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Energy-Saving Performance and Economic Evaluation of Window Performance Grades in Single-Detached Houses, South Korea

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Abstract

Improving window performance is a key strategy for reducing heating energy demand in residential buildings; however, the economic feasibility of upgrading to higher performance grades remains uncertain, particularly for single-detached houses. This study quantitatively evaluates the energy-saving performance and economic feasibility of window performance grade improvements in single-detached houses in South Korea. Heating energy demand was estimated using ECO2-OD (Energy Conservation Optimization Tool for One-zone Dwelling), the national standard simulation tool adopted for the Building Energy Efficiency Certification (BEEC) and Zero Energy Building (ZEB) certification systems. Representative residential prototypes constructed in 1980, 1987, and 2001 were analyzed to reflect differences in envelope performance associated with construction vintage. Window upgrades from the baseline grade to Grades 3, 2, and 1 using polyvinyl chloride (PVC) windows were simulated under consistent building geometry and operating conditions. Heating energy demand reductions were converted into annual energy cost savings using market-based natural gas prices. Economic feasibility was assessed using annual indicator-based metrics—unit cost of energy saving (UCES), payback period (PBP), and return on investment (ROI)—as well as discounted cash flow-based life-cycle metrics, including net present value (NPV) and discounted payback period (DPB). The results show that heating energy demand decreases consistently with improved window performance across all construction years; however, marginal energy savings diminish at higher performance grades, while investment costs increase. Upgrading from the baseline to intermediate performance grades yields the most favorable economic outcomes, particularly for houses constructed in 2001, whereas upgrades to the highest performance grade often fail to achieve economic feasibility when time value is considered. These findings indicate that uniform application of the highest-grade windows may not be economically optimal. Unlike previous studies that mainly focused on thermal performance or case-specific retrofit outcomes, this study compares multiple window performance grades across construction-year-specific single-detached house prototypes under a unified economic evaluation framework. This study highlights the importance of construction year-specific and performance-tiered retrofit strategies and provides quantitative evidence to support cost-effective window retrofit policies for single-detached residential buildings.

Keywords: window retrofit; heating energy demand; economic feasibility; single-detached houses; building energy simulation

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1. Introduction

1.1. Background and Objectives

In response to the global climate crisis and the growing commitment to achieving carbon neutrality by 2050, the building sector has emerged as a central component of national energy reduction strategies. Buildings account for more than 20% of total final energy consumption worldwide [1], and among them, existing residential buildings—including single-detached houses—are recognized as having particularly high potential for energy efficiency improvement due to deteriorated insulation performance, low airtightness, and inefficient building systems. In this context, the Korean government and local authorities have continuously expanded support programs aimed at improving the envelope performance of existing buildings. Within green remodeling and residential environment improvement projects, window replacement has been identified as one of the most frequently prioritized envelope retrofit measures, alongside insulation reinforcement [2]. More broadly, passive retrofit strategies for existing houses include not only window replacement, but also external wall insulation, roof and floor insulation reinforcement, thermal bridge mitigation, airtightness improvement, solar heat gain control, and the coordinated improvement of envelope components. These measures aim to reduce heating and cooling demand by improving the thermal behavior of the building envelope before relying on active mechanical systems. Therefore, a general assessment of passive retrofit strategies should first consider the combined role of envelope insulation, junction performance, airtightness, solar control, and window systems. However, window replacement remains one of the most visible and frequently implemented measures in publicly supported retrofit practice because it directly affects both envelope performance and occupant comfort. Windows are also distinct from opaque envelope components because they simultaneously influence conductive heat loss, solar heat gain, airtightness, visual comfort, and retrofit cost. For this reason, the present study focuses specifically on the economic implications of selecting window performance grades within the broader context of envelope improvement.

Windows are a key component of the building envelope that governs thermal performance through parameters such as thermal transmittance (U-value), solar heat gain coefficient (SHGC), and airtightness, and they have a direct impact on heating energy demand. Accordingly, simulation-based building energy studies consistently identify windows as one of the most sensitive envelope variables influencing heating performance [3–5]. However, improvements in window performance do not necessarily lead to linear increases in energy savings. At higher performance levels, the marginal reduction in heating energy demand may diminish, indicating a phenomenon of decreasing marginal returns. This implies that the economic feasibility of window replacement should be evaluated not only through performance comparison, but also by considering the relationship between heating energy savings achieved through performance improvement and the associated initial investment cost (capital expenditure, CAPEX).

Despite this need, previous studies have mainly focused on the thermal performance effects of window upgrades, whereas studies directly linking the domestic window performance grading system to comparative economic feasibility remain limited. In addition, studies on single-detached houses are often restricted to specific retrofit cases or a single improvement level, which makes it difficult to identify an economically rational performance grade through systematic comparison. As a result, evidence remains insufficient for determining which performance grade should be prioritized under realistic retrofit decision-making conditions.

Moreover, even when the same window performance improvement is applied, the resulting heating energy savings and economic outcomes may vary depending on the existing envelope performance of the building. In Korea, single-detached houses exhibit substantial variation in envelope performance depending on their construction year, reflecting differences in the application of insulation standards over time. As a result, identical window performance upgrades may produce differentiated energy and economic responses across building vintages. Nevertheless, studies that quantitatively compare the effects of window performance improvement while explicitly accounting for construction year differences remain insufficient.

Therefore, this study evaluates the heating energy savings and economic feasibility of window performance grade upgrades in Korean single-detached houses. Within the broader framework of passive retrofit strategies, this study focuses on window performance improvement because windows are a critical envelope component that directly affects heating energy demand while also requiring substantial initial investment. Unlike previous studies, the analysis compares baseline, Grade 3, Grade 2, and Grade 1 window scenarios across construction-year-specific prototypes representing different envelope standards and applies both annual and DCF-based economic indicators within a unified framework. By linking grade-based window performance packages with construction-year-specific prototype models and life-cycle economic indicators, this study aims to clarify whether higher window performance necessarily leads to better economic feasibility under realistic retrofit decision-making conditions. The findings are intended to support rational window grade selection and differentiated retrofit support strategies according to building vintage and target performance level.

The results of this study are expected to provide practical reference data for establishing window performance criteria, differentiating subsidy levels by both construction year and target performance grade, and prioritizing investments in public and private remodeling projects. In particular, the findings support a transition from uniform minimum-performance requirements toward differentiated retrofit support strategies that reflect marginal economic return and building vintage.

1.2. Methodology and Scope

This study analyzes the effects of window performance improvement on heating energy demand and economic feasibility in single-detached houses using simulation results generated with ECO2-OD (Energy Conservation Optimization Tool for One-zone Dwelling). ECO2-OD was selected because it is the standardized assessment tool used within the Korean residential building energy certification and policy framework, and is therefore appropriate for evaluating retrofit implications under conditions consistent with domestic regulatory and implementation practice. In addition, ECO2-OD is suitable for comparative analysis of relative differences among envelope and window-performance variables under identical boundary conditions, which is the primary objective of this study, rather than for reproducing the exact time-varying energy use of individual dwellings. As a one-zone assessment tool, ECO2-OD estimates heating energy demand in a simplified and comparable manner based on envelope performance and system conditions. This structure is advantageous for maintaining consistency and reproducibility across multiple comparative scenarios; however, room-level thermal interactions, intra-building solar gain distribution, and detailed occupant- or schedule-driven dynamic effects are simplified. Accordingly, the present analysis should be interpreted as a standardized comparative assessment framework rather than as a detailed multi-zone dynamic simulation of actual household operation. The analysis was conducted using a standard model representative of Korean single-detached houses, with a primary focus on window performance grades (baseline grade and Grades 1–3).

To reflect the envelope performance characteristics of Korean single-detached houses, the simulation results were organized according to representative construction year categories. Under the Act on the Support for Green Buildings, buildings that have been in use for more than ten years are classified as aged buildings in Korea. Accordingly, this study selected single-detached house models constructed in 1980, 1987, and 2001 as analysis cases, corresponding to major revisions of domestic energy efficiency and environmentally friendly housing standards. These construction year categories represent not only differences in building age, but also distinct envelope insulation levels and design practices associated with each regulatory period. This approach enables comparative analysis of how identical window performance improvements affect heating energy demand and energy savings depending on building vintage.

For each construction year model, heating energy demand (kWh/m^2·yr) was calculated by classifying window performance into the baseline grade and Grades 3, 2, and 1. When multiple prototypes were considered, representative values were derived using area-weighted averages based on floor area. The window-to-wall ratio (WWR) was fixed at 20% as a representative reference-model assumption for comparative analysis, and all envelope components excluding windows—such as external walls, roofs, and floors—as well as internal heat gains and operating conditions, were kept constant across cases. This ensured that the effects of window performance improvement were evaluated independently under a representative controlled condition. However, under higher WWR conditions, the relative contribution of windows to the overall thermal balance could increase, and the economically preferred performance grade could differ.

Based on the calculated heating energy demand, energy savings (ΔE) resulting from improvements from the baseline grade to each higher performance grade were determined, and an economic analysis was subsequently conducted using actual market cost data. The economic evaluation focused on the unit cost of energy saving (UCES), payback period (PBP), and annual return on investment (ROI). For heating energy costs, a unit price of 145 KRW/kWh was applied, corresponding to the residential city gas retail tariff converted to a kWh basis for the year 2023 [6].

The analysis was performed under climate conditions representative of the central region of Korea, which is characterized by heating-dominated energy demand. The scope of the analysis was intentionally limited to heating-oriented comparison. This decision was made because the present study focuses on the relative economic feasibility of window performance-grade upgrades under a representative Korean heating-dominated reference condition, and because the comparative effect of envelope thermal improvement on heating demand can be more directly isolated under fixed operating assumptions. Therefore, the reported results should be interpreted as heating-based comparative evidence rather than as a full-year optimization of both heating and cooling performance. The study places particular emphasis on explaining the economic relationship formed between reductions in heating energy demand and the initial investment cost associated with window performance improvement. The results are expected to contribute to the establishment of practical performance criteria and the evaluation of investment efficiency in future window replacement support programs, green remodeling policies, and envelope performance improvement strategies for single-detached houses.

