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Analyzing the Environmental Impacts and Empirical Limitations of Green Remodeling with Life Cycle Assessment

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Abstract: The Government of Korea uses green remodeling (GR) as a central policy for achieving carbon neutrality in the building sector. However, despite GR's energy-saving benefits, it raises embodied carbon (EC) due to the incorporation of new materials, and there is a lack of impact analysis and assessment research. Thus, this study established the GR-LCA methodology to evaluate the environmental impacts (EIs) of GR, including EC. The methodology disaggregated and assessed the effects of EC and energy on GR in terms of GR's proportion of EC, six EI categories, and the carbon reduction impacts. The analysis revealed that GR's EC accounted for 10.6%, reducing to 9.89% when EPD materials were used. In terms of the reduction impact across six EIs, GWP was reduced to 0.84 and EP to 0.96. However, ODP, ADP, AP, and POCP, all elevated by high EIs from material inputs, increased to 626.7, 1.04, 1.16, and 250.09, respectively. Ultimately, the carbon reduction in GR was 24.9% when considering only energy usage, and 16.1% when including EC. When EPD materials were applied, the efficiency of reduction improved by an additional 0.6%, indicating a minimal application effect. Based on these findings, the differences in GR's EC compared to new constructions, reduction limitations, and potential improvements were discussed.

Keywords: green remodeling (GR); embodied carbon (EC); environmental impacts (EIs); building-LCA; GR-LCA; EPD materials

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1. Introduction

1.1. Background and Purpose of the Study

As the issue of global warming and extreme weather intensifies, the global response to the climate crisis becomes increasingly vital. According to the 2022 UNEP report [1], the building and construction sector produces 37% of global energy-related carbon emissions, and is described as being one of the biggest contributors to climate change. In addition, the building and construction sector is not on track to reduce emissions sufficiently by 2050 [2]. Toward this goal, the Korean government established and enacted the 2050 carbon neutrality scenario in October 2021 and published an amendment to this scenario in April 2023. To meet the 32.8% reduction target for the building sector by 2030, the revised scenario sets a target of ZEB for 46,000 new constructions and GR for 1.6 million existing buildings [3]. Given that the total number of buildings in Korea as of 2022 stands at 7.32 million, expanding GR in existing buildings is identified as a critical strategy for achieving carbon neutrality in the building sector [4–7].

In particular, when comparing GR with reconstruction to enhance the energy performance of old buildings, GR offers significant advantages, such as reduced material usage and minimized waste from the demolition of existing structures [8]. GR serves as a method to decrease greenhouse gas emissions and improve resource utilization in existing buildings [9], while its primary goal for building owners is to enhance energy efficiency and indoor environmental satisfaction for residents [10]. Leveraging these benefits, numerous countries, including the United States with its Energy Policy Act, the United Kingdom with the Green Deal, and China with its 14th Five-Year Plan (FYP), are actively enacting policies that utilize GR to boost the energy performance of old buildings as part of a carbon-neutral initiative in the building sector [5,9,11].

Currently, the carbon reduction impact of GR is assessed based on the energy consumption during the building operation stage before and after GR [5]. However, it has been noted that this method is problematic as it does not account for the increased embedded carbon from materials used during GR [12]. Furthermore, while assessments require the evaluation of various factors beyond carbon emissions that contribute to environmental problems, current methods and research are insufficient. Consequently, to quantitatively assess the effectiveness of GR in achieving carbon neutrality and reducing EI, it is necessary to establish a GR-LCA methodology, analyze environmental impacts via GR-LCA, and refine policies based on the findings [13].

Therefore, this study defines a GR-LCA methodology by exploring the B-LCA methodology that incorporates GR's characteristics. GR-LCA was applied to case buildings that have recently undergone GR using this approach, analyzing the impact of GR in terms of (1) embodied carbon ratio, (2) six major EIs, and (3) carbon reduction effect. Additionally, by employing alternative low-carbon and EPD materials, further improvements in environmental impact and carbon reduction were demonstrated.

This finding led to the proposal of limitations and improvement plans for the application of low-carbon and EPD materials in GR compared to studies on the embodied carbon in new constructions.

1.2. Research Structure and Procedures

This study aimed to investigate the environmental impact reduction effect of GR through B-LCA. To this end, Section 3 establishes the GR-LCA methodology, which is based on the analysis of existing B-LCA methodology and defines the evaluation scope, system boundary, and criteria to reflect GR's characteristics.

Using the GR-LCA methodology, Section 4 carried out the first GR-LCA based on design, material statement, and building energy simulation results for buildings involved in recent GR projects. The analysis yielded the embodied carbon impact of GR, the six major EIs of GR, and the carbon reduction effect. In Section 5, to enhance reduction through GR, a second GR-LCA analysis was conducted using alternative materials with low-carbon and EPD. This analysis provided insights into further embodied carbon reduction, the six major EIs of GR, and the carbon reduction effect.

Section 6 proposed limitations and improvement measures by comparing the reduction effects from using GR's low-carbon and EPD materials against new construction cases. Additionally, the results of both GR-LCA analyses led to an examination of the six EIs through GR and highlighted the need to manage carbon and other environmental impact factors. Figure 1 is the research flow chart for this study.

