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Evaluation of Energy and CO₂ Reduction Through Envelope Retrofitting: A Case Study of a Public Building in South Korea Conducted Using Utility Billing Data

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Abstract

This study empirically evaluates the energy and carbon reduction effects of an envelope retrofit applied to an aging public building in South Korea. Unlike previous studies that primarily relied on simulation-based analyses, this work fills the empirical research gap by using actual utility billing data collected over one pre-retrofit year (2019) and two post-retrofit years (2023–2024). The retrofit included improvements to exterior walls, roofs, and windows, aiming to enhance thermal insulation and airtightness. The analysis revealed that monthly electricity consumption was reduced by 14.7% in 2023 and 8.0% in 2024 compared to that in the baseline year, with corresponding decreases in electricity costs and carbon dioxide emissions. Seasonal variations were evident: energy savings were significant in the winter due to reduced heating demand, while cooling energy use slightly increased in the summer, likely due to diminished solar heat gains resulting from improved insulation. By addressing both heating and cooling impacts, this study offers practical insights into the trade-offs of envelope retrofitting. The findings contribute to the body of knowledge by demonstrating the real-world performance of retrofit technologies and providing data-driven evidence that can inform policies and strategies for improving energy efficiency in public buildings.



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1. Introduction

According to the 2050 Carbon Neutrality Scenario, the building sector is responsible for approximately 7% of South Korea's total greenhouse gas (GHG) emissions, making it the second-largest emitter after the industrial sector. The transition (including power generation), industrial, transport, building, and other (e.g., agriculture, fishing, and waste) sectors emit 269.6 (37%), 260.5 (36%), 98.1 (13%), 52.1 (7%), and 47.4 (6%) million tCO₂eq, respectively. However, these figures only account for direct emissions from the use of fossil fuel, such as natural gas, within buildings. When indirect emissions from electricity and district heating are included, emissions from the building sector account for 24.6% of Korea's total GHG emissions [1].

In April 2023, the Korean government announced the First National Basic Plan for Carbon Neutrality and Green Growth, which highlights the importance of zero-energy building (ZEB) expansion and green remodeling promotion as core strategies for reducing GHG emissions in the building sector [2].

According to the “2022 National Building Statistics” report published by the Ministry of Land, Infrastructure, and Transport (MOLIT) in February 2023, as of the end of 2022, approximately 3.01 million buildings (41%) were over 30 years old. The proportion of aged buildings has steadily increased as follows: 36.5%, 37.1%, and 37.8% in 2017, 2018, and 2019, respectively [3]. However, policies and systems for managing the energy efficiency of aged buildings remain insufficient, and there is a lack of quality control technologies in design and construction for green remodeling. Aged buildings also suffer from multiple defects, such as thermal bridges, poor insulation, airtightness problems, and condensation. Therefore, the green remodeling of aged buildings is one of the most effective solutions for improving energy efficiency and reducing CO₂ emissions at the national level.

The Korean government is actively promoting green remodeling projects for both public and private buildings to improve energy efficiency. These initiatives are intended to ensure the sustainable improvement of existing buildings by enhancing energy performance and expanding the adoption of green technologies. The Green Remodeling Project for Public Buildings, a representative Green New Deal initiative, targets public facilities such as daycare centers, health centers, and medical clinics that are over 10 years old. Since its launch in 2020, the project has supported 821, 895, 575, and 617 cases in 2020, 2021, 2022, and 2023, respectively.

In the private sector, the Green Remodeling Interest Support Program provides financial assistance to building owners who undertake energy-saving renovations. This program covers up to 4% of loan interest for green remodeling construction costs, with a support period of up to 60 months. Since its inception in 2014, approximately KRW 6 billion (USD 4.5 million) has been allocated annually, mainly for residential window replacement projects, and the program’s scope continues to expand [4].

These policies are no longer seen as simple renovation initiatives; rather, they are now evaluated as practical mechanisms aligned with the national carbon neutrality strategy. In this context, the importance of using real-world data in empirical studies assessing the effectiveness of green remodeling is increasingly emphasized.

Several prior studies have investigated the energy performance improvements achieved through the green remodeling of public buildings, primarily using simulation-based approaches. Kim et al. [5] analyzed a small-scale public facility under 500 m² using ECO2 and DesignBuilder simulations, reporting reductions in both heating and cooling energy demands while also highlighting discrepancies between static and dynamic modeling methods. Lee and Yang [6] evaluated the energy performance of a public health center before and after a retrofit using ECO2, demonstrating notable improvements in thermal performance. Jung et al. [7] conducted a sensitivity analysis on a hospital envelope, showing that changes in insulation levels, window types, and airtightness had a significant impact on both heating and cooling loads. These studies offer valuable insights into how passive technologies affect energy demand in healthcare and administrative facilities.

However, the majority of these assessments rely solely on simulated performance and do not reflect actual post-retrofit energy use in operational buildings. There remains a critical research gap in empirical studies that validate the effectiveness of retrofit measures using measured utility billing data. Additionally, while previous studies primarily emphasized insulation and heating performance, few addressed the real-world impact of retrofits on cooling energy consumption, which is increasingly relevant under warming climatic conditions.

This study addresses these gaps by providing an empirical evaluation of a public building in South Korea, using utility billing data to compare pre- and post-retrofit energy performance. The analysis quantifies changes in energy consumption, electricity costs, and

CO₂ emissions over two years following the retrofit, offering evidence-based insights into the practical effectiveness of passive retrofit strategies.

Among the various passive retrofit technologies, external insulation systems and advanced insulation materials have gained particular attention for their ability to significantly improve building envelope performance while minimizing disruptions to building operations. In particular, prefabricated external insulation systems enable rapid on-site installation and minimize construction waste, making them suitable for retrofitting occupied public buildings [8]. These systems enhance thermal performance by adding insulation layers externally, which also reduces thermal bridging risks.

Moreover, vacuum insulation panels (VIPs) have emerged as a cutting-edge solution for maximizing insulation effectiveness within limited thicknesses. VIPs exhibit ultra-low thermal conductivity (approximately 0.004–0.005 W/m·K), allowing them to deliver equivalent or superior insulation performance compared to conventional materials with only a fraction of the thickness [9]. Their application is especially advantageous in retrofit projects where space constraints limit the feasibility of traditional insulation methods. These technologies are increasingly being adopted in high-performance retrofits to achieve substantial reductions in thermal transmittance (U-values) without compromising interior space or usability.

