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Article

Analysis of Energy-Saving Effect of Green Remodeling in Public Welfare Facilities for Net Zero: The Case of Public Daycare Centers, Public Health Centers, and Public Medical Institutions

Sujin Woo [1], Kyungmo Kang [2,*] and Sangyun Lee [3]

[1] Land & Housing Research Institute, Daejeon 34047, Republic of Korea; sjwoo@lh.or.kr
[2] Division of Architectural Engineering, Daejin University, Pocheon-si 11159, Republic of Korea
[3] Department of Architectural Engineering, Yonsei University, Seoul 03722, Republic of Korea; sangyunl@yonsei.ac.kr
* Correspondence: kyungmo@daejin.ac.kr

Abstract: In 2021, the South Korean government highlighted the Green Remodeling Project for Public Buildings as a crucial initiative for reducing building emissions and tackling post-COVID challenges. Aimed at enhancing energy efficiency and living conditions in public buildings, especially those used by children and the elderly, this project represents a novel approach to sustainable building practices. This research aimed to evaluate the project's effectiveness and identify areas for improvement using a two-fold methodological approach. Initially, a survey of 1065 buildings undergoing green remodeling revealed their condition and the impact of such renovations. Additionally, simulations predicted the energy savings to be achievable, uncovering an average improvement of 30% across buildings, with variations by region and building use. Public health centers saw the highest gains. Despite these successes, disparities in outcomes highlighted the need for strategic adjustments to ensure uniform benefits. This study suggests a refined strategy to enhance green remodeling's impact, making a significant contribution to sustainable building practices by addressing both energy saving for carbon neutrality and public health priorities in a post-pandemic context.

Keywords: green remodeling; energy saving; building sector; green remodeling project for public buildings; emission reduction

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1. Introduction

1.1. Research Background and Purpose

Since the outbreak of the COVID-19 pandemic, the need for responding to climate change and finding new growth engines for a post-COVID era has been increasingly emphasized. In July 2020, the Korean government announced the Korean New Deal, focusing on three aspects: the Green New Deal, the Digital New Deal, and strengthening of the safety net, and also selected green remodeling as one of the ten representative projects of the Korean New Deal. In response to climate change and environmental crises, the government promoted green remodeling as a representative project of the Korean Green New Deal to create a green-friendly living environment in urban, public, and daily living infrastructure; disseminate sustainable new and renewable energy across society; and induce a paradigm shift in future energy [1].

Based on this background, the necessity of carbon neutrality has become more prominent, and in October 2021, South Korea submitted the 2050 Carbon Neutrality Scenario and the 2030 Nationally Determined Contributions (NDC) Enhancement Plan to the international community [2–4].

As shown in Table 1, the revised 2030 NDC target considers the severity of the climate crisis and South Korea's role in the international community, substantially raising the target to reduce greenhouse gas (GHG) emissions by 40% compared to the 2018 emission peak by 2030 [3].

Table 1. Nationally determined contributions (NDC) target in South Korea (unit: million tons CO_2 eq).

Category	Sector	Base Year (2018)	Existing NDC (Percentage Reduction from 2018)	NDC Enhancement (Percentage Reduction from 2018)
Emissions *		727.6	536.1 (△191.5, △26.3%)	436.6 (△291.0, △40.0%)
Emissions	Transition	269.6	192.7 (△28.5%)	149.9 (△44.4%)
	Industry	260.5	243.8 (△6.4%)	222.6 (△14.5%)
	Buildings	52.1	41.9 (△19.5%)	35.0 (△32.8%)
	Transportation	98.1	70.6 (△28.1%)	61.0 (△37.8%)
	Agriculture, livestock, and fisheries	24.7	19.4 (△21.6%)	18.0 (△27.1%)
	Waste	17.1	11.0 (△35.6%)	9.1 (△46.8%)
	Hydrogen	-	-	7.6
	Other (omitted, etc.)	5.6	5.2	3.9
Absorption and removal	Absorption source	−41.3	−22.1	−26.7
	CCUS	-	−10.3	−10.3
	Overseas reduction **	-	−16.2	−33.5

* Base year (2018) emissions are total emissions, and 2030 emissions are net emissions (total emissions absorption and removal). ** Credit issued for carrying out greenhouse gas reduction activities in other countries and for reduction performance.

In the building sector, the plan mandates zero-energy construction for new buildings and prioritizes energy efficiency improvements in existing buildings through green remodeling. The target is to reduce GHG emissions in the building sector by 32.8% compared to 2018 through the dissemination of high-efficiency equipment, smart energy management, low-carbon clean energy distribution, and user behavior improvements. Moreover, the government announced an implementation plan to achieve carbon neutrality through an 88.1% reduction by 2050, and to achieve these GHG reduction targets and carbon neutrality, the government selected the Green Remodeling Project for Public Buildings as a key project of the Korean New Deal [2,3].

Green remodeling not only reduces GHG emissions and improves energy performance in existing buildings but also improves living environments. The importance of green remodeling has increased owing to the need for managing group infections in poorly ventilated spaces caused by COVID-19 and the necessity for maintenance and remodeling of old existing buildings [5]. Most existing facilities in Korea have no mechanical ventilation system installed and are conducted by natural ventilation [6,7].

In particular, as facility improvements for public buildings used by vulnerable groups are urgent, the green remodeling project was launched to improve energy performance and indoor air quality in buildings used mainly by children and the elderly. These buildings include public daycare centers, health centers, and public medical institutions that have been in use for at least ten years since approval of use [8]. Table 2 outlines the project and it supports the cost of design and construction for green remodeling to improve energy performance and living environments in old public buildings by the Ministry of Land, Infrastructure and Transport, and Korea Land and Housing Corporation [9,10].

Table 2. Overview of the green remodeling project for public buildings.

Category	Contents
Project name	Green Remodeling Project for Public Buildings
Implementing agency	(Sponsor) Ministry of Land, Infrastructure and Transport/(Supervisor), Korea Land and Housing Corporation (LH), Green Remodeling Center
Project content	Support for project costs to improve energy performance and living environment of old public buildings (matching project for national and local government costs)
Project targets	Public buildings owned or operated by local governments and central and public institutions: daycare centers, health centers, and medical institutions
Support limit	(Seoul, Central, Public) 50% of green remodeling project cost (local government cost: 50%) (Others) 70% of green remodeling project cost (local government cost: 30%)
Project procedure	① Preliminary survey and selection of project targets ② Application for government grants by project target institutions (local government and public) and project cost allocation ③ Provision of final report of preliminary survey and consulting to project target institutions ④ Project implementation and management by project target institutions (design and construction) ⑤ Project performance management (project cost review)

The main procedure involves conducting preliminary surveys of old buildings for local governments and public institutions wishing to undergo green remodeling, selecting suitable buildings for the project, and granting the funds for the green remodeling project. In addition, a green remodeling planning report, which includes the optimal green remodeling plan derived from the preliminary surveys, design consulting, and the expected energy-saving results, is provided to each local government to facilitate project implementation. The local governments then reflect this green remodeling pre-planning in their design and construction, and after completion of construction, the project's implementation and the use of project funds are evaluated to determine if the project was completed appropriately.

Accordingly, this study conducted field surveys to establish design priorities corresponding to the pre-planning stage with a focus on the green remodeling project for public buildings. These priorities were subsequently applied to energy design consulting. Then, ECO2 simulation was utilized to calculate the energy savings resulting from the green remodeling and to assess energy savings by region and building usage.