2. Literature Review

In simulation-based retrofit research, passive measures are generally evaluated as part of an integrated envelope-performance strategy rather than as isolated components. Previous studies have shown that the effects of window and envelope retrofits depend on the baseline thermal condition of the building, the combination of measures applied, and the climatic context. [7–9]. For example, studies on low-rise residential retrofit strategies have reported that envelope improvement measures can produce different energy and cost outcomes depending on the existing building condition and retrofit package. This suggests that window improvement should be interpreted as one component within a broader passive retrofit framework, rather than as an independent technical measure. This section reviews previous studies on window performance improvement by categorizing them into simulation-based studies, measurement-based and cost-effectiveness studies, and policy-oriented studies related to green remodeling and retrofit support frameworks (Table 1). This structured review helps clarify the existing evidence on energy-saving performance, retrofit economics, and policy application, while highlighting the remaining gap addressed in this study. Through this review, the study aims to establish the theoretical foundation necessary for analyzing the economic feasibility of window performance grades and material combinations in single-detached houses. In Table 1, each study is listed only once under its primary analytical category, while its broader relevance to simulation, empirical retrofit performance, or policy interpretation is reflected in the corresponding 'Relevance to This Study' column.

Table 1. Categorized summary of previous studies related to window performance improvement and retrofit economics.

Category	Study	Building/Context	Method	Key Findings	Relevance to This Study
Simulation-based studies on window performance improvement	Oh and Kim [5]	Low-rise residential buildings (South Korea)	ECO2 simulation to compare heating energy saving rate after window replacement	Improved U-value and airtightness significantly reduced heating energy demand	Demonstrates the sensitivity of heating demand to window thermal performance under Korean residential conditions, but does not address grade-based economic feasibility
	Kim et al. [7]	Apartment buildings (South Korea)	Simulation of heating energy saving rates according to window type, glazing and frame composition	Window performance differences produced meaningful variation in heating demand	Shows that window specifications affect heating performance, but does not compare retrofit grades using economic indicators
	He et al. [8]	High-rise residential buildings (China)	Energy simulation of high-performance window retrofit scenarios across multiple climate zones	Energy-saving effects were significant but varied with climate conditions	Supports the importance of climate and building context in window retrofit effects, but not construction-year-specific economic comparison
	Liu et al. [9]	Large office buildings (China)	EnergyPlus simulation of window retrofit scenarios with different U-value & SHGC combinations	Window properties strongly affected heating and cooling loads; higher performance did not always ensure optimal cost-effectiveness	Suggests that better thermal performance does not automatically mean better economic performance, which directly supports the logic of the present study
	Tushar et al. [10]	Window system design alternatives in buildings	Integrated energy simulation, life-cycle assessment (LCA), and life-cycle costing (LCC)	Window-related design decisions should be interpreted not only in terms of operational energy savings but also in relation to long-term environmental and economic performance	Supports the need to assess window improvement within a broader comparative framework rather than through thermal performance alone

Table 1. *Cont.*

Category	Study	Building/Context	Method	Key Findings	Relevance to This Study
	Yang et al. [11]	Aging low-rise residential buildings	Experimental-based evaluation of low-cost retrofit strategies	The effectiveness of envelope improvement depends on the baseline condition of the building and the combination of retrofit elements applied	Supports the interpretation that the effect of window improvement varies with existing envelope performance, which is relevant to the construction-year comparison in this study
	Zhang et al. [12]	Residential buildings (United Kingdom)	Feasibility and simulation study on window size modification and energy consumption	Variations in window size and opening ratio significantly affected building energy consumption	Supports the interpretation that the economic attractiveness of a given window performance grade may differ under alternative WWR conditions
Measurement-based/retrofit effectiveness studies	Jeong et al. [13]	Occupied residential units (South Korea)	Field measurement of indoor temperature and gas consumption before and after window retrofit	Heating energy demand was reduced by 48–55%, and actual gas use decreased by about 25%; thermal comfort also improved	Provides empirical evidence that window retrofit can reduce real heating demand, but does not evaluate multiple performance grades or life-cycle economics
	Yang et al. [11]	Low-rise residential buildings (Seoul, Korea)	Field survey and measured energy-use analysis combined with simulation-based technology evaluation and economic assessment	Actual and simulated results showed similar trends; retrofit technologies yielded substantial energy savings, but economic recovery periods could be long	Provides Korean residential evidence that retrofit effectiveness should be interpreted together with payback considerations, but not compare discrete domestic window performance grades
	Kim and Nam [14]	Energy efficiency retrofit (Seoul, Korea)	Empirical analysis of IEQ and energy effects after full retrofit	Measured post-retrofit performance should be interpreted together with practical implementation conditions rather than assumed solely from design intent	Strengthens the importance of evaluating retrofit measures under realistic operating and implementation conditions
Economic/life-cycle/policy-related studies	Pereira et al. [15]	Multi-family residential building (Mediterranean climate)	Energy–environmental–economic assessment of window retrofit using solar-control films	Film retrofit achieved cooling energy reduction, CO_2 reduction, and short payback	Highlights that low-cost retrofit options may be economically attractive, but the focus is on film application rather than discrete window performance grades
	Valentini et al. [16]	Residential building retrofit involving insulation and window systems	Life-cycle assessment and life-cycle cost analysis under evolving electricity-mix scenarios	Long-term cost-effectiveness varied according to window system and future scenario assumptions	Supports the importance of life-cycle economic interpretation, but does not focus on Korean single-detached houses or domestic grade-based comparison

Table 1. *Cont.*

Category	Study	Building/Context	Method	Key Findings	Relevance to This Study
Economic/life-cycle/policy-related studies	Wu et al. [17]	Existing residential buildings in the HSCW zone (China)	Case-study-based feasibility assessment for retrofit toward the EnerPHit standard, considering technology and economics	High-performance retrofit can improve comfort and energy performance, but feasibility is constrained by high investment cost and long payback; the authors stress the need for life-cycle-oriented evaluation	Reinforces the importance of economic feasibility analysis for high-performance retrofit, but does not provide a construction-year-specific comparison of domestic window grades
	He et al. [18]	Existing high-rise residential buildings in temperate and mixed climate zones (China)	Cost-effective retrofit decision model using NPV to identify optimal retrofit combinations under different climates and building conditions	Optimal retrofit solutions depended on climate, building features, and retrofit cost; upgraded window glazing was one of the economically relevant measures in some cases	Supports the need for cost-based retrofit prioritization rather than uniform high-specification selection, but does not focus on Korean single-detached houses or grade-based window-only comparison
	Hondeborg et al. [19]	Residential building retrofits under a subsidy scheme (Switzerland)	Empirical evaluation of retrofit effectiveness under subsidy-supported conditions	The effectiveness of building retrofit measures can change substantially under subsidy-supported conditions	Suggests that private economic feasibility and policy-supported feasibility should be distinguished, which is relevant to interpreting the no-subsidy condition adopted in this study
	You et al. [20]	Residential building retrofit subsidy allocation	Policy and economic analysis of subsidy allocation strategies by household income	Support levels may need to differ according to household conditions in order to improve both equity and policy efficiency	Supports the argument that retrofit economics are affected by institutional and financial context, not only by technical performance
	Kim and Lim [21]	Residential buildings; EER policy context (South Korea)	Policy analysis proposing a recurrent and staged retrofit framework	A uniform retrofit requirement may not lead to the most effective outcome because buildings differ in baseline condition and retrofit readiness	Supports the need for differentiated retrofit pathways rather than a uniform requirement for the highest window performance grade
	An et al. [22]	Residential buildings; green retrofit policy for carbon neutrality (South Korea)	Integrated energy-environmental-economic assessment of green retrofit policy	Retrofit effectiveness should be assessed in terms of energy savings, GHG reduction, and economic feasibility together, and outcomes vary with building characteristics and policy conditions	Provides policy-level evidence that the value of retrofit measures cannot be assumed constant across the housing stock, supporting the present study's vintage- and grade-specific comparative approach
	Kang et al. [23]	Public daycare centers; publicly supported green remodeling projects (Seoul, South Korea)	Empirical assessment of energy and carbon reduction outcomes after green remodeling	Meaningful reductions in energy use and emissions were achieved when envelope and system improvements were appropriately combined	Although focused on public facilities rather than single-detached houses, this study supports the policy relevance of targeted retrofit planning and differentiated support criteria

2.1. Simulation-Based Studies on Energy Savings from Window Performance Improvement

Windows are among the building envelope components with the highest thermal transmittance, and they have a direct influence on both heating and cooling energy demand. Accordingly, numerous simulation-based studies have been conducted to quantitatively investigate the effects of window performance characteristics—such as thermal transmittance (U-value), airtightness, and solar heat gain coefficient (SHGC)—on building energy performance.

Oh and Kim [5] conducted simulations using ECO2 to estimate the reduction rate of heating energy demand resulting from the replacement of existing windows with high-performance alternatives. Their results confirmed that improvements in window U-value and airtightness have a significant impact on reducing heating load. Kim et al. [7] developed a predictive model for heating energy savings according to window configurations, including glazing and frame types, in Korean apartment buildings, and compared the relative influence of changes in window performance on overall energy savings.

International studies have likewise validated the effects of window performance improvement across various climate zones and building types. He et al. [8] analyzed reductions in heating and cooling energy consumption by applying high-efficiency window retrofit scenarios to high-rise residential buildings in China, demonstrating that the impact of window performance on energy savings can vary substantially depending on regional climatic conditions. Liu et al. [9] evaluated window replacement scenarios with different combinations of U-values and SHGCs in large office buildings in China, identifying window performance as a major determinant of both heating and cooling loads.

More recent studies have further expanded this simulation-based perspective by examining window performance within broader design and evaluation frameworks. Tushar et al. [10] integrated building energy simulation with life-cycle assessment (LCA) and life-cycle costing (LCC) to compare alternative window system options and showed that window-related design decisions should be interpreted not only in terms of operational energy savings, but also in relation to long-term environmental and economic performance. Their findings are relevant because they suggest that the energy effect of window improvement should be assessed within a wider comparative framework rather than through thermal performance alone.