In this context, in this study, we employed a combination of prefabricated external insulation systems and VIPs to maximize thermal performance gains while ensuring constructability and minimizing disruption in the target public building.

Specifically, we examined a community center that underwent envelope retrofitting involving high-performance insulation systems, a dry-type insulated roofing system, and triple-glazed windows. By leveraging actual electricity usage data before and after the retrofit, this research provides a comprehensive assessment of the retrofit's performance in reducing energy use and environmental impact. In doing so, it moves beyond simulation-based projections and contributes valuable empirical evidence that can inform future retrofit policies and architectural practice for public buildings.

2. Research Methodology

To ensure a structured and systematic evaluation of the retrofit outcomes, the research methodology was organized into three main stages, as illustrated in Figure 1. The first stage, Green Remodeling Analysis, involved identifying the physical characteristics and conditions of the target building, followed by the implementation of envelope retrofit technologies, including insulation upgrades, roofing improvements, and the installation of high-performance triple-glazed windows. The second stage, Data Collection, focused on gathering quantitative data necessary for evaluation. This included monthly electricity consumption and electricity billing data obtained from utility records, along with outdoor temperature data used for seasonal normalization and correlation analysis. In the final stage, Comparative Analysis, pre- and post-retrofit performance was evaluated in terms of three key indicators: energy consumption, electricity cost, and CO₂ emissions. This structured approach enabled a comprehensive empirical assessment of the retrofit's effectiveness under real-world operating conditions.

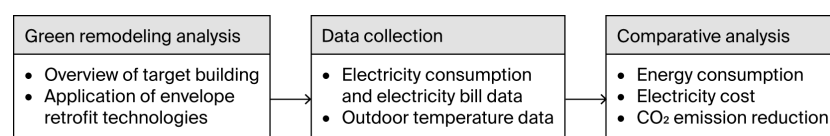


Figure 1. Methodological framework of this study, consisting of three stages: (1) green remodeling analysis, (2) data collection, and (3) comparative analysis of energy performance indicators.

2.1. Overview of the Target Building

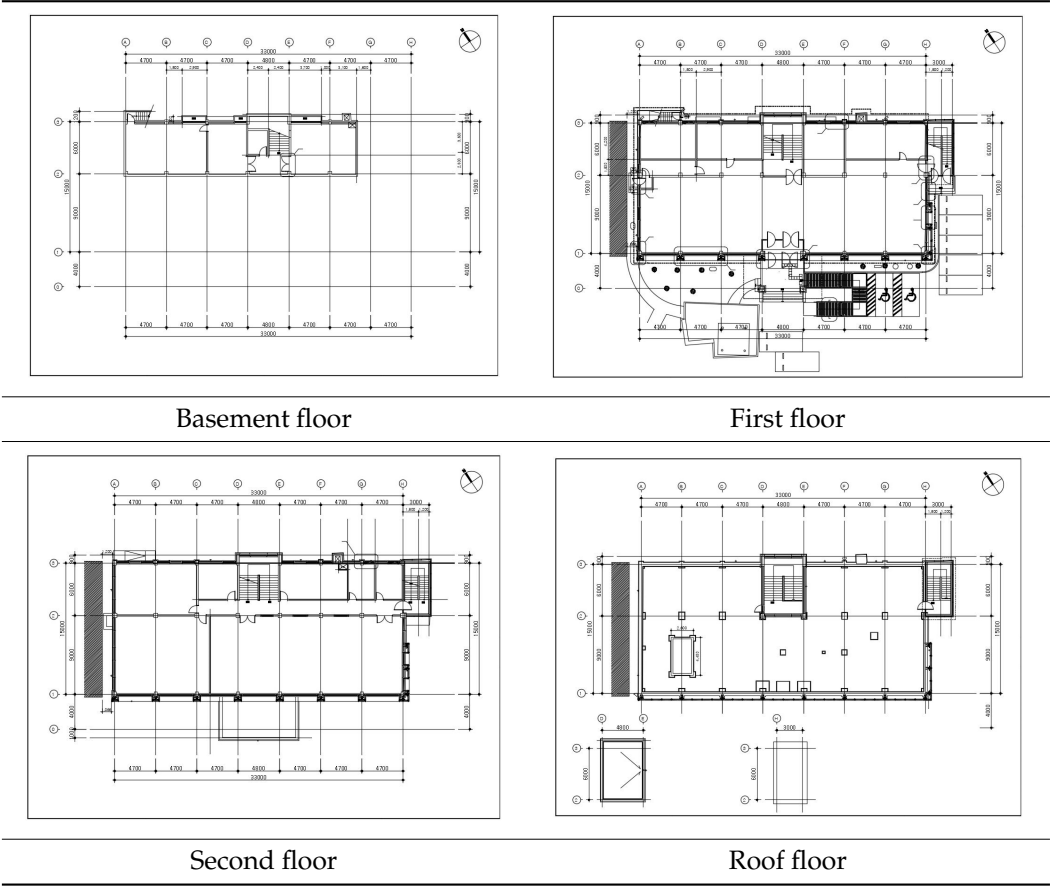
The target building analyzed in this study is a two-story community center located in Siheung, Gyeonggi Province, South Korea. The key characteristics of the building are summarized in Table 1. It was originally constructed in 1995 with a reinforced concrete structure and a total gross floor area of 1163.16 m². The building is equipped with an electric heat pump (EHP) system for both heating and cooling.

Table 1. Target building overview.

Building site	Siheung, Gyeonggi-do, South Korea
Year built	1995
Building use	Community center
Site area	2422.00 m ²
Building area	499.32 m ²
Total floor area	1163.16 m ²
Number of floors	Basement and two above-ground floors
Structure type	Reinforced concrete
HVAC system	EHP (electric heat pump)

After more than 20 years of operation, the building exhibited significant deterioration in envelope performance, leading to the implementation of a comprehensive envelope retrofit project. The retrofit included improvements to the external walls, windows, and roof assemblies. The scope of retrofitting covered the entire building envelope, while the building’s internal usage schedule, occupancy levels, and operational hours remained unchanged before and after the intervention. Table 2 provides the floor plans of the building by level.