1.2. Research Method and Scope

Since the Green Remodeling Project for Public Buildings targets public buildings used by vulnerable populations, the scope of this study also mirrors the project targets as shown in Table 3, consisting of 1065 buildings owned or operated by local governments and public institutions, including public daycare centers, health centers, and public medical institutions that have been in use for at least 10 years since approval of use. The study covers the preliminary survey and design consulting support performed by the Korea Land and Housing Corporation in 2021 [9–11].

The preliminary survey and design consulting for the Green Remodeling Project for Public Buildings were conducted by the Green Remodeling Center of the Korea Land and Housing Corporation, the implementing agency. This is to support quick and thorough decision-making by the participating institutions and derive energy performance improvement plants suited to each building through energy design consulting by evaluating the current status of existing buildings and conducting interviews with managers at the beginning of the project [10].

Table 3. Research targets and scope.

Category	Contents
Research Targets	Daycare centers, health centers, and medical institutions targeted in the preliminary survey and design consulting for the 2021 Green Remodeling Project for Public Buildings (1065 buildings)
Target conditions	Public buildings with at least years of use since approval of use (approved before 1 January 2012)
Research scope	Analysis of energy effects through preliminary survey and design consulting for green remodeling of 1065 buildings
Contents of preliminary survey and design consulting	Building information collection, building site surveys, manager surveys, energy design consulting, and energy-saving simulation

First, field inspections were conducted to evaluate the current status of building aging, and the requirements of the building managers, users, and other stakeholders were estimated using surveys. The results of these evaluations and surveys were used to determine the priorities of green remodeling tasks and provide design consulting to ensure the optimal improvement of energy performance within each local government's limited budget.

As shown in Table 4, in this study, we first collected information on 1065 public buildings and subsequently conducted field surveys and user satisfaction surveys for the target buildings. Next, green remodeling energy design consulting was performed for each building, and the energy-saving effects according to use and region were analyzed. The findings were then used to determine the design focus for energy saving in the planning stage of the green remodeling project for each building and as basic data for promoting future green remodeling.

Table 4. Research Procedure.

<table>
<tr><td colspan="2">Introduction</td></tr>
<tr><td>Research Background and Purpose</td><td>Research Scope and Method</td></tr>
<tr><td colspan="2">↓</td></tr>
<tr><td colspan="2">Analysis of target building aging</td></tr>
<tr><td>Field surveys of target buildings</td><td>Occupant satisfaction survey</td></tr>
<tr><td colspan="2">↓</td></tr>
<tr><td colspan="2">Design consulting for green remodeling of public buildings</td></tr>
<tr><td>Apply energy design of target buildings</td><td>Building energy evaluation simulation</td></tr>
<tr><td colspan="2">↓</td></tr>
<tr><td colspan="2">Analysis of energy saving effect in green remodeled public buildings</td></tr>
<tr><td>Analyze energy saving effect by region</td><td>Analyze energy saving effect by use</td></tr>
<tr><td colspan="2">↓</td></tr>
<tr><td colspan="2">Research conclusions and suggestions</td></tr>
</table>

1.3. Literature Review

A domestic green remodeling policy project has been executed since 2014. The importance of carbon neutrality has grown recently, so research on green remodeling is being actively promoted. According to Jeong (2021), domestic and foreign research aimed at improving the energy performance of existing buildings is known as green remodeling, green renovation, remodeling, green architecture, zero-energy building, and green building [12]. In this study, previous research related to energy-saving effects through green remodeling was analyzed. The target range is only articles published in academic journals after 2014 because the Green Building Construction Support Act was passed in 2014, and green remodeling projects began. A representative case of green remodeling was selected from the literature, and its effect on the building's energy consumption was analyzed.

Han, D. et al. (2021) and Kim, S. et al. (2017), Lee, J. et al. (2019) analyzed a building that was green-remodeled, including the technologies that were included in it and their effect on its energy consumption [13–15]. Lee, H. et al. (2022) also analyzed the effect of green remodeling on a building's energy consumption [16]. Kim, J. et al. (2022) conducted simulations of a green-remodeled public building with ECO2 and Design Builder, which are building energy evaluation programs [17]. Lim, J. et al. (2017) surveyed green remodeling business owners and private green-remodeled building owners about their indoor comfort and energy-cost satisfaction [18]. They also investigated whether green remodeling affected heating energy consumption. Jung et al. (2024) investigated energy-saving impact by green remodeling in nursery school based on simplified multi-objective energy efficiency ratio method [19].

This study was based on a large-scale actual condition survey and analysis of the performance of 1065 public daycare and healthcare centers. It differed from other studies in that improvement plans were derived based on field surveys and simulations. Therefore, this study comprehensively analyzed the problems with the public building green remodeling system and policies through field surveys and simulations of green-remodeled buildings. Based on this, institutional improvement measures were proposed.

2. Preliminary Survey and Analysis for Green Remodeling of Public Buildings

2.1. Field Surveys and Analysis of Building Aging

The preliminary survey, which comprises the pre-planning stage for conducting green remodeling in public buildings, was divided into field surveys to evaluate status and surveys of stakeholders such as managers and users. General information on the buildings' use, size, and date of approval of use was collected to review the general details of the buildings. And also, the aging status of the buildings by construction type such as state of insulation, windows, and finishing, as well as capacity, efficiency, and malfunction status of mechanical and electrical equipment, etc., was confirmed and evaluated for use as basic data in green remodeling design consulting [20].

Before the field surveys, the ages of the buildings were checked by collecting basic building information. The building ages were determined based on the time of approval of use (year) according to the criteria of the Green Remodeling Project for Public Buildings. According to the results shown in Figure 1, buildings that are 10 to less than 15 years old accounted for 42.3% of the total preliminary survey targets, followed by buildings that are 15 to less than 20 years old, which accounted for 23.6%, and buildings that are 20 to less than 25 years old, which accounted for 11.0%. Buildings 25 years old or older accounted for less than 10% of the total preliminary survey targets, for which new construction rather than remodeling should be considered. Buildings with no records accounted for 0.5% of the targets and were classified as "Others".

Among the buildings in the preliminary survey, those constructed between 2006 and 2008 supported green remodeling the most, suggesting that users of buildings that are 10–15 years old, which comprised the highest proportion, appreciate the need for remodeling the most. Buildings that received approval of use less than 10 years ago accounted for 3.7%. Although these buildings were excluded from the Green Remodeling Project for Public Buildings because they did not meet the eligibility criteria, we found that the building managers applied for remodeling because of the perceived need.

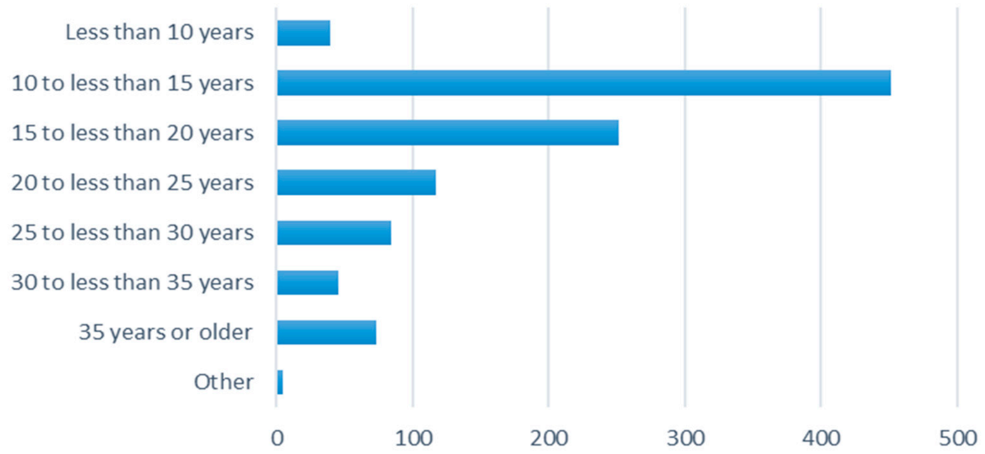

Figure 1. Analysis of aging based on building age.