In addition, Yang et al. [11] evaluated low-cost retrofit strategies for aging low-rise residential buildings and reported that the effectiveness of envelope improvement measures depends on the baseline condition of the building and the combination of retrofit elements applied. This is important because it indicates that the impact of window improvement cannot be interpreted independently of the existing envelope context. Likewise, Yang et al. [24] analyzed energy use and retrofit costs for passive thermal retrofit measures in low-rise residential buildings in Seoul and showed that energy-saving performance and cost recovery vary depending on the selected technology package.

Furthermore, Zhang et al. [12] examined the impact of window size modification on residential building energy consumption and demonstrated that variations in opening ratio can significantly affect the magnitude of window-related energy savings. This finding is particularly relevant to the present study because it supports the interpretation that the economic attractiveness of a given window performance grade may differ under alternative window-to-wall ratio (WWR) conditions.

While these studies consistently demonstrate that window performance improvement plays a critical role in reducing building energy consumption, most analyses remain focused on performance sensitivity and load reduction. Comparative evidence linking discrete window performance grades to economic feasibility under a unified evaluation framework remains limited, particularly for Korean residential retrofit decision-making.

2.2. Studies on Heat Loss Reduction and Cost-Effectiveness of Window Replacement

Window replacement is regarded as a major envelope retrofit strategy not only for reducing heat loss and decreasing heating and cooling energy consumption, but also from an economic perspective. Previous studies have evaluated the cost-effectiveness of window retrofits using various approaches, including measurement-based analyses, retrofit cases involving window films and window systems, and life-cycle-based cost-effectiveness assessments. As summarized in Table 1, these studies can be broadly interpreted as including both empirical retrofit-effectiveness studies and economic decision-support studies, thereby providing complementary evidence on actual energy reduction and investment feasibility.

Jeong et al. [13] conducted a measurement-based window retrofit study on residential units in Korea and reported that heating energy demand was reduced by approximately 48–55% after window replacement, while actual city gas consumption decreased by about 25%. These results empirically demonstrate that window replacement can achieve substantial energy savings and heating cost reductions under real operating conditions, while simultaneously improving indoor thermal environment and occupant comfort. Similarly, Yang et al. [24] examined retrofit effectiveness in low-rise residential buildings in Seoul by combining field-survey-based energy-use analysis with simulation-based technology evaluation and economic assessment. Their results showed that actual and simulated trends were broadly consistent, and that retrofit technologies could achieve meaningful energy savings; however, the corresponding economic recovery periods could still be relatively long. This finding is important because it suggests that even when retrofit effectiveness is confirmed under Korean residential conditions, investment feasibility should be interpreted together with payback performance rather than through energy reduction alone.

International studies have also extensively examined the energy, environmental, and economic impacts of different window retrofit technologies. Pereira et al. [15] analyzed window retrofit cases applying solar control films in apartment buildings located in a Mediterranean climate. Their findings showed that window film retrofits offer relatively low initial investment costs while achieving considerable reductions in cooling load, carbon emissions, and overall economic benefits. In particular, compared to full window replacement, film retrofits exhibited shorter payback periods, indicating their effectiveness as a cost-efficient alternative. Valentini et al. [16] compared building energy retrofit scenarios—including window systems and insulation materials—using life-cycle assessment (LCA) and life-cycle cost (LCC) analyses for buildings in Italy. The results indicated that energy savings and economic performance (life-cycle costs) vary significantly depending on window system performance, glazing combinations, and material characteristics. Furthermore, the study suggested that the long-term cost-effectiveness of window retrofits may increase when future changes in electricity mix and recycling scenarios are taken into account.

In addition, Wu et al. [17] examined the feasibility of upgrading existing residential buildings toward an EnerPHit-level retrofit target and reported that although high-performance retrofit can improve indoor comfort and energy performance, practical feasibility is often constrained by high investment cost and long payback periods. Likewise, He et al. [18] developed a cost-effective retrofit decision model using NPV and showed that optimal retrofit combinations depend on climate, building conditions, and retrofit cost, rather than being uniformly associated with the highest specification. These studies reinforce the need to evaluate retrofit options not only in terms of technical performance but also in relation to investment cost, payback structure, and decision-making context.

Additional empirical and policy-relevant studies further highlight that the economic interpretation of retrofit measures depends strongly on real-world implementation conditions. Kim and Nam [14], for example, analyzed the indoor environmental quality

(IEQ) and energy effects of full energy efficiency retrofit in South Korea and reported that measured post-retrofit performance should be interpreted together with practical implementation considerations rather than assumed solely from design intent. This line of evidence strengthens the importance of evaluating retrofit measures under realistic decision-making conditions.

At the policy and financing level, Hondeborg et al. [19] showed that the effectiveness of building retrofit measures can change substantially under subsidy-supported conditions, implying that private economic feasibility and policy-supported feasibility should be distinguished. Similarly, You et al. [20] examined subsidy allocation strategies for residential building retrofit and argued that support levels may need to differ according to household conditions in order to improve both equity and policy efficiency. These studies are relevant because they suggest that retrofit economics should not be interpreted as a fixed outcome independent of institutional and financial context. Accordingly, studies discussing subsidy design, financing conditions, or policy implementation are grouped under the economic/policy-related category in Table 1, even when they are discussed in Section 2.2 in relation to the cost-effectiveness of window retrofit.

Taken together, existing studies demonstrate that window retrofits can reduce heating energy demand and energy costs under both simulated and real operating conditions, but they also show that economic outcomes depend strongly on technology choice, initial investment cost, payback structure, and evaluation horizon. Measurement-based studies confirm that retrofit effectiveness can be observed in actual residential operation, whereas economic and life-cycle studies suggest that higher technical performance does not necessarily guarantee the most favorable economic result. However, studies that quantitatively compare the economic feasibility of multiple window performance grades for Korean single-detached houses using a unified framework remain limited. In particular, few studies simultaneously reflect building vintage, grade-based performance packages, and multiple economic indicators such as unit cost of energy saving, payback period, return on investment, and discounted cash flow metrics. To address this gap, the present study combines simulation-based performance data with actual market cost information to evaluate window performance upgrades in a construction-year-specific comparative framework.

2.3. Policy-Oriented Studies on Green Remodeling Programs and the Application of Window Performance Criteria

Recent research has extended beyond evaluating the energy-saving effects of individual retrofit technologies to examining how envelope improvement measures are incorporated into public support programs and policy implementation frameworks. In particular, in the residential and public building sectors, retrofit measures such as window replacement, insulation reinforcement, and system upgrades are increasingly promoted through government-supported green remodeling schemes. Under such conditions, the evaluation of retrofit options requires not only a technical assessment of energy performance, but also a broader consideration of economic feasibility, carbon reduction effectiveness, and policy prioritization.

Kim and Lim [21] analyzed the direction of energy efficiency retrofit policy improvement for residential buildings in South Korea and argued that the policy framework should move beyond one-time support schemes toward a recurrent and staged retrofit approach. Their study emphasized that existing buildings differ substantially in baseline performance, investment capacity, and retrofit readiness, and therefore a uniform retrofit requirement may not lead to the most effective policy outcome. This perspective suggests that differentiated retrofit pathways based on existing building conditions are more appropriate than uniformly requiring the highest performance level in all cases.

An et al. [22] conducted an integrated energy–environmental–economic assessment of green retrofit policy for residential buildings in South Korea in the context of the national 2050 carbon neutrality target. Their results showed that the effectiveness of retrofit measures should be interpreted not only in terms of energy reduction, but also in relation to greenhouse gas mitigation, cost burden, and long-term policy efficiency. The study further indicated that the same retrofit measure may yield different outcomes depending on building characteristics and application conditions. This finding is particularly relevant to window retrofit policy, because it implies that the economic and environmental value of performance improvement cannot be assumed to be constant across the housing stock.

In addition, Kang et al. [23] evaluated the energy and carbon reduction effects of green remodeling in daycare centers in Seoul and demonstrated that public building retrofit programs can achieve meaningful reductions in both operational energy use and emissions when envelope and system improvements are appropriately combined. Although the building type differs from single-detached housing, the study is relevant in that it provides empirical support for the policy significance of differentiated retrofit planning in publicly supported projects. It also suggests that practical retrofit strategies should reflect the characteristics of target building groups rather than relying on a single standardized improvement package.

Taken together, these studies indicate that the policy application of window performance improvement should not be approached solely from the perspective of technical efficiency. Rather, retrofit support criteria need to consider baseline building condition, expected economic return, and the broader policy objective of maximizing energy and carbon reduction under limited public resources. These studies provide a policy context for interpreting the present analysis. In this respect, the present study offers construction-year-specific comparative evidence on the economic feasibility of window performance grades in Korean single-detached houses, which may be useful for discussing differentiated green remodeling strategies according to building vintage and target upgrade level.

3. Research Methodology

3.1. Overview of the Study

This study was conducted to analyze the effects of window performance improvement on heating energy demand in single-detached houses and to quantitatively evaluate the economic feasibility of window replacement based on the resulting energy performance changes. The heating energy demand data used in the analysis were obtained from simulations performed using ECO2-OD, an energy performance evaluation framework applied under the Zero Energy Building (ZEB) certification system, which integrated the former Building Energy Efficiency Certification (BEEC) and ZEB certification schemes as of 1 January 2025. ECO2-OD is a national standard energy assessment tool for single-detached houses based on a single-zone concept, and it is officially used in the evaluation of eco-friendly housing design standards as well as in public and private green remodeling projects. The tool estimates heating energy demand under standardized envelope conditions and indoor environmental assumptions, ensuring consistency and comparability across analysis cases. This is particularly advantageous for the present study, which aims to compare the relative effects of window-grade changes across construction-year-specific prototypes under a unified evaluation framework. At the same time, because ECO2-OD is based on a one-zone concept, room-level thermal interactions, solar gain distribution, and inter-zone heat transfer are simplified. Accordingly, the results should be interpreted as policy- and scenario-oriented comparative outputs under a standardized assessment framework rather than as exact predictions of real household energy use or as a detailed multi-zone dynamic simulation.