Table 2. Floor plan of the target building.



2.2. Application of Envelope Retrofit Technologies

In this study, high-performance envelope retrofit technologies were selectively applied to improve the thermal performance of the target building. Prior to selecting the retrofit technologies, an on-site assessment was conducted to evaluate the building's thermal performance and system conditions. The survey identified severe degradation in the insulation and airtightness of the exterior walls, roof, and windows, while the electric heat pump (EHP) system used for both heating and cooling remained in good operational condition with no immediate need for replacement. Accordingly, the retrofit strategy prioritized enhancing the envelope's thermal resistance and airtightness. Vacuum insulation panels (VIPs) were adopted for the exterior walls and rooftop insulation to maximize the thermal performance within limited space, and triple-glazed low-emissivity windows were employed to address substantial heat loss through fenestration. Furthermore, dry-type prefabricated construction methods were employed to reduce the on-site work duration and minimize the disruption to occupants during the retrofit process. The envelope retrofit scope covered all the external walls of both the first and second floors as well as the rooftop and all the windows. No parts of the above-ground building envelope were excluded.

For the exterior walls, a prefabricated dry-type external insulation system was applied on top of the existing insulation layer, effectively enhancing thermal resistance without requiring the removal of existing finishes. Factory-assembled vacuum insulation panels were installed on-site using custom fastening methods that minimized thermal bridges at junctions and corners.

The rooftop underwent simultaneous insulation and waterproofing upgrades using a dry-type method. This system allowed for installation without dismantling the pre-existing wet waterproof layer, thereby minimizing waste and increases in structural load. A thin-film vacuum insulation panel was used to achieve high thermal resistance, and a polyurea spray coating was applied as a durable, elastic waterproof membrane.

All windows were replaced with high-insulation, high-airtightness triple-glazed units. A 0.5 mm ultra-thin glass pane was inserted as the middle layer instead of conventional 5 mm panes, achieving a 30% reduction in overall window weight while maintaining thermal performance equivalent to that of conventional triple glazing. Additional improvements included 42.5 mm Low-E glazing and aluminum frames with advanced thermal breaks.

The U-values (thermal transmittance) before and after the retrofit were compared to evaluate performance improvements. The differences in U-value estimation methods before and after the retrofit reflect the practical data limitations and the specific retrofit strategy employed. For the pre-retrofit condition, detailed construction layer information was unavailable. Therefore, the U-values were obtained by referencing the Building Energy Conservation Design Standards, which specify the minimum required thermal transmittance based on a building's construction year and regional climate conditions. This approach provides a conservative estimate representing typical design standards prior to the retrofit.

In contrast, the post-retrofit U-values were calculated through a layer-by-layer thermal resistance analysis in accordance with ISO 6946 [10], based on the actual materials and thicknesses applied during the retrofit. The retrofit strategy involved adding a prefabricated external insulation system containing vacuum insulation panels (VIPs) on top of the existing insulation layers. VIPs are known for their superior thermal performance, offering very low thermal conductivity even with minimal thickness. To ensure the real-world applicability and reliability of the applied VIP-based external insulation system, a three-dimensional steady-state thermal bridge simulation was performed using PHYSIBEL TRISCO with the RADICON module. The analysis targeted thermal-bridge-prone junctions, such as the window-to-wall interface and the parapet-to-slab connection. The results confirmed that surface condensation would not occur under standard boundary conditions, verifying that the anchoring and installation details effectively minimized thermal bridging.

These simulation results provide critical system-level validation that complements the material-level performance data. Thus, the adopted VIP insulation system is not only thermally efficient in theory but also robust against thermal discontinuities in practice, supporting its deployment in real-world retrofit applications.

In this study, a 10 mm thick VIP was tested according to KS L 9016:2010 (Thermal Insulation—Test Method for Steady-State Thermal Conductivity), and it exhibited an extremely low thermal conductivity of 0.00139 W/(m·K), enabling a significant reduction in U-values despite the limited visible thickness of the added insulation layers in the schematic diagrams. This methodological distinction does not indicate inconsistency but instead reflects a practical and appropriate approach given the retrofit’s technical characteristics. The substantial improvement in thermal transmittance primarily resulted from the application of VIP-based external insulation, effectively enhancing the envelope’s performance without major structural modifications or demolition.

The post-retrofit values were calculated through layer-by-layer thermal resistance analysis (ISO 6946) or obtained from certified product tests, including the evaluation of window performance using KS F 2278:2017 [11]. While the U-values for key envelope components (external walls, roof, and windows) were accurately calculated and reported, the total building heat loss coefficient (H, W/K) could not be determined due to insufficient data on certain envelope elements, such as floor slabs and internal partitions. This limitation arose from the lack of detailed construction documentation for the pre-retrofit condition.

Table 3 illustrates the schematic diagrams of the pre- and post-retrofit envelope assemblies, and Table 4 summarizes the U-value improvements for each component.

Table 3. Schematic diagrams of the exterior wall, roof, and window assemblies applied in the pre- and post-retrofit conditions.