According to the analysis of building aging by use (Figure 2), health centers, daycare centers, and medical institutions all showed the highest distribution of buildings that are 10 to less than 15 years old. Among these, health centers had the highest proportion at 47.55%, followed by daycare centers at 38.65%, and medical institutions at 30.91%. Next, the proportion of buildings that are 15 to less than 20 years old was high, with health centers at 29.8%, daycare centers at 17.5%, and medical institutions at 25.45%. For health centers, the percentage of buildings up to 20 years old was less than 10%, showing a substantial difference in distribution compared to buildings under 20 years old. Daycare centers showed a similar distribution, with 13.65% of buildings being 20 years old or older and less than 15 years old and 13.46% of buildings being 25 or less than 30 years old. The age of medical institutions was evenly distributed from 20 years to less 35 years old, with no buildings 35 years old or older.

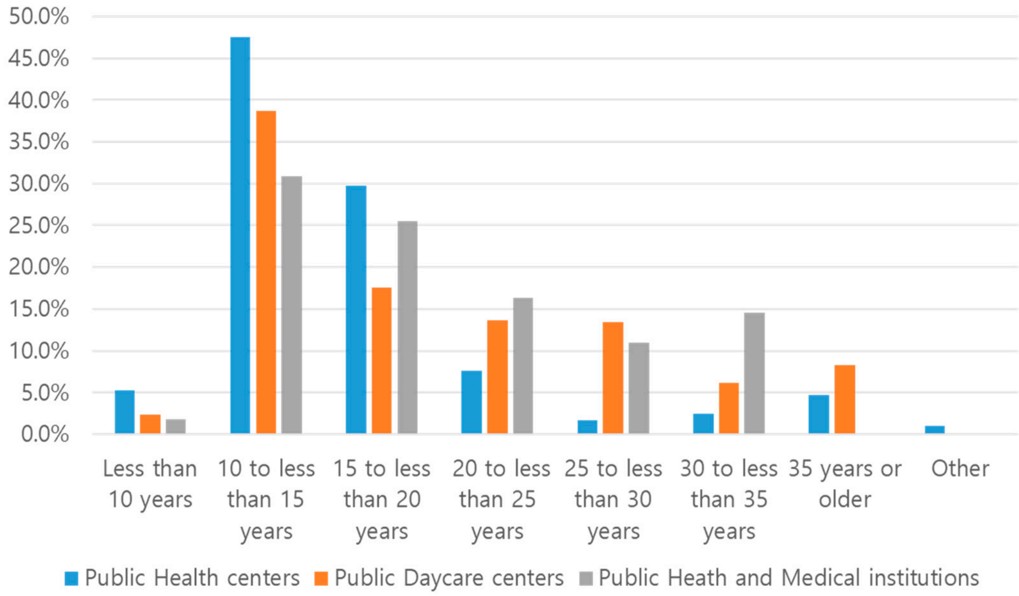

Figure 2. Analysis of building aging by use.

After identifying the aging status of the buildings based on basic information, field surveys were conducted to analyze building aging by identifying the conditions of the daycare centers, health centers, and medical institutions. As shown in Table 5, the field survey methods for the target buildings, required equipment, and field survey items were categorized according to the parts of the building.

Table 5. Building field survey methods.

Category	Field Survey Equipment		Field Survey Targets	Field Survey Items	Data Usage Plan
Indoor and outdoor environments	Visual assessment Thermo-hygrometer		Condensation, leaks, defects, cracks, indoor temperature and humidity, etc.	Weak areas and structural areas such as exterior walls and windows Measure indoor temperature and humidity with datalogger	Identify defects; measure indoor temperature and humidity
Window performance	Glass thickness meter		Window performance	Composition of window glass in major spaces	Inspect glass thickness and composition
	Optical performance meter		Window performance	Optical performance of window glass in major spaces	Measure and verify SHGC, VLT, etc.
Envelope insulation performance	Surface thermometer		Walls Verify thermal transmittance (U-value)	Verify insulation performance by measuring the surface temperature compared to the outside air temperature	
	Thermal imaging camera		Defect patterns and interior wall surface temperature	Weak areas and structural areas such as exterior walls and windows	Determine defects and measure surface temperature

The indoor and outdoor environmental field surveys focused on investigating issues such as condensation, leaks, cracks, and indoor temperature and humidity, while defects in structural parts (exterior walls, windows, etc.) and indoor temperature and humidity were measured through data loggers using equipment such as thermo-hygrometers. Regarding window performance, to assess the buildings' insulation performance, the window and glass composition and solar heat gain coefficient (SHGC) were measured using glass thickness gauges and optical performance meters. In addition, to determine the insulation performance of external walls, thermal imaging cameras and surface thermometers were used to measure exterior wall surface temperatures and thermal transmittance (U-value).

The capacity, rated power consumption, and energy consumption of the buildings' heating and cooling systems were verified through visual assessments and equipment inspections using the design documents. All structural and asbestos surveys that do not affect energy but should be reflected in the remodeling plans were incorporated into future action plans through structural simulations, material lists, and visual assessments by the surveyors.

The building aging evaluation conducted using the equipment listed in Table 5 was categorized into insulation, windows, heating and cooling equipment, ventilation equipment, and lighting equipment according to the green remodeling support items listed in Table 6. The field surveyors prepared an aging checklist and evaluated each standard in three stages: good, average, and poor. For windows, considering the durability and performance standards and repair and replacement cycles, windows less than 3 years old were evaluated as good, those that are 3 to less than 10 years old as average, and those with damage or reduced sealing as poor [21,22].

Table 6. Evaluation criteria for building aging in field surveys.

Category		Standard
Windows	Good	Less than 3 years old
	Average	3 to less than 10 years old
	Poor	Damaged, poorly caulked, reduced sealing, etc.
Insulation	Good	At or above current legal insulation standards
	Average	Insulation reinforced since completion
	Poor	Insulation material missing or damaged, or not reinforced after completion and requires reinforcement
Finishing	Good	No defects or interior work conducted within 2 years
	Average	Minor defects such as contamination; finishing requires replacement for asbestos removal
	Poor	Repairs needed for damage, etc.
Cooling/heating and hot water equipment	Good	Less than 3 years old
	Average	3 to less than 10 years old
	Poor	10 years old or older
Lighting equipment	Good	LED lighting installation rate of 100% or more
	Average	LED lighting installation rate of 30% or more
	Poor	LED lighting installation rate of less than 30%

If the insulation meets the current legal insulation standards for energy-saving design, it is considered good. If insulation reinforcement has been implemented since completion, it is considered average. If the insulation material is missing or damaged, or if no insulation reinforcement has been performed since completion and reinforcement is needed, it is considered poor. For interior finishing, cases with interior work done within the past two years or no defects are considered good, cases with minor defects such as contamination or those requiring finishing replacement due to asbestos removal are considered average, and cases requiring repairs due to damage are considered poor. Heating, cooling, and hot water supply equipment, serving as heat sources, were evaluated according to their replacement cycles determined by their service life, while lighting equipment was assessed based on the installation rate of LED lighting.