In this study, differences in heating energy demand resulting from changes in window performance grades (baseline grade and Grades 3, 2, and 1) were set as the primary analytical variable. Window materials were limited to PVC windows, which are the most commonly applied window type in domestic single-detached house remodeling and green remodeling projects. This scope was defined to clearly identify differences in economic feasibility associated with the selection of window performance grades under representative and widely adopted retrofit conditions.

To further reflect the envelope performance characteristics of Korean single-detached houses, representative construction year categories were incorporated into the analysis. Accordingly, single-detached house models constructed in 1980, 1987, and 2001 were selected as analysis cases. This approach enabled a comparative assessment of how identical window performance improvements affect heating energy demand and economic outcomes depending on building vintage. Figure 1 presents the overall analytical framework of the study, including the definition of construction-year-specific prototypes, the window grade scenarios, the distinction between heating energy demand and heating energy consumption, and the linkage between simulation outputs and economic indicators.

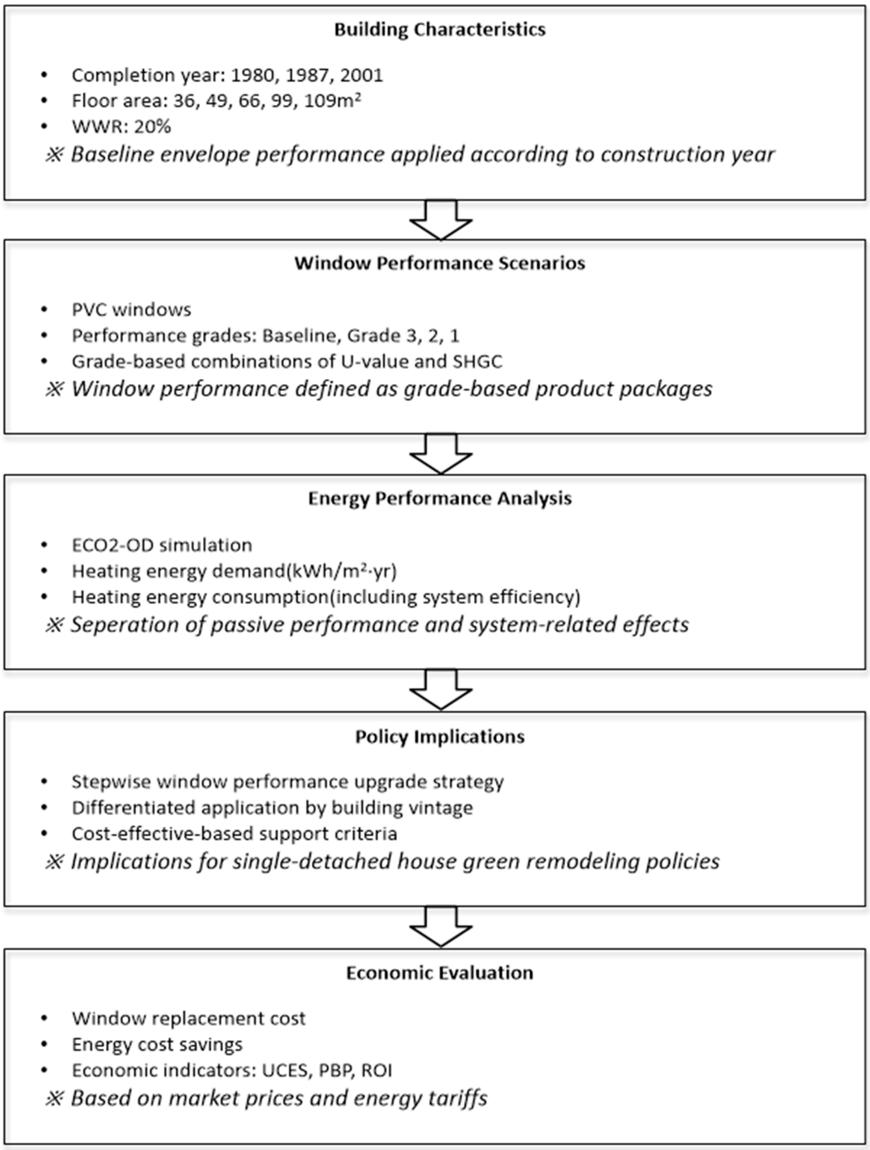

Figure 1. Analytical framework for evaluating heating energy performance and economic feasibility of window performance upgrades in single-detached houses.

3.2. Simulation Conditions and Input Data Configuration

The heating energy performance indicators used in this study were derived from ECO2-OD-based simulations and were structured to quantitatively evaluate the relative effects of changes in window performance on heating performance. The simulations were conducted for single-detached houses, and to reflect differences in envelope performance by construction period, models representing houses built in 1980, 1987, and 2001 were selected as analysis cases.

For each construction year, the single-detached house models were defined as a set of prototypes consisting of multiple standard exclusive floor area categories ranging from 36 to 109 m^2. These area categories were based on the exclusive floor area classifications presented in existing reference models for low-rise residential buildings and were adopted to reflect the structural influence of differences in the surface-to-volume (S/V) ratio on heating performance as floor area varies. In the present study, these floor-area categories were used as standardized prototype groups for comparative analysis rather than as a direct statistical reconstruction of the full national stock distribution of Korean single-detached houses. In this study, by controlling envelope performance and operating conditions across different floor area sizes, the effects of building scale were isolated, allowing a relative comparison of heating performance according to changes in window performance grades. The floor area of each prototype was used as the reference value for calculating area-weighted averages of heating performance indicators.

The thermal transmittance (U-values) of major envelope components—including external walls, roofs, and floors—were set in accordance with the insulation standards applicable to each construction year and were kept identical across all prototypes within the same construction period. Other conditions influencing heating load, such as heating system efficiency, internal heat gains, and ventilation rates, were also applied consistently across all cases.

Window performance was classified into the baseline grade and Grades 3, 2, and 1, reflecting the domestic energy efficiency grading system. For each grade, a combined set of performance parameters—including thermal transmittance (U-value) and solar heat gain coefficient (SHGC)—was applied. This approach reflects the fact that, in actual window products, insulation performance and solar characteristics are interrelated depending on glazing type, number of panes, and gas filling conditions. In this study, SHGC was fixed within each grade, and only performance differences associated with grade transitions were compared, enabling an evaluation of the overall changes in heating performance resulting from window performance improvement. For reproducibility, the grade-based window performance packages were treated as fixed combinations of U-value and SHGC and were applied consistently across all scenarios. The corresponding grade-specific input values are explicitly reported in Table 2 to improve transparency and facilitate interpretation of the comparative economic analysis.

The window-to-wall ratio (WWR) was fixed at 20% as a standardized reference-model assumption based on conditions applied in low-rise residential reference models and standard housing models. This assumption was adopted to isolate the relative effect of window performance-grade changes under a representative condition, rather than to represent the full diversity of the Korean single-detached housing stock. By fixing the WWR, the effects of building geometry and opening ratio variations were excluded, allowing the analysis to focus on differences in heating performance attributable solely to changes in window performance grades. Under different WWR conditions, however, the relative contribution of windows to the total thermal balance may change, and the economically preferred performance grade may also differ. Because the purpose of the present simulation framework is to compare relative heating-related differences attributable to window performance under controlled boundary conditions, all other operating variables were kept constant across cases.

Table 2. ECO2-OD simulation input conditions for single-detached houses.

Classification	Input Parameter		Assigned Value	Remarks
Analysis Target	Building type		Single-detached house	Low-rise residential
	Construction year (vintage)		1980/1987/2001	Reflects envelope standards by period
Geometry & Scale	Exclusive floor area (m^2)		36, 49, 66, 99, 109	Standard area groups
	Window-to-wall ratio (WWR) (%)		20	Fixed reference-model assumption for comparative analysis
Envelope Performance	U-value ($W/m^2 \cdot K$)	External wall	1980: 1.047/1987: 0.582/2001: 0.582	Fixed within each vintage
		Roof	1980: 1.05/1987: 0.58/2001: 0.41	
		Floor	1980: 1.74/1987: 1.16/2001: 0.58	
Window Conditions	Window material		PVC	Identical for all cases
	Window performance grade		Baseline/Grade 3/Grade 2/Grade 1	Primary analysis variable
	U-value	Baseline	1980: 3.489/1987: 3.489/2001: 3.373	Explicit grade-based inputs reported for reproducibility
		Grade 3	1.8	
		Grade 2	1.2	
		Grade 1	0.9	
	SHGC	Baseline	1980: 0.647/1987: 0.647/2001: 0.45	Explicit grade-based inputs reported for reproducibility
		Grade 3	0.6	
		Grade 2	0.5	
		Grade 1	0.4	
System Conditions	Heating system efficiency (%)		80	Fixed
Operation Conditions	Heating setpoint temperature (°C)		20	Fixed
	Other operating conditions		Internal heat gains, ventilation rate, and other boundary conditions kept constant across all cases	Controlled for comparative analysis
Output Indicators	Heating energy demand		$kWh/m^2 \cdot yr$	Performance analysis
	Heating energy consumption		$kWh/m^2 \cdot yr$	Economic analysis

Heating performance indicators were calculated by distinguishing between heating energy demand and heating energy consumption per unit floor area ($kWh/m^2 \cdot yr$). Heating energy demand was used as an indicator to assess the influence of passive elements such as envelope and window performance. In the economic analysis, heating energy consumption—which reflects heating system efficiency and system losses—was used to estimate energy cost savings. Accordingly, the two indicators were applied separately depending on the analytical purpose of the study.

Table 2 summarizes the key input conditions adopted in this study, including the baseline external wall, roof, and floor U-values assigned to each construction-year prototype (1980, 1987, and 2001), as well as the grade-specific window U-values and SHGC values applied in the comparative simulation framework.

3.3. Estimation of Heating Energy Demand and Energy Savings (ΔE) by Window Performance Grade

This section compares and analyzes heating energy demand according to construction year (1980, 1987, and 2001) and window performance grade (baseline grade and Grades 3, 2, and 1) (Table 3 and Figure 2). For each construction year and performance grade, representative heating energy demand values were derived by calculating area-weighted averages of results from multiple prototypes based on floor area.