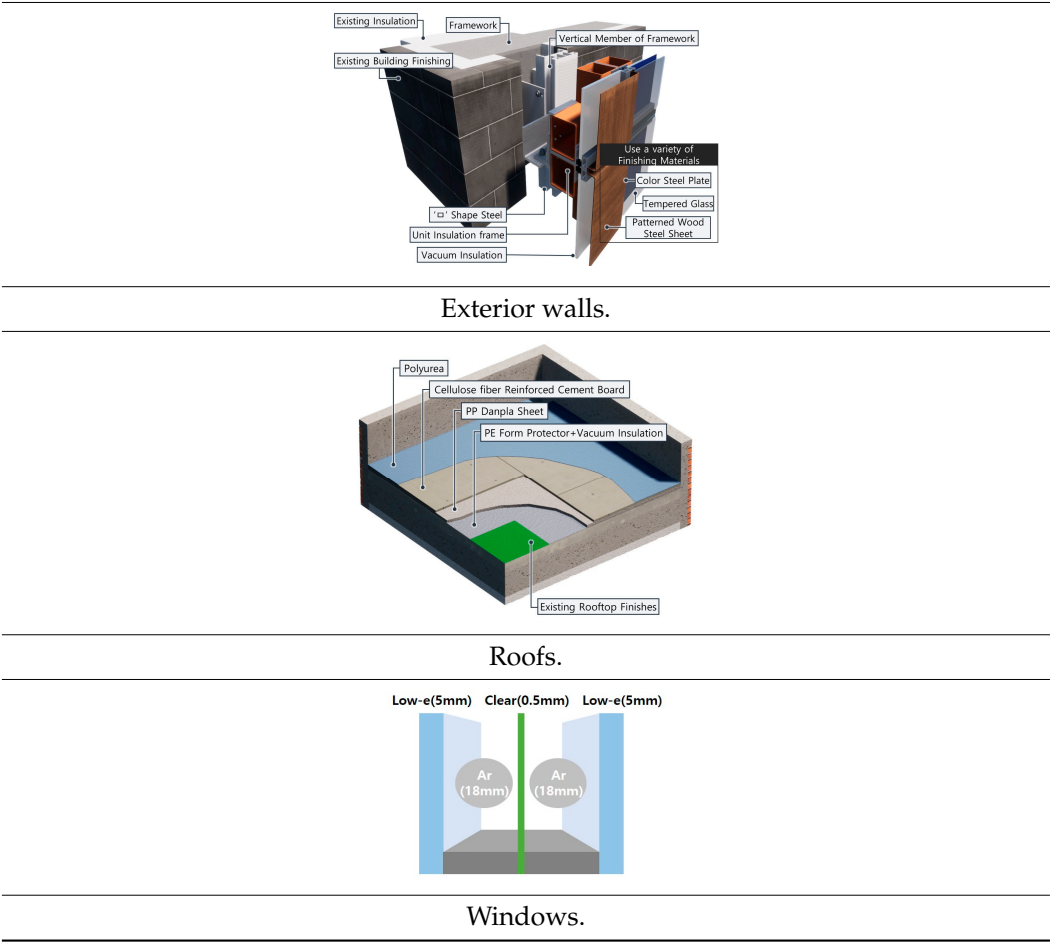


Table 4. Comparison of U-values for the exterior walls, roofs, and windows in the pre- and post-retrofit conditions.

Category	U-Values (W/(m ² ·K))	
	Pre-Retrofit	Post-Retrofit
Exterior walls	0.714	0.194
Roofs	0.329	0.119
Windows	2.319	1.055

Additionally, the target building is oriented toward the southeast. The window-to-wall ratios by façade orientation are as follows: southeast, 46.2%; northwest, 26.78%; northeast, 22.31%; and southwest, 41.53%. Because of the higher solar exposure on the southeast-facing façades, passive solar gains are expected to contribute to heating load reductions in the winter. Conversely, the northwest-facing side, primarily housing stairwells and restrooms (non-conditioned spaces), is not expected to significantly influence internal loads.

2.3. Data Collection and Analysis Methods

The monthly electricity consumption (kWh) and electricity bill data (KRW) were collected for the pre-retrofit year (2019) and the post-retrofit years (2023–2024) to assess the energy performance improvement resulting from the envelope retrofitting of the target building.

The retrofit project was conducted in 2022. Due to operational disruptions during the COVID-19 pandemic, data from 2020 and 2021 were excluded, as the building experienced reduced use due to telecommuting policies and a decrease in public visitation. As a result, 2019 was selected as the representative pre-retrofit year to ensure a valid comparison with post-retrofit use. However, the use of a single pre-retrofit year and two post-retrofit years constitutes a limitation of this study. Given the potential for inter-annual variability in energy use patterns, future studies should incorporate longer baseline and post-intervention periods to improve result generalizability and account for external influencing factors.

The energy data were obtained from the Korea Electric Power Corporation (KEPCO) [12] based on actual monthly billing records. The analysis period covered January to December of each year, allowing for seasonal comparisons. To account for climatic variations, monthly average outdoor temperature data were collected from the Korea Meteorological Administration (KMA) [13], referencing the nearest weather station in Siheung, Gyeonggi Province. Correlation analysis between temperature and energy use was conducted using Excel's CORREL function, with the correlation coefficient (r) used to assess the sensitivity of energy consumption to outdoor temperature changes.

The target building is equipped with an electric heat pump (EHP) system for both heating and cooling, and it does not have separately zoned or metered systems for ventilation or HVAC subcomponents. As such, all the energy used for HVAC, lighting, plug loads, and building operations is supplied by electricity. Due to the integrated nature of the electrical system in this aged facility, disaggregating the electricity consumption into specific end uses was unfeasible. Therefore, the analysis was conducted using the total electricity consumption, which comprehensively reflects the building's overall energy demand under real-world operating conditions.

The building's functional use, occupancy pattern, and operational hours remained consistent during the study period. However, detailed data on internal heat gains, plug loads, thermostat setpoints, or ventilation air change rates were not available and are acknowledged as limitations of the current analysis.

To evaluate the environmental impact of energy savings, carbon dioxide (CO₂) emissions were estimated using the standard national emission factor of 0.4747 tCO₂/MWh, as

published by the Greenhouse Gas Inventory and Research Center of Korea (GIR) [14,15]. The emissions were calculated by multiplying electricity consumption by this factor, providing a consistent basis for environmental comparison.

3. Results and Discussion

3.1. Energy Consumption Analysis

In this study, we quantitatively assessed the changes in monthly electricity consumption before and after the envelope retrofit—specifically improvements to the exterior walls, roofs, and windows—using actual utility billing data. While many previous studies relied on simulation-based predictions, this research offers empirical evidence from a real-world public building during use. Seasonal energy performance was also examined to better understand how retrofitting affected both heating and cooling demands under different climatic conditions.

As shown in Figure 2, the monthly outdoor temperatures in 2023 and 2024 demonstrated seasonal patterns comparable to those in 2019. This consistency in climate conditions enabled a reliable year-to-year comparison of energy consumption trends. Figure 3 presents the monthly electricity consumption for each year along with the corresponding energy saving rates, allowing for a clear visualization of the retrofit's effectiveness.

