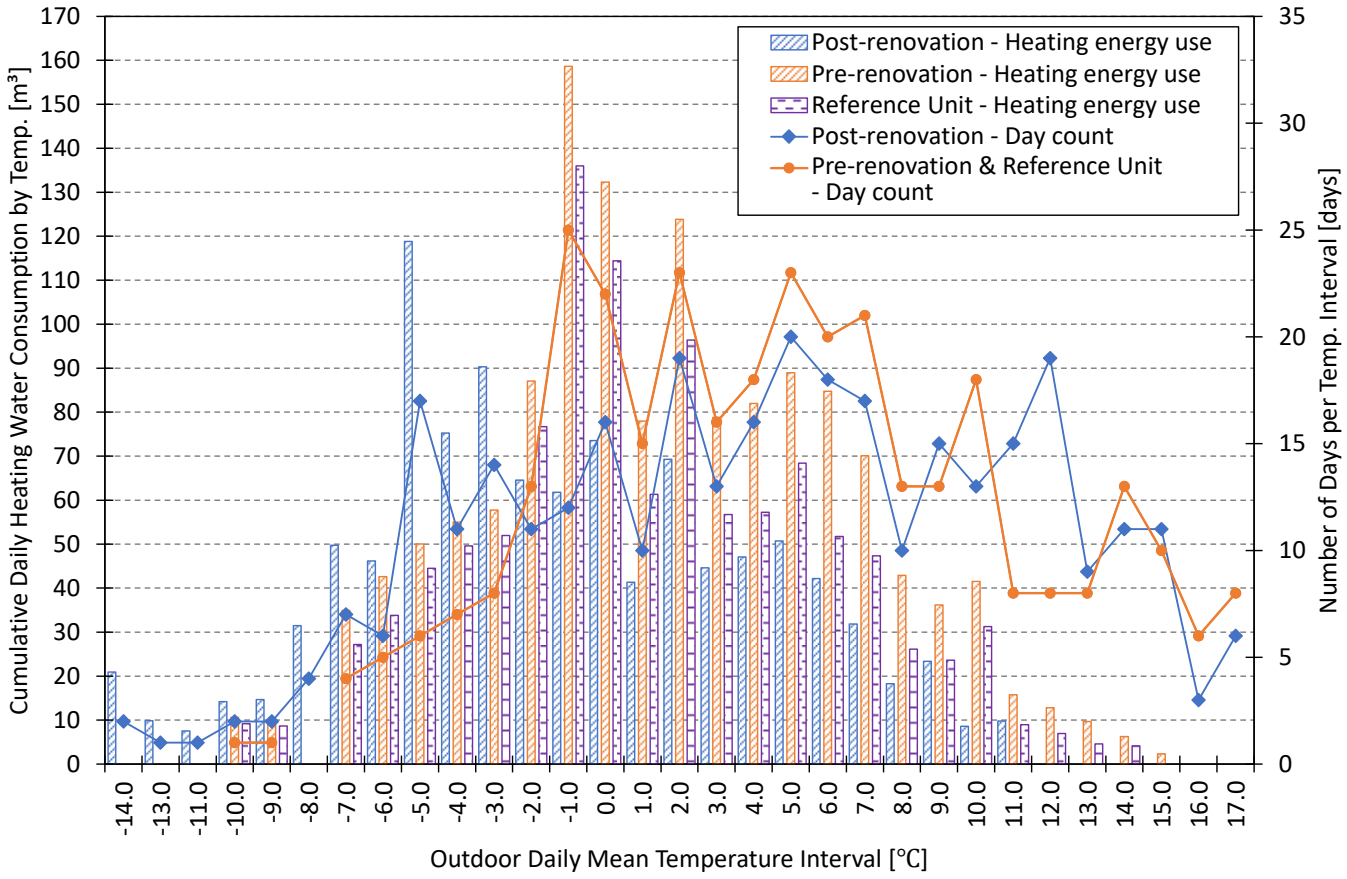


Figure 4. Cumulative daily heating water consumption by outdoor temperature intervals in pre- and post-renovation periods.