According to the field survey evaluation results in Figure 3, windows showed the highest defect rate at 89%. Insulation also showed a high defect rate at 84%, indicating that passive construction work for windows and insulation was most urgent.

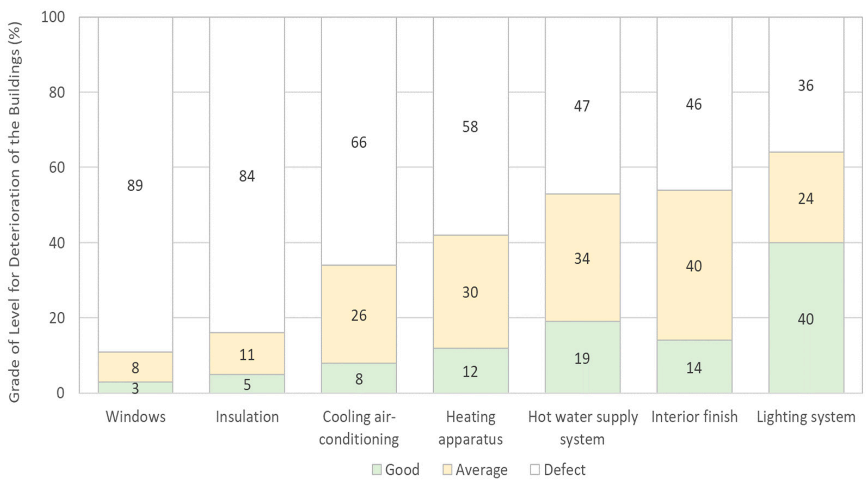

Figure 3. The level of deterioration of the buildings.

In descending order, the building conditions with poor ratings were as follows: windows (89%) > insulation (84%) > cooling equipment (66%) > heating equipment (58%) > hot water supply equipment (47%) > interior finishing (45%) > lighting equipment (36%). The equipment, such as cooling, heating, and lighting, was in better condition than windows and insulation because their replacement work was easier and cheaper than construction work involving windows and insulation, which required installing scaffolding and relocating users. Therefore, some improvements had already been made.

2.2. Analysis of User Indoor Environment Satisfaction Survey

In addition to the evaluation of building aging, as shown in Table 7, a satisfaction survey was conducted on the current indoor environments of the buildings with 1831 managers (permanent staff) and users of each building to derive priorities for energy design consulting in green remodeling.

Table 7. Overview of user satisfaction survey for public buildings.

Survey Overview	Contents
Survey purpose	Identify indoor environmental conditions in public buildings and derive green remodeling priorities
Survey targets	1831 permanent staff of public buildings
Survey items	Indoor environment of building
Survey method	Stakeholder interviews and in-person surveys
Analysis of results	$\sum$ (Points per item $\times$ Number of respondents per item)/Total respondents

We surveyed user satisfaction with the indoor environment, including the thermal, lighting, noise, and air environments of each public building, and analyzed the causes of dissatisfaction to utilize them as indicators for deriving improvement priorities of the buildings. As shown in Table 8, the satisfaction survey used a 7-point Likert scale, with responses categorized as very satisfied (7), satisfied (6), slightly satisfied (5), average (4), slightly dissatisfied (3), dissatisfied (2), and very dissatisfied (1). The satisfaction results were obtained by multiplying the item weight and the number of respondents and dividing the product by the total number of respondents. As shown in the survey results in Table 9, winter thermal environment scored the lowest satisfaction at 3.54, followed by summer thermal environment (3.79) and all-season thermal environment (3.80). This indicates that improvements to windows and insulation, which affect the indoor thermal environment, are the most urgent.

Table 8. Point scale for survey items.

Points	7	6	5	4	3	2	1
Category	Very satisfied	Satisfied	Slightly satisfied	Average	Slightly dissatisfied	Dissatisfied	Very dissatisfied

Table 9. Results of user satisfaction survey.

Item	Category	Survey Results	
		Satisfaction	Score
Thermal environment	All seasons	Slightly dissatisfied	3.80
	Winter	Slightly dissatisfied	3.54
	Summer	Slightly dissatisfied	3.79
Indoor humidity	Winter	Slightly dissatisfied	3.81
	Summer	Slightly dissatisfied	3.81
Air quality	All seasons	Average	4.20
Noise environment	All seasons	Average	4.14
Lighting environment	All seasons	Average	4.48

For indoor humidity, the survey results for both winter and summer showed a slightly dissatisfied score (3.81), indicating poor indoor humidity, regardless of the season. Both the thermal environment and indoor humidity items showed slightly dissatisfied scores. This can be attributed to the aging of insulation and windows that control indoor temperature and humidity, which is consistent with the building condition assessment results. In contrast, indoor air quality, noise environment, and lighting environment all showed average scores, with lighting environment scoring the highest at 4.48. This is likely because lighting replacement work is easier than other construction types; thus, several improvements were implemented. However, the survey items showed slightly dissatisfied and average scores overall, indicating that users' discomfort attributed to the aging of daycare centers, health centers, and medical institutions was high.

2.3. Discussion of Preliminary Survey

Table 10 presents the examination results of general information such as building use, size, and approval date based on the collected building information. Of the 1065 total buildings, 520 daycare centers accounted for the largest number of targets for the green remodeling preliminary survey and design consulting, with an average total floor area of 493.7 m^2. This was followed by 490 health centers and 55 medical institutions; medical institutions had the largest average area, followed by daycare centers and health centers, and most health centers and daycare centers were small-scale facilities with a total floor area of less than 500 m^2. Although there were only 55 medical institutions, their combined total floor area was the largest at 550,000 m^2, owing to the size of individual buildings.

Table 10. Results of the analysis of green remodeling of public buildings.

Classification		**Public Day Care Center**	**Public Health Center**	**Public Health and Medical Institution**
Number of buildings		520	490	55
Total Floor Area (m^2)	Average	493.7	396.2	10,091.97
	Total	256,732.7	194,125.2	555,058.3

Both the building aging assessment and stakeholder satisfaction survey results showed that the condition of insulation and windows was the worst, causing the greatest dissatisfaction among users and requiring urgent improvements. Lighting conditions were found to be the best, with lighting environment also scoring the highest satisfaction at an "average" rating in the satisfaction survey. These results seemed to be very consistent between the building assessment and satisfaction survey results and were reflected to derive priorities for green remodeling.

3. Energy Design Consulting for Green Remodeling

3.1. Deriving Design Priorities

By combining the above results of the public building aging assessment and stakeholder indoor environment survey, the improvement priorities for public building green remodeling were derived. We derived priorities to ensure energy performance improvement considering the urgency of each individual building's status assessment and satisfaction survey results, referring to the support criteria for each construction type of the Green Remodeling Project for Public Buildings in Table 11.

Table 11. Supported technical elements for green remodeling of public buildings.

Category		Supported Technical Elements for Green Remodeling
Supported technical elements	Mandatory construction (apply at least one)	High-performance windows and doors, heat recovery ventilation systems, internal and external insulation reinforcement, high-efficiency heating and cooling systems, high-efficiency boilers, high-efficiency lighting (LED), renewable energy (solar power), building energy management systems (BEMS), or remote electronic meters
	Optional construction	Cool roofs (heat reflective coating), solar control devices, smart air showers, instantaneous water heaters, and other construction for improving energy performance and indoor air quality
	Additional supported construction	Demolition and disposal of existing construction, asbestos investigation and removal, structural safety reinforcement, other construction related to green remodeling, construction for heat source replacement, electrical capacity expansion, and other electrical construction for green remodeling

According to the building aging assessment and questionnaire survey results, windows and insulation showed the highest priority for energy performance improvement through green remodeling at 95.7%. Regarding the other design priorities for green remodeling, this was followed by heating and cooling equipment, ventilation equipment, lighting equipment, and renewable energy equipment.