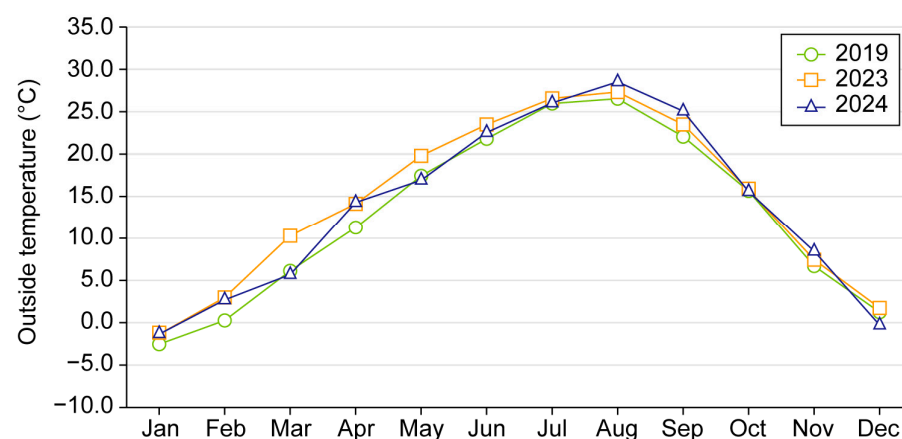


Figure 2. Comparison of pre- and post-retrofit monthly outdoor temperatures.

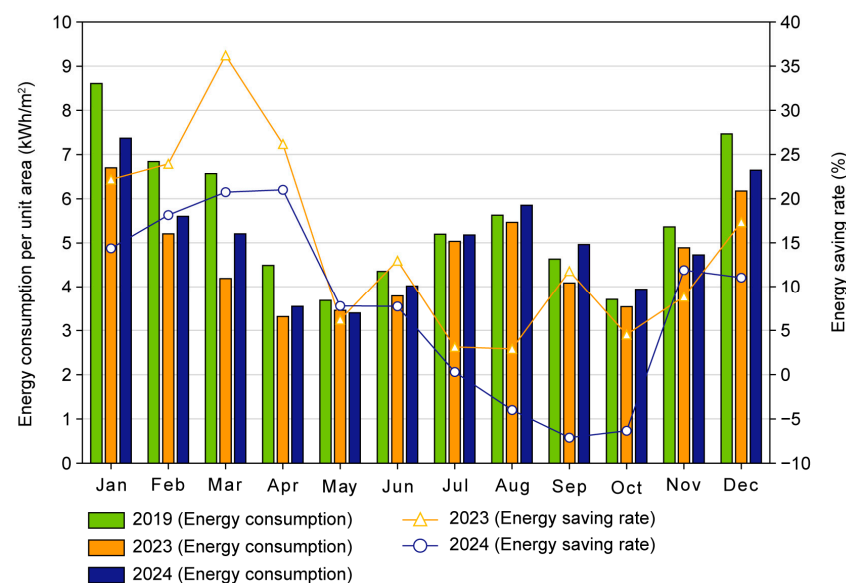


Figure 3. Comparison of pre- and post-retrofit monthly energy consumption and saving rates.

The results reveal that the post-retrofit electricity consumption decreased across most months, particularly in transitional seasons. In 2023, the first year after retrofitting, the average monthly energy saving rate was 14.7%, with the highest monthly reduction of 36.2% observed in March. However, in 2024, the energy saving rate declined to 8.0%, with the peak saving of 21.0% recorded in April. This drop may suggest a diminishing retrofit effect over time or influence from operational and behavioral changes.

The seasonal analysis also showed that while heating energy demand significantly decreased during colder months, cooling loads slightly increased during the summer of 2024. This trend is presumed to be linked to the enhanced thermal insulation and airtightness, which, while effective in reducing heat loss in the winter, may have also led to greater retention of heat gains during the summer. The application of triple-glazed Low-E windows likely contributed to this phenomenon by minimizing solar heat gains during periods when such gains would be beneficial or detrimental, depending on the season. This may be attributed to the fact that the upgraded triple-glazed windows with low-emissivity coatings not only reduced heat loss during the winter but also limited beneficial solar heat gain. While this improvement enhanced insulation performance and reduced heating demand, it may have inadvertently increased cooling loads during the summer by restricting passive solar heat gains. This emphasizes the importance of considering both insulation performance and solar gain strategies, particularly in mixed or cooling-dominant climates.

While the majority of the energy savings observed can be attributed to improved envelope performance, it is essential to acknowledge other potential contributing factors, such as changes in building operation or user behavior. Post-retrofit adjustments in HVAC control strategies, increased occupant awareness of energy conservation, or shifts in space usage patterns may also have played a role. However, due to the building's integrated HVAC system—an electric heat pump (EHP)—which supplies power for all heating, cooling, and lighting loads, it was not possible to disaggregate energy use by function. As such, this analysis relied on the building's total electricity usage.

In future research, capturing more granular operational data—such as occupancy rates, HVAC schedules, and internal heat gains—would allow for a more comprehensive evaluation of retrofit effects. Nevertheless, this study provides meaningful insights into the real-world impacts of envelope retrofitting under consistent operational conditions, validated by energy data measured over a two-year post-retrofit period.

To further contextualize these findings, we referenced a prior empirical study [16,17] that investigated the energy performance of a comparable administrative welfare center in the same region (Gyeonggi Province, South Korea). In this earlier study, the authors used actual utility billing data to assess the effects of green remodeling, reporting that annual electricity consumption was reduced from 171.73 kWh/m²/year before the retrofit to 117.72 kWh/m²/year after the retrofit—an approximate energy savings rate of 31.5%.

Although differences in building scale and operational characteristics exist between the two facilities, the comparison underscores the consistent energy-saving potential of envelope retrofitting in public buildings. Notably, the post-retrofit electricity consumption of our target building also fell within a similar range, demonstrating comparable levels of retrofit effectiveness under practical operating conditions.