Table 3. Heating energy demand and energy savings (ΔE) by window performance grade for single-detached houses by construction year.

Construction Year	Window Performance Grade	Heating Energy Demand	ΔE (Baseline → Target Grade)
		$kWh/m^2{\cdot}yr$	$kWh/m^2{\cdot}yr$
1980	Baseline grade	223.20	-
	Grade 3	208.06	15.14
	Grade 2	206.06	17.14
	Grade 1	205.04	18.16
1987	Baseline grade	152.68	-
	Grade 3	137.58	15.10
	Grade 2	135.40	17.28
	Grade 1	134.28	18.40
2001	Baseline grade	125.26	-
	Grade 3	102.78	22.48
	Grade 2	100.24	25.02
	Grade 1	99.06	26.20

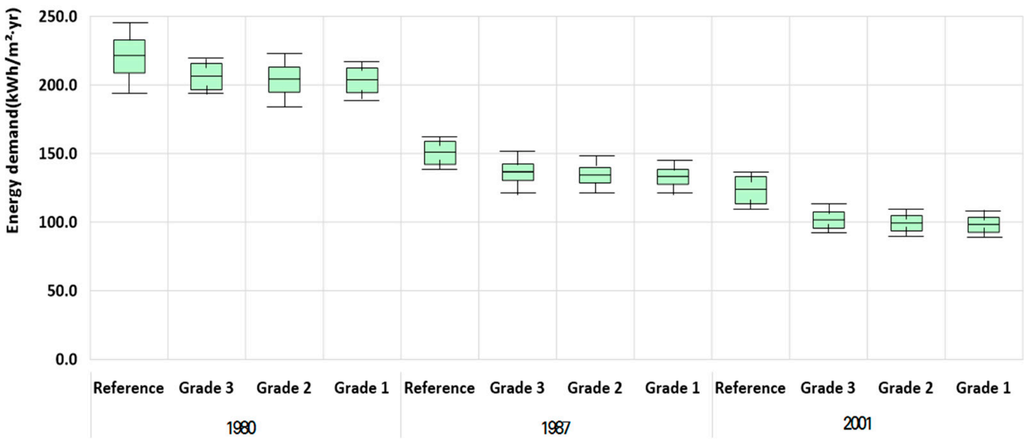

Figure 2. Box-plot of heating energy demand by window performance grade.

The results indicate that, across all construction years, heating energy demand consistently decreases as window performance improves. The largest absolute reduction was observed in the transition from the baseline grade to Grade 3, while additional upgrades to Grades 2 and 1 resulted in progressively smaller reductions in heating energy demand.

For single-detached houses constructed in 1980, heating energy demand under the baseline-grade windows was the highest, at 223.20 $kWh/m^2{\cdot}yr$. When Grade 3, Grade 2, and Grade 1 windows were applied, heating energy demand decreased to 208.06, 206.06, and 205.04 $kWh/m^2{\cdot}yr$, respectively. The corresponding energy savings relative to the baseline grade were calculated as 15.14 $kWh/m^2{\cdot}yr$ for Grade 3, 17.14 $kWh/m^2{\cdot}yr$ for Grade 2, and 18.16 $kWh/m^2{\cdot}yr$ for Grade 1. These results indicate that houses with lower baseline envelope performance tend to exhibit larger absolute reductions in heating energy demand when window performance is improved.

In the case of single-detached houses constructed in 1987, heating energy demand under the baseline-grade windows was 152.68 $kWh/m^2{\cdot}yr$, decreasing to 137.58, 135.40, and 134.28 $kWh/m^2{\cdot}yr$ for Grades 3, 2, and 1, respectively. The resulting energy savings

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relative to the baseline grade were 15.10, 17.28, and 18.40 kWh/m^2·yr, respectively. While the overall reduction pattern was similar to that observed for houses constructed in 1980, the absolute level of heating energy demand was lower.

By contrast, single-detached houses constructed in 2001 exhibited the lowest baseline heating energy demand, at 125.26 kWh/m^2·yr; however, the magnitude of energy savings associated with window performance improvement was relatively larger. When Grade 3, Grade 2, and Grade 1 windows were applied, heating energy demand decreased to 102.78, 100.24, and 99.06 kWh/m^2·yr, respectively. The corresponding energy savings relative to the baseline grade were 22.48, 25.02, and 26.20 kWh/m^2·yr. This suggests that, under the prototype assumptions used in this study, the relative contribution of window performance to the overall thermal balance may become more pronounced once a moderate baseline envelope level has already been secured.

Across all construction years, the largest absolute reduction in heating energy demand consistently occurred in the transition from the baseline grade to Grade 3, while the incremental increase in energy savings diminished with further upgrades to higher performance grades. This pattern reflects diminishing marginal returns: although the thermal performance of the window continues to improve, the additional reduction in total building heat loss becomes progressively smaller once a substantial portion of the window-related loss has already been reduced. Under the fixed WWR condition of 20% adopted in this study, this result indicates that uniformly applying the highest window performance grade may not necessarily be rational from a cost-to-performance perspective. Under higher WWR conditions, however, the relative energy-saving effect of higher-grade windows could become larger.

The heating energy savings (ΔE) derived for each construction year and window performance grade in this section are used as key input data for estimating annual energy cost savings in the subsequent economic analysis.

4. Results of Economic Analysis

4.1. Overview of Economic Analysis and Input Parameter Settings

4.1.1. Common Input Parameters and Cash Flow Structure

In this chapter, the economic feasibility of window performance improvement is quantitatively evaluated based on the heating energy demand analysis results for single-detached houses derived in Chapter 3. The economic analysis was conducted for PVC windows, and a total of nine scenarios were established by upgrading baseline-grade windows to Grade 3, Grade 2, and Grade 1 PVC windows for single-detached houses of each construction year. Heating energy demand reductions were converted into annual energy cost savings and subsequently compared with the initial investment costs.

In this process, heating energy demand results obtained from multiple single-detached house prototypes were aggregated into representative values for each construction year and window performance grade using area-weighted averages based on floor area. The investment cost associated with window replacement was estimated using the window area information included in the model input data, and the initial investment cost was normalized on a per–square-meter-of-floor-area basis.

The annual energy cost savings (S) derived from the reduction in heating energy demand (ΔE, kWh/m^2·yr) were calculated by converting the energy savings into monetary values, as defined below:

$$S = \Delta E \times P_0$$

where P_0 represents the unit price of heating energy (KRW/kWh). In this study, a reference-year residential natural gas tariff was applied to convert heating energy savings into annual cost savings. The detailed basis of the applied tariff is described in Section 4.1.2.

Window costs were determined based on domestic window market data for the third quarter of 2023, and average unit prices for PVC (polyvinyl chloride) windows were established by performance grade (Table 4). The Grade 1 and Grade 3 values were based on available domestic market quotation data, and the unit cost of PVC windows was 215,022 KRW/m^2 for Grade 1 and 121,231 KRW/m^2 for Grade 3. For Grade 2 windows, for which officially published market price data were unavailable, a unit cost of 168,127 KRW/m^2—calculated as the arithmetic mean of the Grade 1 and Grade 3 prices—was applied. This assumption was adopted to preserve the relative price hierarchy across performance grades while maintaining a realistic range of market prices. However, because the Grade 2 value is a simplified proxy rather than an officially reported market average, the economic results associated with this grade should be interpreted with appropriate caution. Accordingly, the Grade 2 scenario should be interpreted as an intermediate comparative case under an assumed cost level rather than as a directly observed market-price condition.

Table 4. Unit cost structure of PVC windows by performance grade (Q3 2023, KRW/m^2).

Window Type	Performance Grade	Unit Cost	Incremental Cost	Remarks
		KRW/m^2	KRW/m^2	
PVC window	Grade 1	215,022	+46,895 (Grade 2 → Grade 1)	Market average
	Grade 2	(168,127)	+46,896 (Grade 3 → Grade 2)	Estimated value
	Grade 3	121,231		Market average

Based on the common input parameters and cash flow structure established above, the following section first evaluates cost-effectiveness and simple payback characteristics using annual indicator-based economic metrics, including the unit cost of energy saving (UCES), payback period (PBP), and return on investment (ROI). Subsequently, investment feasibility accounting for the time value of money is further examined through a life-cycle economic assessment based on discounted cash flow (DCF) indicators, namely net present value (NPV) and discounted payback period (DPB).

4.1.2. Annual Indicator-Based Economic Evaluation

For the estimation of heating energy costs, a unit energy price of 145 KRW/kWh was applied. This value was obtained by converting the residential natural gas retail tariff announced by the Korea City Gas Association for December 2023 into a kWh basis, using the sum of the wholesale gas tariff and supply cost. In other words, the present study applied a fixed reference-year residential gas price of 145 KRW/kWh based on the combined wholesale tariff and supply charge as of December 2023. This assumption was adopted to ensure a transparent and consistent basis for comparing the relative economics of all upgrade scenarios under identical price conditions.

The economic evaluation was conducted using three indicators: the unit cost of energy saving (UCES), payback period (PBP), and annual return on investment (ROI). UCES represents the cost required per unit of heating energy savings and is used to assess cost-effectiveness. PBP indicates the period required for the cumulative annual energy cost savings to recover the initial investment cost. ROI expresses the ratio of annual cost savings to the initial investment cost as a percentage, providing an economic perspective on investment performance associated with window performance improvement.

4.1.3. Life-Cycle Economic Evaluation Based on Discounted Cash Flow

While annual indicator-based economic evaluation is useful for intuitive comparisons, life-cycle economic assessment based on discounted cash flow (DCF) plays a critical role from an investment decision-making perspective. In this study, a life-cycle economic evaluation was conducted based on the same annual energy cost savings (S) and initial investment costs (C_0), in order to account for the time value of money and the expected service life over the analysis period. For this purpose, net present value (NPV) and discounted payback period (DPB) were calculated.

The analysis period (*n*) was set to 15 years (from the first to the fifteenth year after improvement), considering the expected service life of windows [25]. A real discount rate of 4.5% was applied [26]. The consumer price inflation rate (CPI) was set to 1.89%/yr, corresponding to the average annual consumer price inflation rate over the period from 2014 to 2024 [27].