Moreover, according to the results for additional construction items that do not affect energy performance but are necessary for building use such as maintenance and repair (Figure 4), waterproofing showed the highest priority; thus, green remodeling design consulting that reflected this result was performed.

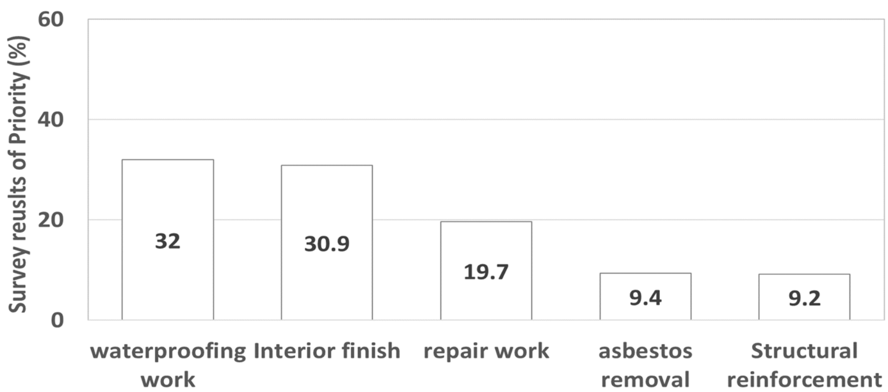

Figure 4. Priority of subsidiary construction related to green remodeling.

3.2. *Application of Energy Design Consulting for Green Remodeling of Public Buildings*

Energy design consulting was performed for each individual building by applying the design priorities obtained from the preliminary survey of 1065 buildings and the questionnaire survey. For design consulting, the improvement directions were set according to the green remodeling needs of each building, and consulting tailored to the 1065 buildings was provided. We provided energy design consulting for each individual building and combined the findings to analyze the applied technologies for green remodeling of all buildings.

According to the results, window construction was the most frequently applied for energy performance improvement, and the top five technical elements applied in the mandatory construction were windows (88.4%) > heating and cooling equipment (81.1%) > ventilation equipment (68.2%) > external wall insulation (64.8%) > high-airtight doors (63%). This was followed by boilers (56.1%), roof insulation (50.8%), LED lighting (45.8%), and solar power (28.9%).

Insulation work, which was found to be most urgent in the status assessment and questionnaire survey, showed a lower application rate than heating, cooling, and ventilation equipment because insulation work inevitably requires users to relocate to spaces, as well as dismantling of exterior walls and scaffolding construction. This makes insulation work more difficult to apply on-site than heating, cooling, and ventilation work, resulting in a difference from the derived green remodeling priorities.

Based on the current energy performance level of the buildings before green remodeling and the design consulting contents reflecting the improvement technologies above, we proposed performance improvement methods and calculated the corresponding difference in energy saving rates before and after green remodeling to bring existing old buildings up to current legal energy standards.

The ECO2 building energy evaluation program is a simulation program developed for the building energy efficiency grade certification system in South Korea [23,24]. The energy evaluation method is based on ISO 13790 and DIN V 18599 and calculates the monthly energy demand of the building based on monthly average weather data [25–27]. It can predict the monthly energy consumption of the building according to system performance. The energy consumption is divided into heating, cooling, hot water, lighting, and ventilation energy based on the monthly average weather data for 13 regions in South Korea. The primary energy consumption and carbon dioxide emissions of the building can be comprehensively calculated and predicted from the calculated energy.

The energy savings rate was calculated using ECO2 based on the customized consulting contents for each individual building according to the energy design priorities derived in Section 3. As shown in Table 12, the current state of each building was applied as the state before green remodeling, and the performance improvement plan reflecting green remodeling consulting was set as the state after improvement for the simulation. If there was insufficient drawing information for the current state of the building before improvement, then the legal energy standards in the building permit year were applied through the building register [28,29].

Through these simulations, we analyzed the energy saving rate for each building using ECO2 as shown in Figure 5. The purpose of these simulations was to determine how much building energy could be saved if green remodeling was implemented, considering the results of the preliminary surveys and consulting, and to help local governments and public institutions in making decisions for project promotion.

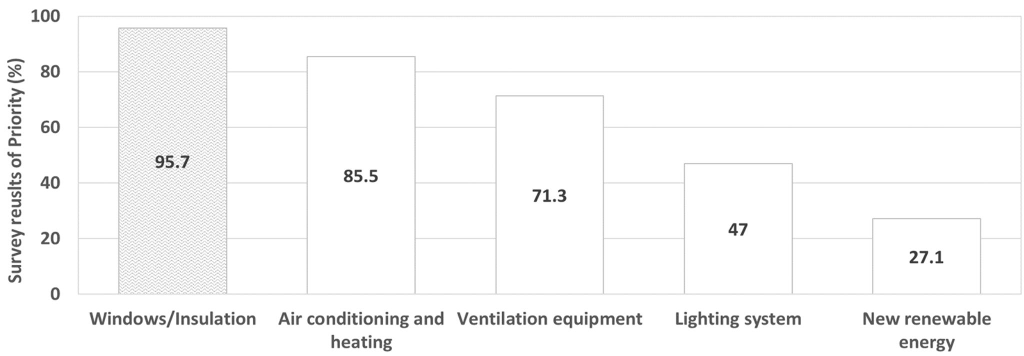

Figure 5. Priority of energy performance improvement construction for green remodeling.

Table 12. ECO2 inputs for calculating building energy savings.

<Building Category>

Category	Before Green Remodeling	After Green Remodeling
Insulation	① If drawings are available: Calculate thermal transmittance in drawings ② If drawings are not available: The energy-saving design standards at the time of building permit shall be applied.	Insulation thickness: But, existing insulation material is not included in the thermal transmittance calculation

Insulation thickness (After Green Remodeling):

Region		Central 1	Central 2	Southern	Jeju
Exterior walls	Direct	190	140	110	90
	Indirect	190	170	130	100
Floors		190	120	100	70
Roofs Internal insulation		220	220	180	130
Inverted roofs		190	190	160	110

Category	Before Green Remodeling	After Green Remodeling
Windows/Doors (thermal transmittance/SHGC)	Windows: ③ If drawings or performance certificates are available, apply those values ④ If drawings or performance certificates are not available: apply ④-1. ④-1 Thermal transmittance :	Windows: Enter the window thermal transmittance rate equal or higher in compliance with the current energy-saving design standard

Before Green Remodeling:

Glass type	SC	SHGC
Single-pane	0.9	0.774
Double-glazed	0.8	0.688
Low-E single-pane	0.67	0.576
Low-E double-glazed	0.6	0.516
Low-E triple-glazed	-	0.374
Double-glazed window	-	0.563

After Green Remodeling:

Region	Window type	U-value ($W/m^2 \cdot K$)	SHGC
Central1	T24 Low-E double-glazed	1.300	0.348
Central2	T22 Low-E double-glazed	1.500	0.348
Southern	T22 Low-E double-glazed (argon)	1.800	0.516
Jeju	T22 Low-E	2.200	0.516

Before Green Remodeling	After Green Remodeling
Door: Thermal transmittance apply Energy Saving Design Standards <Annex 1>.	Door: Thermal transmittance apply Energy Saving Design Standards <Annex 1>.