3.2. Correlation Analysis Between the Outdoor Temperature and Energy Consumption

To further evaluate the energy performance improvements resulting from the envelope retrofit, we analyzed the correlation between outdoor temperature and electricity consumption before and after retrofitting. The aim of this approach was to quantify how sensitive the building's energy usage was to external temperature fluctuations and identify changes in thermal responsiveness attributable to envelope improvements.

Monthly average outdoor temperature data were obtained from the Korea Meteorological Administration, while monthly electricity consumption data were sourced from utility billing records provided by KEPCO. Correlation coefficients (r) were calculated for each year—2019 (pre-retrofit), 2023, and 2024 (post-retrofit)—using outdoor temperature as the independent variable and electricity use as the dependent variable.

As shown in Figure 4 and summarized in Table 5, the correlation coefficient before the retrofit (2019) was -0.72 , indicating a strong inverse relationship in which electricity consumption increased significantly during colder periods—primarily due to heating loads. In contrast, the post-retrofit coefficients were -0.51 in 2023 and -0.48 in 2024. These reduced magnitudes suggest that the building's energy demand became less sensitive to outdoor temperature changes following retrofit improvements. This finding reflects enhanced thermal insulation and airtightness of the building envelope, which helped stabilize indoor conditions and reduced heating-related energy demand.

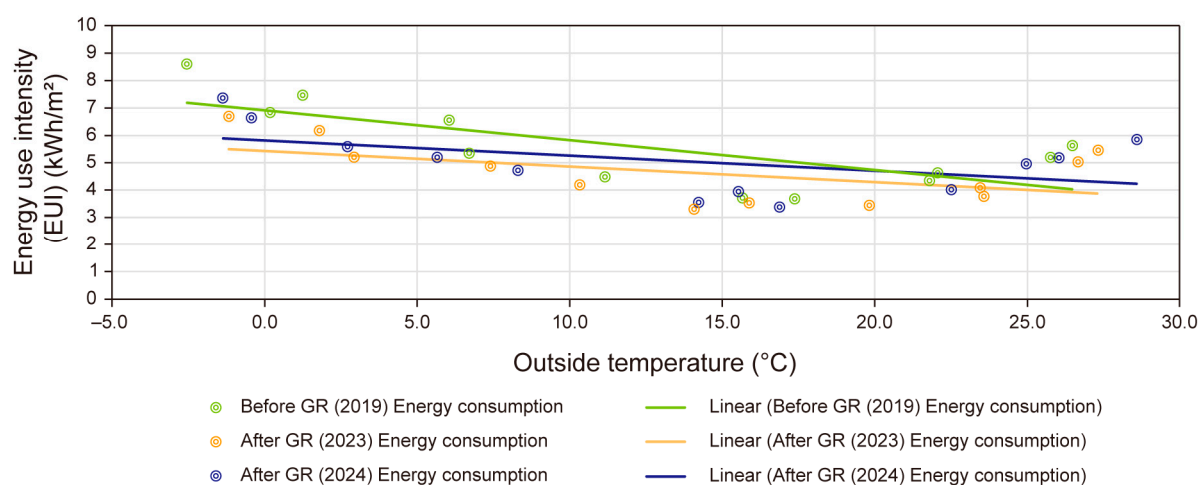


Figure 4. Comparison of the coefficients of correlation between pre- and post-retrofit temperature and energy consumption.

Table 5. Coefficients of correlation (r) between ambient temperature and energy consumption.

Year of Analysis	Correlation Coefficient (r)
Pre-retrofit (2019)	-0.72
Post-retrofit (2023)	-0.51
Post-retrofit (2024)	-0.48

While energy consumption data were not disaggregated by end use (e.g., heating, cooling, and lighting), seasonal patterns were assessed to infer cooling performance. In particular, summer energy use (June to August) was analyzed to estimate cooling-related trends. The results showed that although overall electricity use declined after the retrofit, the reduction in energy consumption during summer months was less pronounced than that in transitional seasons or in the winter. In some cases, a slight increase in summer electricity use was observed.

This trend may be attributed to improved insulation and airtight windows, which effectively minimized winter heat loss but also reduced beneficial solar gains and natural ventilation during the summer. The use of Low-E triple glazing and enhanced airtightness can lead to heat retention, increasing the cooling load unless balanced by appropriate shading or ventilation strategies. These findings underscore the importance of employing seasonally balanced design approaches when implementing envelope retrofits.

Although we recognize that heating degree days (HDDs) and cooling degree days (CDDs) could offer a more standardized basis for inter-annual comparisons, this study focused on direct empirical analyses using monthly outdoor temperature and utility billing data. Given the building's integrated electric heat pump (EHP) system without separate metering for heating and cooling and the limited availability of detailed operational data, we prioritized straightforward correlation analysis as a practical and replicable approach for this case study.

In conclusion, the correlation analysis supports the hypothesis that envelope retrofitting improves the building's thermal stability and reduces its dependence on outdoor temperature—particularly for heating. However, the observed trends also highlight the potential trade-offs related to cooling performance, reinforcing the need for comprehensive retrofit strategies that address both winter and summer conditions.

Furthermore, to improve the reliability of year-to-year comparisons under varying climatic conditions, future studies should incorporate standardized climate indices such as heating degree days (HDDs) and cooling degree days (CDDs). Such indicators would provide more accurate normalization of weather effects and help isolate retrofit impacts more effectively [18–20].

3.3. Analysis of Electricity Cost Savings

Enhancements to the building envelope through retrofitting directly contribute to reduced energy demand, leading to lower electricity consumption and, consequently, electricity cost savings. To quantify these economic benefits, we analyzed monthly electricity expenses before and after the retrofit by comparing 2019 (pre-retrofit) data with post-retrofit data from 2023 and 2024.

Electricity costs were calculated by applying the 2024 rate structure provided by the Korea Electric Power Corporation (KEPCO) uniformly across all years. This approach ensured consistency in cost estimation and allowed for an accurate assessment of cost savings attributable solely to changes in energy usage rather than fluctuations in tariff policy. The applied structure included a basic charge, an energy usage-based charge, and climate/environmental fees, which together reflect actual billing components for public facilities in South Korea.