The reference unit's 75th percentile value was 3.87 m^3/day; thus, 4.0 m^3 daily heating water consumption was established as the high-dependency criterion. Analysis revealed high dependency in the range of −10 °C to 2 °C, recording an average of 5.5 m^3/day over 130 days (26.7%). Both units showed sharp consumption increases at sub-zero temperatures, though the renovated unit recorded higher overall consumption. These differences quantitatively demonstrate the influence of occupants' preferred indoor temperature levels on heating behavior. Under identical envelope performance conditions, the renovated unit's high-dependency days being 1.4 times greater than the reference unit reflects the high indoor temperature preference tendency confirmed in Section 3.1.

Post-renovation, the renovated unit's high-dependency temperature range shifted to −14 °C to 1 °C, including newly emerged extreme low-temperature ranges. The critical change is that the high-dependency upper limit shifted downward by 5 °C from 6 °C to 1 °C, with the post-renovation upper limit (1 °C) becoming lower than even the reference unit's upper limit (2 °C). This is interpreted as envelope performance improvements adjusting occupants' heating activation decision points downward, forming more efficient heating patterns than the energy-conserving reference unit. The downward shift in the high-dependency range's upper limit and the heating water consumption reduction under mild conditions as was confirmed through detailed temperature-specific analysis are consistent with the change-point temperature downward shift derived in Section 3.2.1, quantitatively demonstrating that envelope renovation substantially induced changes in occupants' heating behavior.

Table 7. Average daily district heating water consumption by outdoor temperature ranges.

Daily Outdoor Mean Temp. (°C)	Renovated Unit		Reference Unit [m^3/Day]
	Pre-Renovation [m^3/Day]	Post-Renovation [m^3/Day]	
−14.0	-	10.5	-
−13.0	-	9.9	-
−12.0	-	-	-
−11.0	-	7.5	-
−10.0	10.6	7.1	9.2
−9.0	10.0	7.3	8.6
−8.0	-	7.9	-
−7.0	8.7	7.1	6.8
−6.0	8.5	7.7	6.8
−5.0	8.3	7.0	7.4
−4.0	7.9	6.8	7.1
−3.0	7.2	6.5	6.5
−2.0	6.7	5.9	5.9
−1.0	6.3	5.2	5.4
0.0	6.0	4.6	5.2
1.0	5.2	4.1	4.1
2.0	5.4	3.6	4.2
3.0	4.9	3.4	3.5
4.0	4.6	2.9	3.2
5.0	3.9	2.5	3.0
6.0	4.2	2.3	2.6
7.0	3.3	1.9	2.3
8.0	3.3	1.8	2.0
9.0	2.8	1.6	1.8
10.0	2.3	0.7	1.7

3.3. Limitations and Future Research

While this research quantitatively demonstrates how envelope renovation influences occupant heating behavior patterns, several methodological constraints warrant acknowledgment. The fundamental constraint of this investigation stems from its focus on a single household case study. Moreover, the inability to control for variables such as personal characteristics, economic status, and lifestyle preferences of residents limits the broader applicability of these findings. Unlike the comprehensive work by Majcen et al. [9], who analyzed approximately 50,000 Dutch dwellings and demonstrated that building characteristics, household attributes, and behavioral factors all significantly affect heating energy consumption, our investigation concentrated on one specific case without capturing these complex variable interactions.

Relying exclusively on physical measurement data presents additional constraints. Although we conducted quantitative analysis based on indoor temperature–humidity monitoring and heating water consumption records to ensure objectivity, understanding the

intrinsic motivations behind behavioral changes—such as subjective thermal comfort evaluations, heating operation decision-making processes, and post-renovation satisfaction—remained beyond reach. Du et al. [24] emphasize that combining physical measurements with occupant surveys proves essential for understanding both the "what" and "why" of behavioral patterns. Consequently, the psychological and social mechanisms underlying the observed changes, including the downward shift in change-point temperature and reduced heating water consumption under mild conditions, remain incompletely explained. Given that Gill et al. [40] found occupant behavior accounts for over 50% of heating energy variations in low-energy housing, the absence of qualitative data constrains the depth of our interpretation.

Methodological uncertainties in daily energy estimation algorithms also merit consideration. Although we developed an approach to distribute monthly meter readings into daily values using outdoor temperature-weighted allocation, this method may not capture all actual daily consumption variability. Laskari et al. [20] demonstrated that weekday–weekend occupancy patterns, extreme weather events, and personal schedule variations substantially influence heating energy consumption, yet our algorithm does not incorporate these factors. Furthermore, district heating system characteristics restricted our analysis to heating water flow rates as energy indicators, preventing accurate heat quantity calculations considering supply return temperature differentials. Without smart meters or real-time measurement data, algorithm accuracy verification proved challenging.