<Mechanical system and electricity category>

Category	Before green remodeling	After green remodeling
EHP	⑤ If drawings or performance certificates are available:	Capacity and COP:

Before green remodeling:

Reference area	Cooling/heating	Power consumption	COP
20 m^2 or less	2.3/2.8	0.59	3.0 COP
40 m^2 or less	5.2/6.0	1.50/1.75	
70 m^2 or less	8.3/9.2	2.35/2.15	
90 m^2 or less	Cooling: 0.12 kW per m^2 Heating: 0.148 kW per m^2	Capacity ÷ COP	
100 m^2 or less			
300 m^2 or less			
900 m^2 or less			

After green remodeling:

Reference area	Cooling/heating	Power consumption	COP
20 m^2 or less	2.3/2.8	0.59/0.83	3.89/3.37
40 m^2 or less	5.2/6.0	1.50/1.75	-
70 m^2 or less	8.3/9.2	2.35/2.15	-
90 m^2 or less	Cooling: 0.12 kW per m^2 Heating: 0.148 kW per m^2	per m^2 Capacity ÷ COP	-
100 m^2 or less			-
300 m^2 or less			-
900 m^2 or less			-
Other	Cooling/heating COP when applied together		

Before green remodeling	After green remodeling
⑥ Capacity (indoor unit): 30 W (wall-mounted), 60 W (ceiling)	Indoor unit power consumption: Input the same as before green remodeling

Table 12. *Cont.*

<table>
<tr><td>Boilers</td><td colspan="2">⑦ If drawings or performance certificates are available, apply those values
⑧ If drawings or performance certificates are not available: apply ⑧-1 or ⑧-2, ⑧-3, ⑧-4.
⑧-1 Heating capacity (refer to District Heating Corporation Heat Use Facility Standards):
If facilities for the elderly and children, Area × 100 W/m^2 or 122.1 W/m^2 (with AHU heating)
If medical institutions, Area × 122.1 W/m^2 or 145.3 W/m^2 (with AHU heating)
⑧-2 Hot water capacity (refer to District Heating Corporation Heat Use Facility Standards):
If facilities for the elderly and children, Area × 8.1 W/m^2
If medical institutions, Area × 29.1 W/m^2
⑧-3 Boiler efficiency: Gas and oil boilers 80% , Electric boilers 90%
⑧-4 Pump capacity:
If Centralized pump capacity, apply drawing /nameplate standard. 0.1 kW per pump (centralized)</td><td colspan="3">Heating capacity:
If facilities for the elderly and children, Area × 100 W/m^2 or 122.1 W/m^2 (with AHU heating)
If medical institutions, Area × 122.1 W/m^2 or 145.3 W/m^2 (with AHU heating)

Hot water capacity:
If facilities for the elderly and children, Area × 8.1 W/m^2
If medical institutions, Area × 29.1 W/m^2

Boiler efficiency:
If Gas and oil boilers 91%
When applying condensing boilers: 95%
If electric boilers 100%

Pump capacity:
If centralized pump capacity, apply drawings/ nameplate standard 0.1 kW per pump (centralized)</td></tr>
<tr><td>Ventilation</td><td colspan="2">⑨ If drawings or performance certificates are available, apply those values
⑩ If drawings or performance certificates are not available, apply as exhaust fan</td><td colspan="3">Ventilation rate:
Area (m^2) × 0.1/m^2 × 36 m3/person·h
Input number of units × baseline heat exchanger ventilation rate, considering the required ventilation rate</td></tr>
<tr><td>Lighting</td><td colspan="2">⑪ If drawings or performance certificates are available, apply those values
⑫ If drawings or performance certificates are not available: apply ⑫-1 or ⑫-2.
⑫-1 Fluorescent(residential/non-residential): 9/15 W/m^2
⑫-2 LED (residential/non-residential): 6/9 W/m^2
If mixed, multiply by the percentage of fixtures among the total and sum
Input lighting power according to lighting density</td><td colspan="3">Lighting power:
LED (residential/non-residential) 6/9 W/m^2</td></tr>
<tr><td rowspan="9">Renewable energy</td><td colspan="2">⑬ If drawings or performance certificates are available, apply those values
⑭ If drawings or performance certificates are not available, apply solar according to the table below</td><td colspan="3">Solar panels:
Same as before improvement</td></tr>
<tr><td>Item</td><td>Input value</td><td>Item</td><td colspan="2">Input value</td></tr>
<tr><td>Panel capacity</td><td>Construction cost statement. Automatically calculated capacity per area</td><td>Panel capacity</td><td colspan="2">Construction cost statement. Automatically calculated capacity per area</td></tr>
<tr><td>Module area</td><td>5.32 m^2/kW</td><td>Module area</td><td colspan="2">5.32 m^2/kW</td></tr>
<tr><td>Module tilt</td><td>45°</td><td>Module tilt</td><td colspan="2">45°</td></tr>
<tr><td>Module orientation</td><td>South</td><td>Module orientation</td><td colspan="2">South</td></tr>
<tr><td>Module classification</td><td>Single crystal</td><td>Module classification</td><td>Single crystal</td><td rowspan="2">(Optional)</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>Module efficiency</td><td>(When performance values input)/19.4%</td></tr>
<tr><td>Module type</td><td colspan="2">Rear-vented</td></tr>
</table>

4. Analysis of Energy Saving Effects through Green Remodeling of Public Buildings

4.1. Analysis of Energy Saving Effects by Region

The 1065 target buildings that received design consulting were divided into regions (Seoul, Gyeonggi-Incheon, Gangwon, Chungcheong, Jeolla-Jeju, Gyeongsang) and the energy saving effects were analyzed. The administrative divisions consisting of 17 metropolitan cities and provinces nationwide were combined into Seoul, Gyeonggi-Incheon, Gangwon, Chungcheong-Daejeon-Sejong, Jeolla-Gwangju-Jeju, and Gyeongsang-Daegu-Ulsan-Busan, taking into account geographical and climatic characteristics.

Table 13 shows the analysis results of average energy saving rate by region. The overall average energy saving rate was 32.39%. The average primary energy consumption before green remodeling was 216.27 kWh/m^2, and if green remodeling was conducted as proposed based on the preliminary survey and consulting, the average primary energy consumption was projected to be 139.37 kWh/m^2, representing energy savings of 76.56 kWh/m^2.

Table 13. Analysis of energy saving rate by region.

Region	Number of Buildings	Total Floor Area (m^2)	Avg. [a] Primary Energy Consumption before Improvements (kWh/m^2)	Avg. Primary Energy Consumption after Improvements (kWh/m^2)	Avg. Primary Energy Consumption Savings (kWh/m^2)	Primary Energy Consumption Saving Rate (%)
Seoul	113	137,418	161.54	129.71	31.84	20.19
Gyeonggi-Incheon	202	291,093	202.47	151.26	51.21	24.19
Gangwon	106	80,553	277.92	182.63	93.26	31.95
Chungcheong	131	116,209	231.13	133.02	98.11	39.56
Jeolla-Jeju	272	154,507	246.48	116.85	129.63	50.14
Gyeongsang	241	226,136	178.08	122.77	55.30	28.34
Total	1065	1,005,916	216.27	139.37	76.56	32.39

[a] Avg.: Average.