Net present value (NPV) is defined as the difference between the present value of cumulative energy cost savings over the analysis period (15 years) and the initial investment cost, and is expressed as follows:

$$\mathrm{NPV} = -\mathrm{C}_0 + \sum_{t=1}^{n} \frac{\mathrm{S}(1+\mathrm{g})^{t-1}}{(1+\mathrm{r})^{t}}$$

where r is the real discount rate, n is the analysis period (years), and g is the energy price escalation rate.

The discounted payback period (DPB) is defined as the earliest point at which the cumulative discounted energy cost savings exceed the initial investment cost, and it is determined as the minimum value of t that satisfies the following condition:

$$\mathrm{DPB} = \min t : \sum_{k=1}^{t} \frac{\mathrm{S}(1+\mathrm{g})^{t-1}}{(1+\mathrm{r})^{k}} \geq \mathrm{C}_0$$

In this study, economic feasibility was considered to be satisfied when the NPV was positive. In addition, when the discounted payback period (DPB) was calculated to be within the analysis period (i.e., n = 15 years), the investment was interpreted as being recoverable within the expected service life. In the reference DCF analysis, no explicit residential gas tariff escalation rate was assumed, because future residential gas price trajectories are influenced not only by market conditions but also by policy intervention and social acceptability, which introduce substantial uncertainty into long-term escalation assumptions. Therefore, the reference DCF results should be interpreted as comparative economic outcomes under a fixed-price tariff condition rather than as exact forecasts of future realized investment returns. To address this uncertainty, supplementary tariff sensitivity cases were additionally examined in Section 4.2.

4.2. Results of Economic Analysis by Improvement Scenario

For the nine improvement scenarios defined for single-detached houses by construction year, economic feasibility was evaluated by converting the heating energy demand savings (ΔE) into annual energy cost savings and comparing them with the initial investment cost (CAPEX). The economic analysis was conducted using two approaches: (1) annual savings-based economic indicators (UCES, PBP, and ROI), and (2) life-cycle economic indicators based on discounted cash flow that account for the time value of money (NPV and DPB).

The results of the annual indicator-based analysis first confirmed that improvements in window performance led to reductions in heating energy consumption and corresponding annual energy cost savings across all construction years (Table 5). However, even under the same level of performance improvement, the values of the economic indicators varied substantially depending on construction year and target window performance grade.

Table 5. Annual indicator-based economic analysis results by construction year and window upgrade scenario.

Construction Year	Scenario (Baseline → Target Grade)	ΔE	Investment Cost	Annual Cost Savings	UCES	PBP	ROI
		kWh/m^2·yr	KRW/m^2 Floor Area	KRW/m^2·yr	KRW/kWh	Years	%/yr
1980	Baseline → Grade 1	16.65	47,616	2414	2860	19.7	5.1
	Baseline → Grade 2	15.73	37,231	2281	2367	16.3	6.1
	Baseline → Grade 3	13.90	26,846	2015	1931	13.3	7.5
1987	Baseline → Grade 1	16.89	47,616	2449	2819	19.4	5.1
	Baseline → Grade 2	15.87	37,231	2301	2346	16.2	6.2
	Baseline → Grade 3	13.87	26,846	2011	1935	13.3	7.5
2001	Baseline → Grade 1	24.05	47,616	3487	1980	13.7	7.3
	Baseline → Grade 2	22.97	37,231	3331	1621	11.2	8.9
	Baseline → Grade 3	20.68	26,846	2998	1298	9.0	11.2

For single-detached houses constructed in 1980, upgrading from baseline-grade windows to Grade 3 PVC windows resulted in a payback period of approximately 13 years and an ROI of around 7%/yr. In contrast, further performance upgrades to Grades 2 and 1 led to additional reductions in heating energy consumption; however, the corresponding increases in initial investment costs extended the payback period to approximately 16 and 20 years, respectively, while ROI gradually declined.

A similar economic structure was observed for single-detached houses constructed in 1987. Relatively favorable economic performance was achieved in the transition from the baseline grade to Grade 3, whereas further upgrades to Grades 2 and 1 increased the payback period to more than 16 years and reduced ROI to below 6%. This outcome indicates that the incremental gains in heating energy savings associated with higher performance grades were insufficient to fully offset the increase in investment costs.

In contrast, single-detached houses constructed in 2001 exhibited comparatively superior economic performance. When upgrading from the baseline grade to Grade 3 PVC windows, the payback period was approximately 9 years and ROI reached about 11%/yr, representing the most favorable results among the analyzed construction years. Even for upgrades to Grades 2 and 1, payback periods of approximately 11 and 14 years and ROI values in the range of 7–9%/yr were obtained, indicating shorter payback periods and higher returns overall compared to houses constructed in 1980 and 1987.

When the annual indicator-based results are compared in terms of the relationship between energy savings (ΔE) and ROI (Figure 3), ROI does not increase monotonically with increasing ΔE for any construction year. This indicates that higher energy savings do not automatically translate into higher profitability. Because ROI is determined by both annual monetary savings and initial investment cost, ROI declines when the additional investment required for higher-grade windows increases faster than the corresponding annual savings. In this sense, a profitability slowdown pattern emerges beyond a certain level of energy savings, reflecting the diminishing incremental gains in energy savings from higher window performance grades while the associated window costs continue to increase.

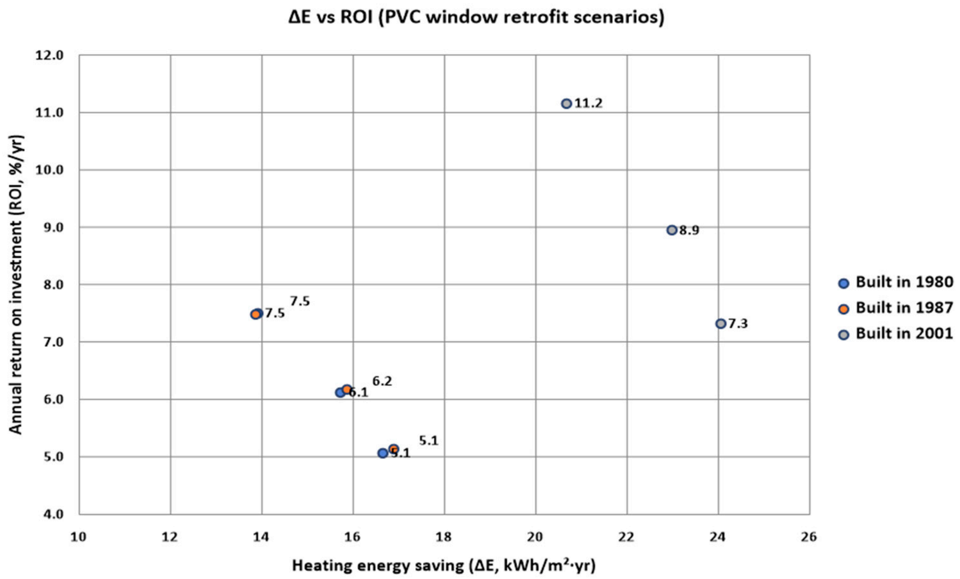

Figure 3. Relationship between heating energy saving (ΔE) and annual return on investment (ROI) for window retrofit scenarios by construction year.

Next, to incorporate the time value of money from an investment decision-making perspective, this study conducted a life-cycle economic evaluation based on discounted cash flow (DCF). The real discount rate was set at 4.5%, and the analysis period (n) was defined as 15 years, considering the expected service life of windows. Because energy price escalation is influenced not only by market-based factors but also by policy decisions and social acceptability, the reference DCF analysis did not assume a single forecasted tariff escalation rate.

The consumer price inflation rate (CPI) was applied as 1.89%/yr, corresponding to the average annual CPI over the period from 2014 to 2024. In addition, to facilitate visual comparison of DCF-based indicators, the distribution of discounted payback periods (DPB) across scenarios is illustrated in Figure 4.

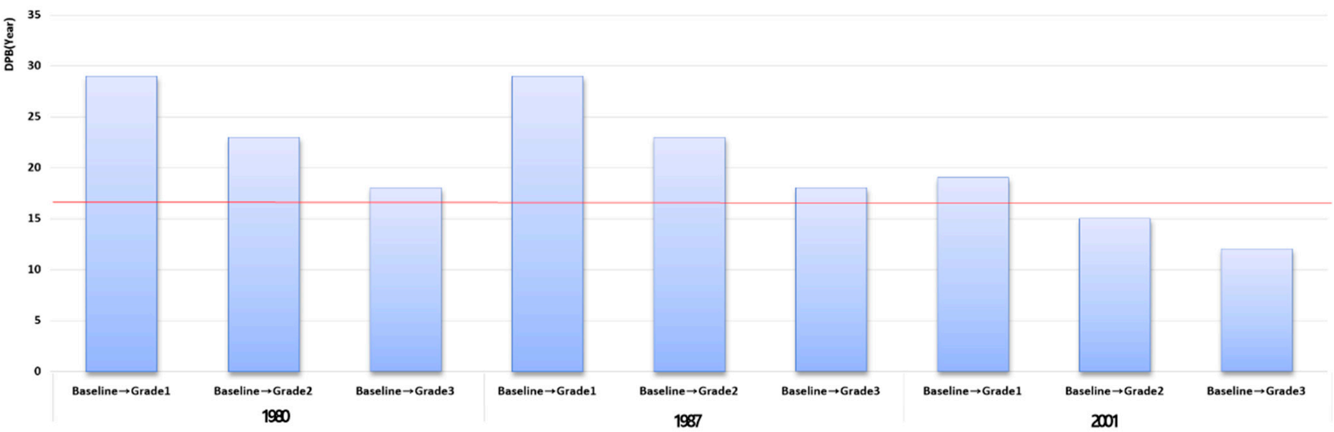

Figure 4. Comparison of discounted payback period (DPB) by construction year and upgrade scenario. The red horizontal line indicates the 15-year analysis horizon.

Based on the DCF-based results presented in Figure 4 and Table 6, all improvement scenarios for single-detached houses constructed in 1980 and 1987 exhibited negative net present values (NPV). In addition, the discounted payback period (DPB) exceeded the analysis period, indicating that investment cost recovery within 15 years was not achievable for these scenarios.