As illustrated in Figure 5, monthly electricity cost savings were observed in nearly every month post-retrofit. The average monthly cost reduction in 2023 was KRW 37,396, amounting to an annual saving of approximately KRW 448,753. In 2024, the average monthly savings increased significantly to KRW 83,432, resulting in an annual reduction of KRW 1,001,181. These trends demonstrate a growing cumulative effect of retrofit measures on building energy economics over time.

The highest monthly electricity cost savings occurred in January for both 2023 and 2024. This trend corresponds with the winter, during which heating demand is typically high. The notable reduction in electricity costs during colder months implies that the retrofitting—particularly the application of high-performance insulation and airtight triple-glazed windows—effectively lowered heating energy use.

However, it should be noted that actual electricity billing in Korea involves a tiered and time-sensitive pricing system. While the 2024 tariff structure was applied for uniform comparison, real-world pricing fluctuates annually, potentially varying based on demand, seasonal adjustments, and consumption bands. As a result, discrepancies between energy savings and monetary savings may arise from this complexity in rate structures. Additionally, electricity cost reductions were not perfectly proportional to energy use reductions because of the presence of fixed charges and non-linear rate increments.

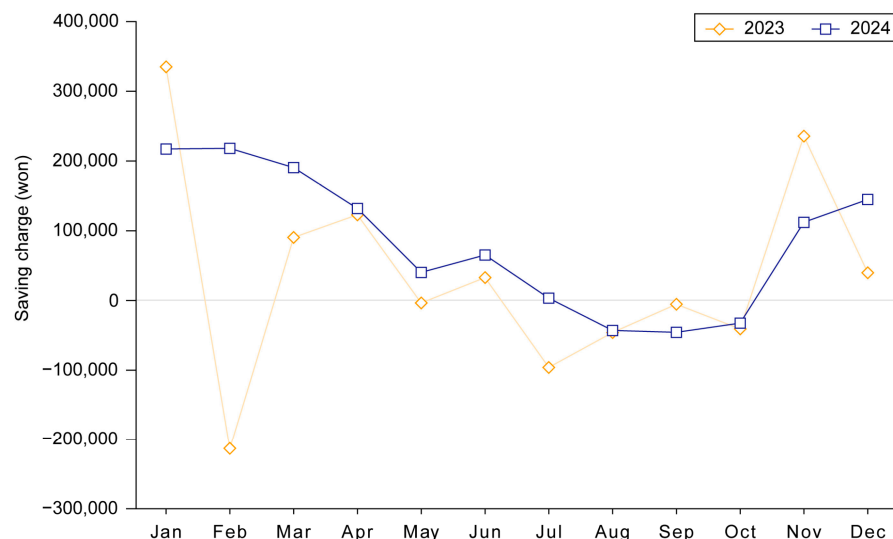


Figure 5. Monthly electricity cost savings in 2023 and 2024 post-retrofit compared to the 2019 baseline.

To further maximize electricity cost savings, especially during summer peak periods, complementary strategies such as demand response programs or peak load management could be considered. These approaches would help mitigate high-cost billing impacts during high-consumption intervals, thereby improving the overall economic benefits of envelope retrofitting.

3.4. Analysis of the CO₂ Emission Reduction Effects

This study evaluated the environmental benefits of envelope retrofitting by quantifying the reduction in carbon dioxide (CO₂) emissions resulting from decreased electricity consumption. The CO₂ emissions were calculated by applying a standardized emission factor of 0.4747 kgCO₂/kWh, as provided by the Greenhouse Gas Inventory and Research Center of Korea [15], to the monthly electricity usage data for each year.

Figure 6 presents the monthly CO₂ emission reductions for the post-retrofit years (2023 and 2024) compared to the baseline year (2019), thereby illustrating the environmental effectiveness of the retrofit strategy over different seasons.

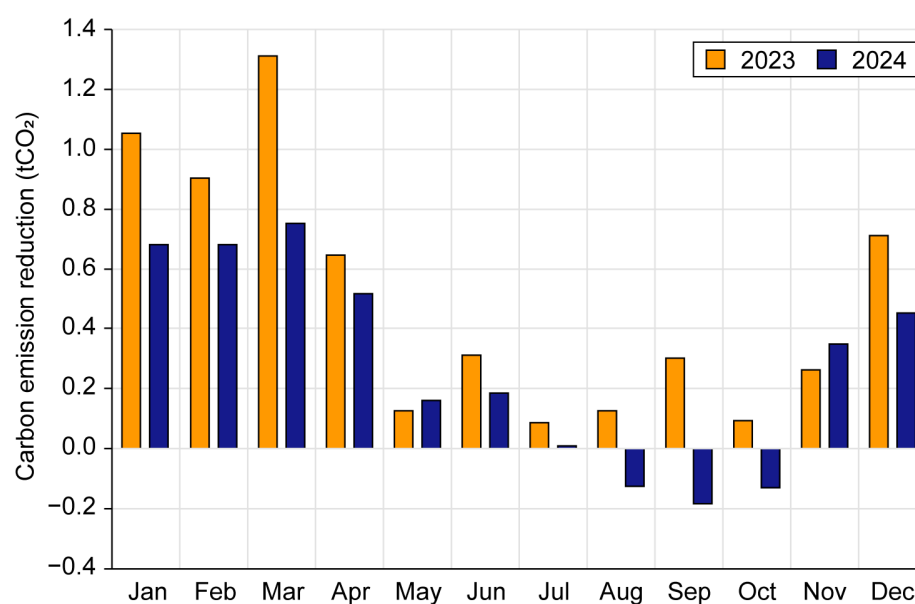


Figure 6. Monthly CO₂ emission reductions in 2023 and 2024 post-retrofit compared to the 2019 baseline.

In 2023, the annual CO₂ emissions were reduced by approximately 5.91 tCO₂, while in 2024, the reduction was 3.36 tCO₂. The largest monthly reductions were recorded during the winter heating season, particularly in January, consistent with the notable decline in electricity consumption during colder months. These findings confirm the impact of improved insulation and high-performance windows in lowering heating loads and associated emissions.

However, from August to October 2024, CO₂ emissions slightly exceeded 2019 levels, indicating negative savings during this period. This reversal was attributed to increased cooling energy demand, which likely stemmed from reduced solar heat gain due to enhanced airtightness and thermal insulation. While the envelope upgrades successfully minimized heat loss in the winter, they may have inadvertently increased reliance on mechanical cooling in warmer seasons by limiting beneficial passive solar gains.