By region, Jeolla (Jeolla, Gwangju)-Jeju showed the highest average energy saving rate of 50.13%. This was followed by Chungcheong (Chungcheong, Daejeon, Sejong) at 39.56%, Gyeongsang (Gyeongsang, Busan, Ulsan, Daegu) at 28.34%, Gangwon at 31.95%, and Gyeonggi (Gyeonggi, Incheon) at 24.19%. In comparison, the average energy saving rate in Seoul was the lowest at 20.19%. The primary energy consumption savings per unit area were also the highest in Jeolla-Jeju at 129 kWh/m^2, followed by Chungcheong at 98 kWh/m^2, Gangwon at 93.26 kWh/m^2, Gyeongsang at 55.30 kWh/m^2, Gyeonggi-Incheon at 51.21 kWh/m^2, and Seoul at 31.84 kWh/m^2.

As shown in Figure 6, the energy saving rate was the highest in Jeolla-Jeju because it has the highest proportion of small-scale buildings and old buildings with several years of use, as well as the highest overall ratio of health centers reflecting green remodeling construction. The proportion of health centers in Jeolla-Jeju targeted for green remodeling was 35.1%, the largest number of health centers among all regions and 63.2% of the green-remodeled buildings in Jeolla-Jeju. Thus, the percentage of old health centers is overwhelmingly high, resulting in a substantial energy improvement effect.

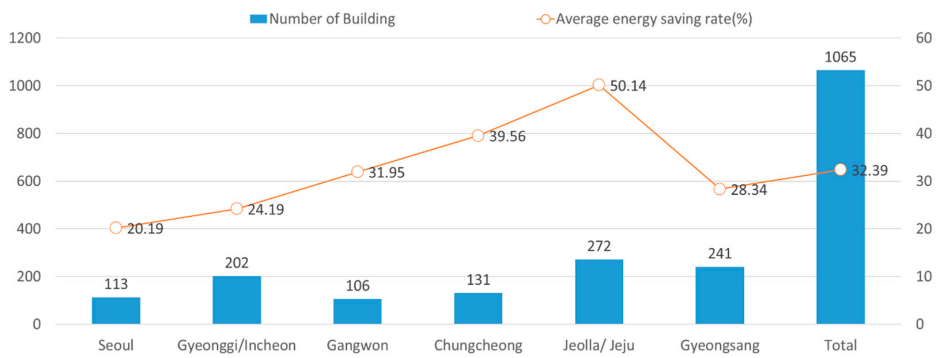

Figure 6. Analysis of energy saving rate by region.

In contrast, in Seoul, which showed the lowest energy saving rate, the percentage of daycare centers among all green-remodeled buildings in Seoul was overwhelmingly high at 96.4%. Moreover, there were limitations in green remodeling construction owing to difficulties in relocating occupants and the on-site construction constraints in daycare centers. Additionally, only partial green remodeling was reflected due to continuous environmental improvements for the daycare center certification evaluations, resulting in a low energy performance improvement effect through green remodeling.

The regional energy saving effects are closely related to the energy saving effects by use in Section 4.2 below. In particular, the higher the proportion of health centers, the higher the energy saving rate, and the ranking of regional energy saving rates and health center energy saving rates were found to be similar. But the energy saving effect increased as the distance from the Seoul Capital Area (SCA, Seoul-Gyeonggi-Incheon) increased.

4.2. Analysis of Energy Saving Effects by Use

Table 14 shows the average energy saving rate before and after green remodeling through ECO2, classified by building use. The overall average energy saving rate was 36.85% for the three categories of daycare centers, health centers, and medical institutions. The average primary energy consumption before green remodeling was 223.07 kWh/m^2, and if green remodeling was conducted as proposed based on the preliminary survey and consulting, the average primary energy consumption was projected to be 132.89 kWh/m^2, representing energy savings of 89.98 kWh/m^2. Health centers had the highest rate at 46.14%, followed by daycare centers at 29.53% and medical institutions at 23.27%. The average energy saving rate by use was 36.85%, which was about 5% different from the regional average saving rate. The energy saving rate by use was in the order of health centers (46.14%) > daycare centers (29.53%) > medical institutions (23.27%), whereas the primary energy consumption savings per unit area were in the order of health centers (123.2 kWh/m^2) > medical institutions (64.77 kWh/m^2) > daycare centers (61.34 kWh/m^2).

Table 14. Results of the analysis of energy saving through green remodeling of public buildings.

Classification	Public Day Care Center	Public Health Center	Public Health and Medical Institution	Total
Average primary energy consumption before improvements (kWh/m^2)	190.8	251.85	271.68	223.07
Average primary energy consumption after improvements (kWh/m^2)	129.46	128.22	206.91	132.89
Average primary energy consumption savings (kWh/m^2)	61.34	123.2	64.77	89.98
Average energy saving rate (%)	29.53	46.14	23.27	36.85

As shown in Figure 7, health centers exhibited the highest saving effect because those outside the SCA are mostly health center branches and clinics, and unlike health centers located in urban centers, many of them are small, single-family homes. As shown in Table 14, they have the smallest average total floor area and the aging of these health centers outside the SCA was found to be more severe than that of daycare centers and medical institutions.

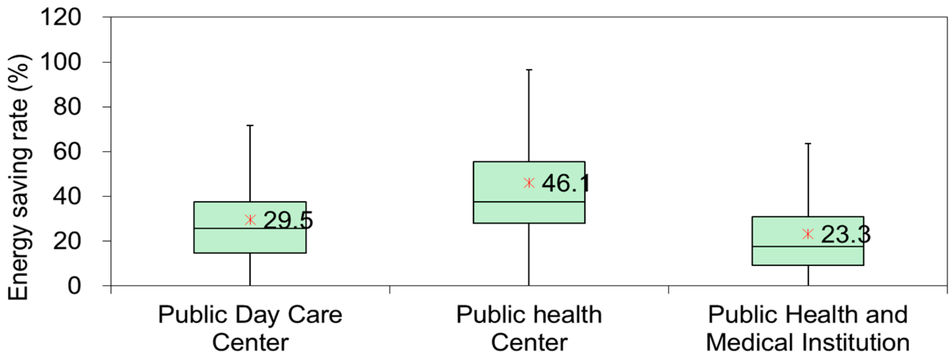

Figure 7. Energy saving rate (Figures 7–10 data shows median, 1st quartile, and 3rd quartile values. Whiskers shows minimum and maximum data within 1.5 interquartile range (IQR) of lower and upper quartile).

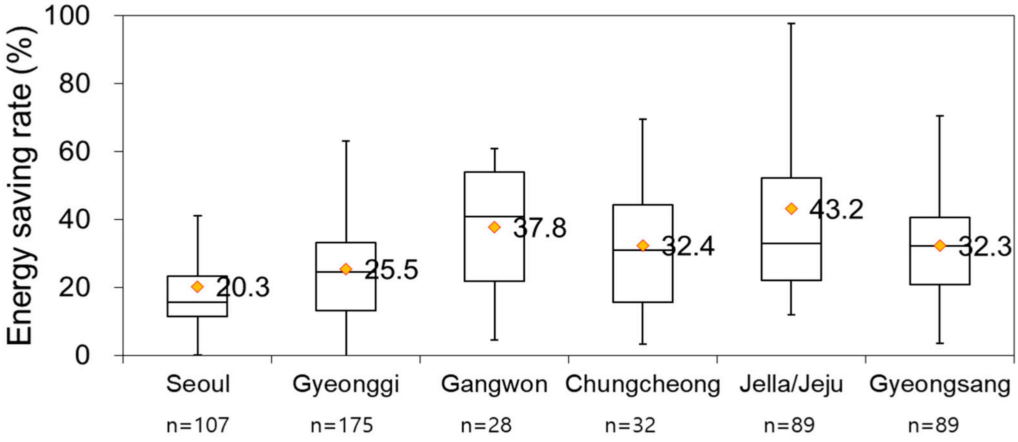

Figure 8. Energy saving rate by public day care centers.