Table 6. DCF metrics and payback feasibility by completion year and scenario (analysis horizon: n = 15).

Construction Year	Scenario (Baseline → Target Grade)	NPV	DPB	Payback Within 15 Years
		KRW/m^2 Floor Area	Years	
1980	Baseline → Grade 1	−17,854	>15	No
	Baseline → Grade 2	−9116	>15	No
	Baseline → Grade 3	−2003	>15	No
1987	Baseline → Grade 1	−17,425	>15	No
	Baseline → Grade 2	−8870	>15	No
	Baseline → Grade 3	−2054	>15	No
2001	Baseline → Grade 1	−4635	>15	No
	Baseline → Grade 2	3828	14	Yes
	Baseline → Grade 3	10,111	11	Yes

Note: Yes indicates that the scenario satisfies the payback criterion within the 15-year analysis horizon; No indicates that the criterion is not satisfied.

In other words, even when some scenarios appear to achieve cost recovery within 15 years based on annual indicator-based analysis (PBP), incorporating the time value of money reveals that investment feasibility under the same conditions is not sufficiently secured.

In contrast, for single-detached houses constructed in 2001, the scenarios involving upgrades from the baseline grade to Grades 3 and 2 satisfied the investment feasibility criteria from a DCF perspective. The baseline-to-Grade 3 scenario showed the most favorable outcome, with a positive NPV and a DPB within 15 years, while the baseline-to-Grade 2 scenario also exhibited a positive NPV and recoverability within the analysis period. Conversely, although the baseline-to-Grade 1 scenario yielded the largest energy savings (ΔE) and annual cost reductions, the substantial increase in investment cost resulted in a DPB exceeding 15 years and a negative NPV, indicating that DCF-based feasibility was not achieved. These findings suggest that upgrading to the highest performance grade does not necessarily improve economic feasibility and that diminishing returns become more pronounced when the time value of money is considered.

To further examine whether the economic feasibility of higher-grade window upgrades could improve under future residential gas tariff increases, a supplementary tariff sensitivity analysis was conducted using the same DCF framework. In the reference DCF analysis, the CPI escalation rate and real discount rate were applied to reflect general economic conditions and to convert future cash flows into present values; however, the residential gas tariff itself was held constant at the 2023 reference level, with no explicit tariff escalation pathway assumed. Because higher future gas tariffs could increase annual energy cost savings and thereby improve the NPV of higher-cost upgrade scenarios, the supplementary analysis considered two tariff increase assumptions: a one-time tariff uplift and a cumulative annual tariff escalation.

In the one-time tariff uplift case, the residential gas tariff was assumed to increase once at the beginning of the analysis period and remain constant thereafter. In the cumulative annual tariff escalation case, the tariff was assumed to increase every year throughout the 15-year DCF horizon. These two assumptions were not intended to forecast a specific future tariff pathway, but to define a sensitivity range from a relatively moderate price-adjustment case to a more aggressive cumulative escalation case.

Figure 5 presents the NPV sensitivity results under two residential gas tariff increase assumptions: (a) a one-time tariff uplift and (b) cumulative annual tariff escalation. In each panel, the results are presented for the 1980, 1987, and 2001 construction-year models. In the one-time tariff uplift case, NPV increases only gradually as the tariff uplift rate increases, and the overall feasibility structure remains largely consistent with the reference DCF condition. For the 1980 and 1987 construction-year cases, most upgrade scenarios remain economically infeasible within the tested one-time uplift range, whereas the baseline-to-Grade 2 and baseline-to-Grade 3 scenarios for the 2001 case remain feasible.

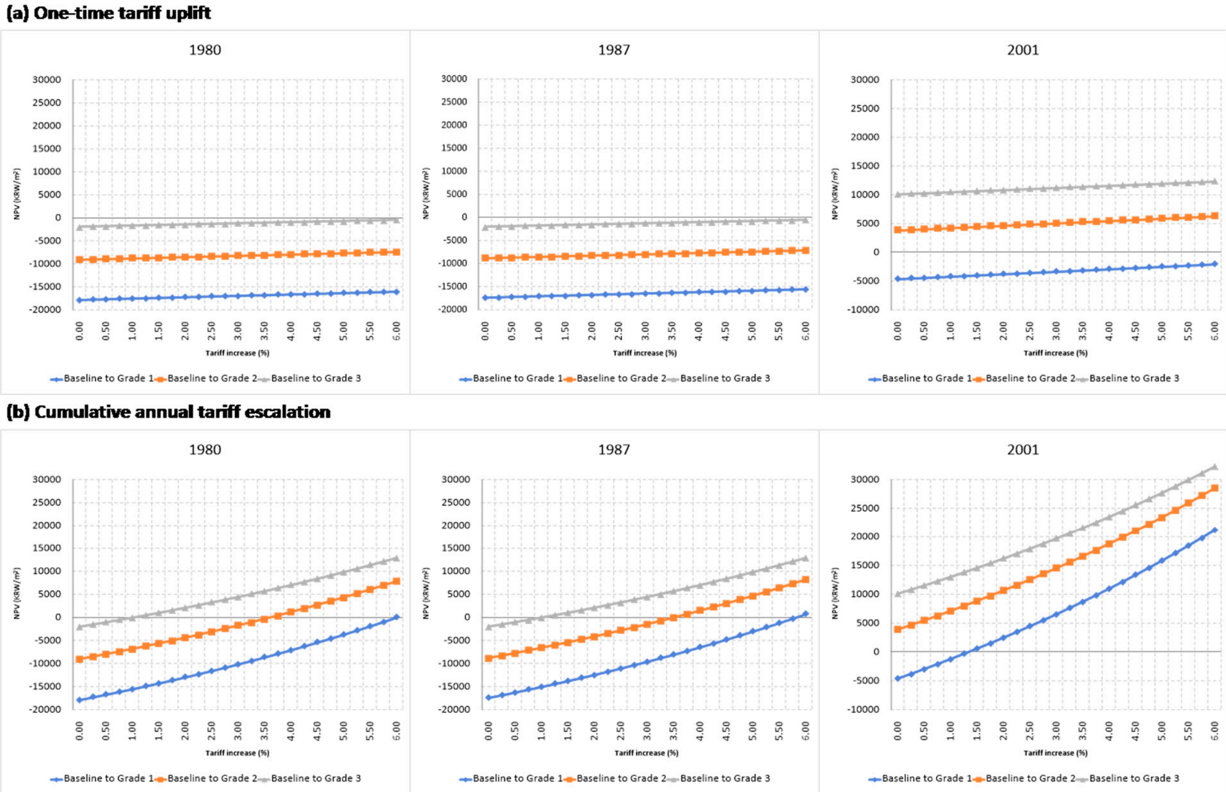

Figure 5. Sensitivity of NPV under two residential gas tariff increase assumptions: (**a**) one-time tariff uplift and (**b**) cumulative annual tariff escalation.

By contrast, the cumulative annual tariff escalation case shows a more pronounced increase in NPV because annual energy cost savings increase progressively over the 15-year analysis period. Under this assumption, several marginal scenarios move closer to or beyond the feasibility threshold, particularly the baseline-to-Grade 3 scenarios for the 1980 and 1987 cases and the baseline-to-Grade 1 scenario for the 2001 case. Nevertheless, the relative interpretation remains broadly consistent with the reference analysis. Intermediate-grade upgrades, especially the baseline-to-Grade 3 scenario, generally show more robust economic feasibility than uniform upgrading to the highest window performance grade. These results indicate that sustained annual tariff escalation can improve the feasibility of some high-cost or marginal scenarios, but it does not fundamentally overturn the cost-effectiveness pattern identified in the reference DCF analysis.

In addition to tariff-related uncertainty, the DCF-based feasibility results were also examined under an extended analysis horizon. When the analysis period (n), corresponding to the expected service life of windows, was extended to 20 years (Table 7), the baseline-to-Grade 3 scenario for houses constructed in 1980 and 1987 was found to satisfy the DCF-based feasibility criteria. For houses constructed in 2001, the range of economically feasible scenarios expanded to include the baseline-to-Grade 1 upgrade. This result demonstrates that investment feasibility assessments can vary significantly depending on the assumed service life of windows, even under identical annual energy cost savings.

Table 7. Decision matrix for economic feasibility under alternative analysis horizons (n = 15 vs. n = 20).

Construction Year	Scenario (Baseline → Target Grade)	n = 15			n = 20		
		NPV > 0	DPB ≤ n	Feasible	NPV > 0	DPB ≤ n	Feasible
1980	Baseline → Grade 1	-	-	-	-	-	-
	Baseline → Grade 2	-	-	-	-	-	-
	Baseline → Grade 3	-	-	-	Yes	Yes	Yes
1987	Baseline → Grade 1	-	-	-	-	-	-
	Baseline → Grade 2	-	-	-	-	-	-
	Baseline → Grade 3	-	-	-	Yes	Yes	Yes
2001	Baseline → Grade 1	-	-	-	Yes	Yes	Yes
	Baseline → Grade 2	Yes	Yes	Yes	Yes	Yes	Yes
	Baseline → Grade 3	Yes	Yes	Yes	Yes	Yes	Yes

Note: Yes indicates that the corresponding feasibility criterion is satisfied; No indicates that the criterion is not satisfied.

4.3. Comparison of Economic Feasibility by Construction Year and Window Performance Grade

A synthesis of the economic analysis results by construction year indicates that single-detached houses constructed in 2001—characterized by relatively improved envelope insulation performance—exhibited larger reductions in heating energy consumption resulting from window performance improvements, along with more favorable economic indicators. This finding suggests that, under the prototype assumptions used in this study, the relative contribution of window performance to the overall thermal balance may become more pronounced once a moderate baseline envelope level has already been secured.

Across all construction years, the most favorable economic performance was consistently observed in the improvement range from the baseline grade to Grade 3 under the adopted assumptions of this study. In contrast, further upgrades to Grades 2 and 1 were associated with increasing payback periods (PBP) and decreasing ROI values (Table 8). This trend reflects the diminishing marginal gains in heating energy savings beyond a certain performance level, while investment costs continue to rise due to higher window prices.