The observed reduction in total CO₂ savings in 2024 compared to 2023 suggests that the initial post-retrofit energy savings may stabilize or diminish over time, possibly because of changes in building operation, occupant behavior, or external temperature patterns. These results emphasize the importance of incorporating dynamic design considerations—such as seasonal solar control strategies or hybrid ventilation—in retrofit projects to ensure year-round performance optimization.

Furthermore, this study highlights the need for integrated approaches that combine technical retrofit interventions with occupant engagement and operational strategies to maximize long-term energy and carbon reduction outcomes. Such multi-dimensional frameworks are essential for achieving policy targets aligned with national carbon neutrality goals.

3.5. Construction Cost Analysis

In addition to evaluating energy performance improvements, we also conducted an economic feasibility analysis based on actual construction cost comparisons between conventional and newly developed retrofit methods. The applied technologies—including a prefabricated dry-type external insulation system for the exterior walls and a dry-type insulation and waterproofing system for the roof—were implemented in the target building to assess their cost-effectiveness in real-world application.

In the analysis, we used the actual construction cost breakdowns of the pilot project and compared them with estimates for conventional methods. The results showed that while certain trades, such as waterproofing and metal works, experienced cost increases of 117.70% and 12.32%, respectively, significant cost reductions were achieved in demolition works (95.98% reduction). When aggregated, the developed retrofit method ultimately resulted in a 23.53% reduction in total construction costs. Moreover, when comparing total cost items by category, an even greater reduction of 27.74% was confirmed.

Notably, because the building serves as a community service center with frequent visitors, conventional retrofitting methods would have required full evacuation and temporary workspace rentals, incurring significant additional costs. The proposed retrofit methods minimized demolition work, allowing renovation to proceed while the building remained in operation, thus avoiding relocation expenses. These avoided costs were estimated to represent 18.35% of the conventional method's total project cost.

This analysis demonstrates that the developed retrofit technologies offer not only technical and environmental advantages but also substantial economic benefits in terms of construction efficiency and cost savings—particularly for public facilities that must maintain continuous service operations.

4. Conclusions

In this study, we empirically evaluated the effects of envelope retrofitting—comprising upgrades to exterior walls, roofs, and windows—on the energy consumption, electricity costs, and CO₂ emissions of a public building. By using actual utility billing data collected before (2019) and after (2023–2024) the retrofit, this study provides evidence-based insights into the real-world impacts of passive building improvements.

The analysis demonstrated that the retrofit significantly enhanced the building's energy performance, with average monthly energy savings of 14.7% in 2023 and 8.0% in 2024. The highest savings were observed during transitional seasons (March–April), suggesting that improved insulation effectively reduced heating loads. However, the energy savings during the summer months were limited, and even negative savings were observed in some months of 2024, indicating increased cooling demand due to reduced solar heat gains. These results highlight the need to consider seasonal solar dynamics and climate-specific strategies when designing envelope retrofits.

Correlation analysis further supported the improvement in thermal stability. The correlation coefficients between outdoor temperature and electricity consumption were -0.72 in 2019, -0.51 in 2023, and -0.48 in 2024, confirming that the building became less sensitive to external temperature variations after retrofitting.

The electricity cost savings were also substantial. When the 2024 KEPCO tariff was uniformly applied, the retrofit yielded average monthly cost reductions of KRW 37,396 in 2023 and KRW 83,432 in 2024. While these trends underscore the economic benefits of passive retrofits, they also reveal how the complex structure of electricity pricing, including seasonal and tiered charges, may cause discrepancies between energy savings and cost reductions.

The retrofit also contributed to environmental performance, with estimated annual CO₂ emission reductions of 5.91 tCO₂ in 2023 and 3.36 tCO₂ in 2024, in accordance with the national electricity emission factor (0.4747 kgCO₂/kWh) issued by the Greenhouse Gas Inventory and Research Center of Korea [15]. The decrease in CO₂ savings in the second year may reflect stabilized retrofit effects or variations in building operations and user behavior.

Importantly, an economic feasibility analysis based on actual construction costs demonstrated that the developed retrofit technologies resulted in a 23.53% reduction in total project cost compared to conventional methods. When factoring in avoided costs from tenant relocation and temporary workspace rentals—amounting to 18.35% of the traditional cost—the total savings reached 27.74%. These findings underscore that envelope retrofitting can yield not only environmental benefits but also substantial cost savings, particularly for public-use buildings requiring continuous operation.

Overall, this study confirms the practical effectiveness of envelope retrofitting in enhancing energy efficiency and economic sustainability in public buildings. However, the study's scope—focusing on a single building with a relatively short two-year post-retrofit monitoring period—presents inherent limitations regarding the generalizability of the findings. Future research should therefore incorporate multi-year analyses covering diverse building types and climatic regions, along with more detailed monitoring of operational variables, to improve the robustness and broader applicability of retrofit performance evaluations.

Additionally, incorporating standardized climate indicators such as heating degree days (HDDs) and cooling degree days (CDDs) in future analyses would provide more precise normalization of inter-annual variations in weather conditions. This approach would enhance the comparability and reliability of long-term retrofit performance assessments, particularly in studies involving multiple years and diverse climates.

Moreover, the results highlight that sustaining retrofit benefits over time requires a holistic approach that integrates adaptive building operation strategies, user engagement, and long-term performance tracking. From a policy perspective, these findings support the need for expanding standardized and evidence-based public retrofit programs, particularly those focusing on envelope performance improvements.

In addition to these findings, this study highlights the necessity of incorporating adaptive design measures to mitigate potential cooling load increases following envelope retrofits. For practitioners planning similar retrofit projects, strategies such as using external shading devices, natural ventilation techniques, and optimized window opening controls should be carefully considered alongside insulation and airtightness improvements. These approaches can help balance heating and cooling demands throughout the year, particularly in climates with significant seasonal variation.

To maximize effectiveness, future programs should incorporate seasonally adaptive design measures and user behavior feedback mechanisms. Continued empirical research using longitudinal, real-world data will be essential for developing retrofit strategies that are both technically robust and operationally sustainable.

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