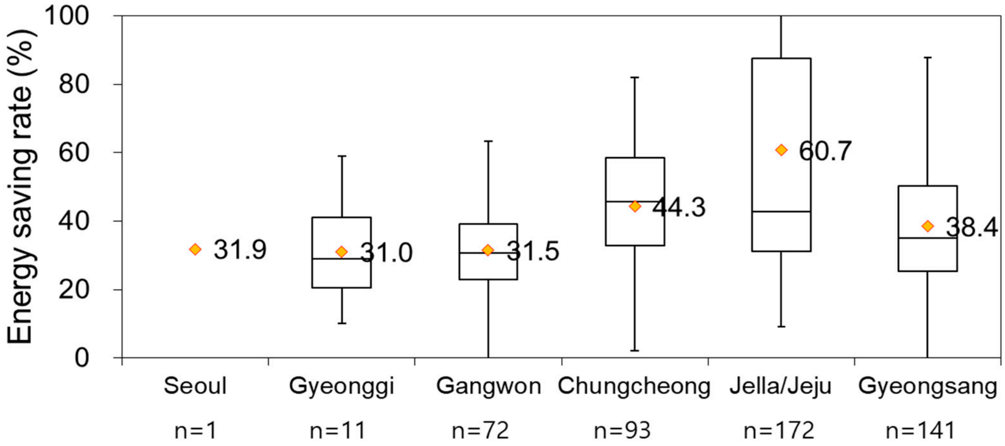

Figure 9. Energy saving rate by public health centers.

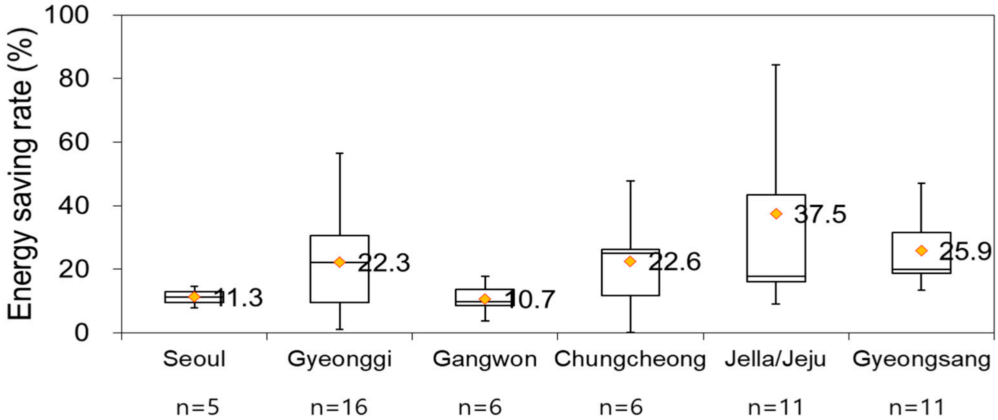

Figure 10. Energy saving rate by public health and medical institutions.

Moreover, in the event of construction in daycare centers, it is necessary to persuade the parent customers and provide alternative spaces, and in the case of medical institutions, it is necessary to relocate the patients. On the other hand, in health centers, which are smaller and have fewer users, the process was relatively smooth and there were fewer constraints on the scope of construction, allowing various technical elements to be applied. Hence, the green remodeling improvements were properly reflected, resulting in a high energy saving rate.

As shown in Figure 8, daycare centers in the Seoul·Gyeonggi·Incheon accounted for more than 54.2% of the total at 282 centers. The average energy saving rate was 29.53%, exceeding the rate of 20% or more for all regions. Several daycare centers underwent interior finishing and LED lighting replacements to improve the indoor environment due to regular administrative evaluations (e.g., daycare center certification evaluations). Therefore, improvements for green remodeling were selectively applied, resulting in a lower energy saving rate than health centers. As mentioned earlier, health centers showed the largest energy savings of the three building types at 46.14%.

By region, Jeolla-Jeju had the highest energy saving rate at 60.7%, followed by Chungcheong and Gyeongsang. As shown in Figure 9, 313 out of the 490 health centers (63.9%) are located in Jeolla-Jeju and Gyeongsang; thus, the need for green remodeling of health centers increased as the distance from the Seoul, Gyeonggi, Incheon increased. The average energy saving rate of health centers was 46.14%, exceeding the 30% saving rate in all regions.

As shown in Figure 10, the average energy saving rate of medical institutions through green remodeling was 23.27%. Medical institutions had the smallest number of buildings at 55, and Gyeonggi-Incheon contained the highest share at 16 buildings (29%). The average energy saving rate was 23.27%, and medical institutions in other regions excluding Gyeonggi, Jeolla-Jeju, and Chungcheong did not meet the energy saving rate target performance of 20% under the Green Remodeling Project for Public Buildings.

This is because, although medical institutions had the largest total floor area, there were constraints such as patient mobility, construction noise, dust, and safety issues. This greatly reduced the area where green remodeling could be applied relative to the entire building area, mainly for equipment work in some spaces rather than construction work such as windows and insulation. As a result, the energy saving effect was low.

5. Conclusions

Green remodeling stands as a pivotal strategy for retrofitting aging infrastructure to meet 2050 carbon neutrality and the 2030 national GHG reduction goals, aligning with global climate change initiatives. This study embarked on an ambitious evaluation of 1065 public facilities, including daycares, health centers, and medical institutions, under the Green Remodeling Project for Public Buildings. Through meticulous aging assessments and stakeholder consultations, it identified a significant need for green remodeling, particularly in buildings over a decade old.

Utilizing the ECO2 building energy evaluation program, our analysis revealed that green remodeling could lead to an average energy savings exceeding 30%, with regional differences highlighting the impact of building age and type on potential savings. Notably, Jeolla-Jeju experienced the highest savings at 50.14%, contrasting with Seoul's 20.19%. Among the facilities, health and medical institutions varied in their energy savings, with health centers at 46.14% and daycare centers at 29.53%, underscoring the diverse potential for energy efficiency gains across building types.

The study uncovered that logistical challenges, such as safety and noise concerns, and the physical limitations of certain buildings particularly influence energy savings outcomes. This was especially evident in regions with a higher density of daycare centers, such as Seoul-Gyeonggi-Incheon, pointing to the need for tailored remodeling approaches that consider regional and building-specific characteristics.

Our findings advocate for a strategic, high-quality approach to green remodeling, emphasizing the importance of detailed project planning and energy design tailored to each building's unique needs. This strategy not only promises substantial energy savings, but also supports the broader adoption of green remodeling practices among local governments and stakeholders. As the initiative is still in its nascent stages, expanding its scope to include more public spaces, such as libraries and community centers, could significantly enhance community well-being and environmental sustainability.

Moreover, the research underscores the necessity of incorporating innovative technologies and flexible remodeling practices to accommodate the specificities of each building, beyond traditional renewable energy solutions. Such a holistic approach to green remodeling is essential for achieving long-term sustainability goals and ensuring the success of national and global efforts to combat climate change.

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