The rebound effect, though not observed in our study, represents an important consideration. Heesen et al. [19] revealed in their German multi-family housing research that reduced per-unit energy service costs from efficiency improvements can paradoxically increase energy consumption. While we confirmed overall heating water consumption decreased post-renovation, higher consumption than the reference unit during extreme cold conditions suggests potential partial rebound effects.

Future investigations should adopt multifaceted approaches to address these limitations. Multi-case comparative research encompassing diverse building types, geographic locations, and household characteristics must validate the external validity of our methodology and findings. Following Majcen et al.'s [9] approach, large-scale stratified sampling designs should incorporate physical characteristics like floor location, unit configuration, and dwelling area alongside socioeconomic factors, including household size, age distribution, and income levels.

Integrating quantitative measurements with qualitative investigations proved essential. The differential patterns we observed—higher heating water consumption during extreme cold yet substantial savings under mild conditions—suggest occupants adaptively respond to envelope performance improvements. Systematic analysis of relationships between subjective thermal sensation and objective environmental conditions, applying standardized thermal comfort evaluation protocols such as ASHRAE Standard 55 [43] or EN 15251 [44], would clarify behavioral change mechanisms. Additionally, in-depth interviews or structured surveys should explore how energy conservation awareness, thermal comfort preferences, and economic factors collectively influence heating behavior.

Technically, high-resolution real-time monitoring systems utilizing smart meters and IoT sensors become necessary. Following Bae et al.'s [21] approach, real-time measurement of space-specific heating water consumption, supply return temperature differentials, room-level temperature–humidity, window opening status, and occupancy patterns would verify and refine daily estimation algorithm accuracy. Through such comprehensive approaches, integrated evaluation models considering building physical characteristics, climatic conditions, occupant attributes, and energy pricing can be developed. Ultimately, this would

provide policy decision-support tools capable of accurately predicting renovation investment effectiveness.

4. Conclusions

This study quantified the effects of envelope renovation on occupants' actual heating operation patterns in aging apartment buildings through temperature-specific daily energy distribution analysis. The integrated envelope improvements comprising high-performance windows, entrance doors, and vacuum insulation systems applied to a 30-year-old apartment achieved heating energy savings, even under more severe climate conditions, confirming that these results extended beyond total consumption reduction to encompass changes in occupants' heating behavioral patterns.

The academic contribution of this research lies in the daily energy distribution methodology that overcomes limitations of monthly billing data-based analysis and detailed tracking of occupant behavior. Comparative analysis between renovated and reference units confirmed that occupants adopt different heating strategies even under identical environments. The renovated unit showed patterns of maintaining high indoor temperatures by consuming more heating water than the reference unit even in extreme cold after renovation. Nevertheless, the upper limit of temperature ranges showing high heating dependency shifted downward after renovation, improving to levels lower than even the energy-conserving reference unit. This change indicates that the threshold temperature at which occupants decide whether to operate heating has shifted to lower temperatures due to envelope performance improvements. The multi-stage reduction pattern appearing after renovation demonstrates that occupants could operate heating intermittently in this improved thermal environment, leading to heating energy savings under mild conditions and an overall reduction in heating water consumption.

However, this study has representativeness limitations as a case study of a single household, requiring future research to expand to various floor plan types and geographic ranges. Additionally, uncertainty analysis of the daily energy estimation algorithm was limited, necessitating validation based on detailed measured data including smart meters and space-specific heating water consumption measurements. The use of heating water flow alone as an energy indicator suggests the need for supplementary research incorporating calorimeter data or supply/return temperature values. Furthermore, comparative studies across diverse climate zones and building typologies are essential to validate the generalizability of the methodology presented in this study.

Through the development of integrated evaluation models that comprehensively consider building physical characteristics, climatic conditions, occupant attributes, and energy pricing structures, future research should provide policy decision-support tools capable of accurately predicting renovation investment effectiveness. The temperature-specific daily distribution methodology presented in this study can serve as a foundational framework for such integrated models. By incorporating qualitative data through structured surveys and in-depth interviews, these enhanced approaches would enable a more complete understanding of the mechanisms through which envelope renovation induces occupant behavioral changes, ultimately bridging the gap between technical improvements and actual energy performance outcomes.

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