Table 8. Summary of the most favorable economic scenarios under the adopted assumptions by construction year.

Construction Year	Economically Optimal Scenario	ΔE	PBP	ROI
		kWh/m^2·yr	Year	%/yr
1980	Baseline → Grade 3	13.90	13.3	7.5
1987	Baseline → Grade 3	13.87	13.3	7.5
2001	Baseline → Grade 3	20.68	9.0	11.2

In particular, although Grade 1 PVC windows yielded the largest reductions in heating energy consumption, they were associated with relatively long payback periods and low ROI values across all construction years, indicating that they may not represent the optimal choice from an economic perspective. By contrast, Grade 3 and Grade 2 PVC windows achieved meaningful reductions in heating energy consumption with comparatively lower initial investment costs, and are therefore evaluated as more favorable comparative alternatives under the adopted assumptions in terms of cost-effectiveness.

In the DCF-based comparison, these trends became more pronounced. Under the 15-year analysis period, only the baseline-to-Grade 3 and baseline-to-Grade 2 scenarios for single-detached houses constructed in 2001 simultaneously satisfied the criteria of NPV > 0 and DPB ≤ 15 years, indicating DCF-based feasibility under the adopted assumptions

(Table 6). In contrast, for houses constructed in 1980 and 1987, the DPB exceeded 15 years for all scenarios, suggesting conditions under which voluntary investment by private stakeholders would be difficult to induce. This finding implies that even when heating energy savings are achieved, investment feasibility assessments can vary substantially depending on the combined effects of (i) the level of initial investment cost, (ii) the time value of money (discounting), and (iii) assumptions regarding expected service life (analysis period).

Meanwhile, when the analysis period was extended to 20 years, the baseline-to-Grade 3 scenario was evaluated as economically feasible across all construction years. This result confirms that, rather than uniformly selecting the highest-performance windows, considering economic feasibility—even with relatively lower performance grades—can represent a more realistic alternative. Although upgrading to high-performance (Grade 1) windows yields greater energy savings, the associated increase in investment cost continues to limit economic feasibility. These findings suggest that, under identical assumptions regarding window service life and financial conditions, a stepwise performance improvement strategy that accounts for both construction year and target performance level may be more economically rational than a uniform upgrade to the highest performance grade.

From a policy implementation perspective, this suggests that subsidy intensity may need to be differentiated not only by target performance grade but also by construction year, since the same upgrade scenario does not yield the same economic return across vintages.

4.4. Summary of Findings

The results of this chapter indicate that the heating energy demand-based economic evaluation of PVC window replacement yields different outcomes depending on construction year and window performance grade. In the annual indicator-based assessment, houses constructed more recently (2001) exhibited higher ROI values and shorter payback periods (PBP), and across all construction years, the improvement range from the baseline grade to Grade 3 consistently demonstrated the highest cost-effectiveness. In contrast, the DCF-based evaluation, which incorporates the time value of money, further constrained the range of scenarios that satisfied investment feasibility. Under the assumption of a 15-year service life and in the absence of subsidies or financial support, only the baseline-to-Grade 3 and baseline-to-Grade 2 scenarios for houses constructed in 2001 were found to achieve acceptable profitability from a private investor's perspective. This result suggests that, even when heating energy savings exist, the combination of high initial investment costs and discounting effects can create conditions under which voluntary retrofit investments are difficult to induce. The supplementary tariff sensitivity analysis further showed that sustained annual tariff escalation can improve the feasibility of some marginal scenarios, but it does not fundamentally change the relative advantage of intermediate-grade upgrades.

Therefore, rather than uniformly applying a single performance standard, the findings of this study can serve as foundational evidence for establishing differentiated support criteria in window replacement programs and green remodeling policies for single-detached houses, taking into account both construction year and target performance level.

From a policy perspective, these results suggest that subsidy schemes for window replacement should not be uniformly structured. The present economic analysis was intentionally conducted under a no-subsidy condition in order to identify the baseline private economic feasibility of each upgrade scenario. For older houses with weak DCF-based feasibility, stronger support may be required even for intermediate-grade upgrades, whereas for relatively newer houses, performance-tiered incentives centered on Grade 3 or Grade 2 upgrades may be sufficient. A differentiated support matrix based on construction year and target performance grade may therefore improve the efficiency of publicly supported retrofit programs. Accordingly, the policy implications discussed here should be interpreted as evidence for informing future differentiated subsidy design rather than as a direct evaluation of current subsidy programs themselves.

5. Conclusions and Policy Implications

5.1. Main Findings

This study quantitatively analyzed the effects of window performance grade improvement on heating energy demand and economic feasibility in single-detached houses. Based on heating energy demand results derived from ECO2-OD simulations, improvement scenarios were established by upgrading baseline-grade windows to Grade 3, Grade 2, and Grade 1 PVC windows. Using actual market prices and energy tariffs, economic performance was evaluated through the unit cost of energy saving (UCES), payback period (PBP), and annual return on investment (ROI). In particular, representative values were derived by applying area-weighted averages to results from multiple single-detached house prototypes, enabling an assessment of window performance improvement effects and economic feasibility at a more realistic scale.

The analysis showed that heating energy demand consistently decreased with window performance improvement across all construction years; however, the increase in energy savings did not follow a linear pattern with higher performance grades. While relatively large reductions were observed in the transition from the baseline grade to Grade 3, additional upgrades from Grade 3 to Grade 2 and from Grade 2 to Grade 1 exhibited progressively diminishing marginal gains. Diminishing returns indicate that once window performance exceeds a certain level, further performance enhancement yields limited additional reductions in heating energy demand.

The economic analysis reflected these performance characteristics. Across all construction years, upgrading from the baseline grade to Grade 3 PVC windows demonstrated the most favorable economic performance. Further upgrades to Grade 2 and Grade 1 resulted in longer payback periods and declining ROI values due to increased initial investment costs. Although Grade 1 PVC windows provided the largest heating energy savings, their cost-effectiveness was relatively low, indicating that they are not necessarily the optimal choice from an economic perspective. These findings suggest that a uniform application of the highest window performance grade may not be rational in terms of cost-to-performance balance, and that a stepwise performance improvement strategy that considers building age and investment conditions may be more effective.

A comparison by construction year revealed that single-detached houses constructed in 2001 exhibited larger heating energy savings and more favorable economic indicators than those constructed in 1980 and 1987 under the adopted prototype assumptions. This result suggests that, under the prototype assumptions used in this study, the relative contribution of window performance to the overall thermal balance may become more pronounced once a moderate baseline envelope level has already been secured. In contrast, older houses with lower baseline envelope performance showed higher absolute heating energy demand, but the economic feasibility of window performance improvement was constrained by the investment cost structure. These findings highlight that energy savings potential alone does not guarantee economic feasibility, particularly in older housing stock.

The results of this study provide several important implications for window replacement and green remodeling policies targeting single-detached houses. First, rather than uniformly requiring upgrades to the highest performance grade, a stepwise improvement strategy focusing on performance ranges with higher cost-effectiveness may represent a more rational approach. For older single-detached houses, which are more likely to have shorter remaining service lives prior to major renovation or reconstruction, economically oriented performance selection based on payback period and unit cost of energy saving may be more realistic than pursuing long-term maximum performance. In this context, upgrades from the baseline grade to intermediate performance levels (Grade 3 or Grade 2) can be considered priority targets for policy support, as they offer relatively short payback periods and stable investment returns.

Second, given that economic responses to identical window performance improvements vary by construction year, future window replacement support programs should adopt differentiated criteria that account for construction year, existing envelope performance, and window-to-wall ratio. In older single-detached houses, limitations such as weak wall insulation, thermal bridges around window frames, and degraded wall–window junction performance may restrict the realized benefits of high-performance windows. Under such conditions, setting a rational target performance level—potentially in combination with wall insulation reinforcement or thermal bridge mitigation—may be more effective than applying high-performance windows alone. This approach can help ensure more efficient use of limited public resources while maximizing actual energy savings.

Overall, this study demonstrates that the economic feasibility of window performance improvement in single-detached houses varies significantly by performance grade and construction year, and that beyond a certain performance level, cost-effectiveness may be limited. These findings can serve as a foundational reference for supporting rational decision-making that balances performance and cost in future envelope performance improvement policies and window replacement support programs for single-detached houses.

5.2. Limitations and Future Research

This study has several limitations. First, the analysis was conducted using ECO2-OD, a one-zone assessment tool, and therefore room-level thermal interactions, solar gain distribution, and inter-zone heat transfer were simplified. Second, although South Korea also experiences substantial summer cooling demand, cooling-load effects and cooling-related economic impacts were not explicitly included in the present analysis. Third, the WWR was fixed at 20% under a standardized reference-model condition, and the prototype floor-area categories were used as comparative analysis groups; therefore, the framework does not fully capture the diversity of the Korean single-detached housing stock. Fourth, although supplementary tariff sensitivity cases were added to examine the effects of one-time tariff uplift and cumulative annual tariff escalation, the analysis did not aim to forecast actual future residential gas price trajectories. Therefore, actual long-term economic outcomes may still differ depending on future energy market conditions, policy decisions, and tariff structures. Fifth, the Grade 2 window cost was treated as an intermediate proxy value rather than as a directly observed market-average price, which introduces additional uncertainty into the corresponding economic results. Sixth, the analysis was intentionally conducted under a no-subsidy condition and without a full multi-parameter sensitivity analysis; therefore, the reported rankings should be interpreted as comparative results under the adopted assumptions rather than as universally transferable outcomes. In addition, real-world factors such as occupant heating behavior, indoor setpoint temperatures, airtightness and ventilation conditions were not fully captured in the present framework. These limitations suggest that the present findings should be interpreted as comparative evidence under a standardized reference framework rather than as universally transferable predictions for all detached-house retrofit conditions. Future studies should extend the analysis by incorporating cooling-energy effects, alternative WWR and prototype assumptions, explicit subsidy scenarios, and more detailed multi-parameter sensitivity analyses for key economic and physical parameters, including energy price trajectories, window service life, and grade-specific investment cost.

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