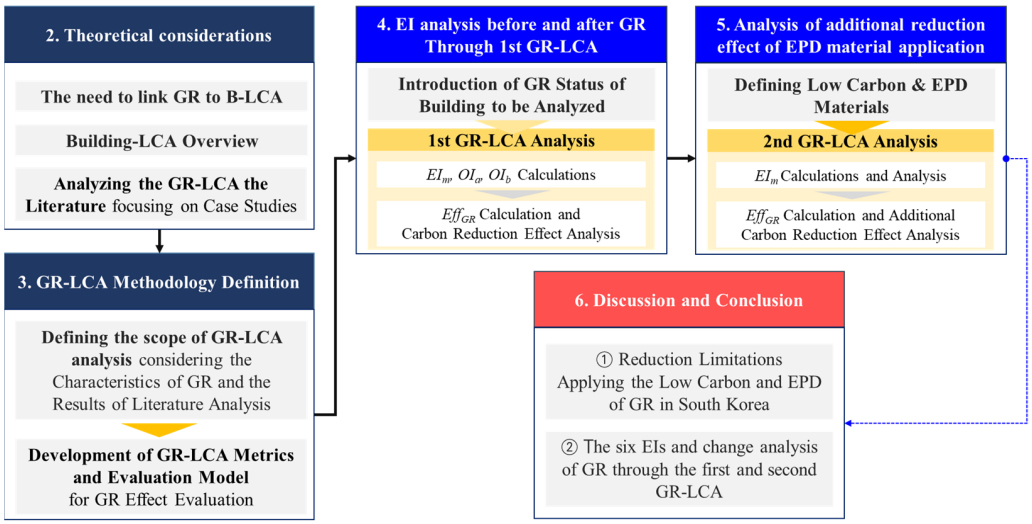


Figure 1. Research flowchart.

2. Theoretical Considerations

2.1. The Need to Link GR to B-LCA

In Korea, GR, as defined by Article 27 of the Green Building Construction Support Act, involves remodeling to enhance energy performance and efficiency [14]. It typically includes projects that improve insulation and equipment performance in older buildings to reduce cooling and heating costs while lowering GHG emissions, thus fostering a comfortable and healthy residential environment. While GR aims to curtail GHG emissions in the building sector to achieve carbon neutrality, its GHG emission reduction is typically assessed focusing on operational energy consumption [6,15]. However, GR involves replacing or retrofitting elements like insulation and windows to boost energy performance, along with HVAC and lighting systems, introducing new materials that contribute to EI. This study seeks a quantitative and comprehensive assessment of the EIs from new materials and the energy savings post-GR by employing the B-LCA methodology.

2.2. B-LCA Overview

A life cycle assessment (LCA) evaluates the EI over a product's entire life cycle, including all materials and energy used during production, transportation, construction, operation, disposal, and decommissioning. It is recognized as an international technical standard under the ISO 14040 series [16].

According to ISO 14040, a life cycle assessment of a building entails four steps. The first step, purpose and scope, establishes the study's purpose, functional units, scope, and data collection methods, which may be modified based on circumstances encountered during the assessment. The second step, inventory analysis, involves collecting and organizing the necessary data for the assessment and quantifying all EIs for the system defined in the scope. The third step, impact assessment, includes classification, characterization, normalization, and valuation. The final step, results analysis, leverages the results from the inventory and impact assessments to formulate conclusions and recommendations consistent with the research objectives. Additionally, it presents the findings from the sensitivity and uncertainty analyses conducted within the life cycle assessment.

The B-LCA flow adheres to ISO 21930 [17], evaluating the EIs of all materials and energy throughout a building's life cycle, from material production and transportation to site, construction, operation, and eventual disposal and decommissioning. This process is broken down into the following sub-divided unit processes as depicted in Figure 2.

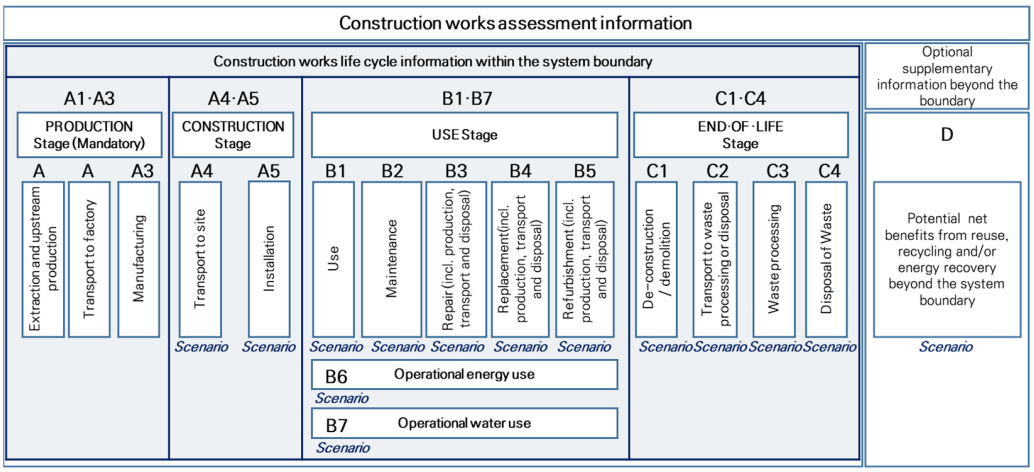


Figure 2. ISO 21930, B-LCA system boundary.

Here, the material production stage (A1~A3) encompasses all resources and energy used in collecting, transporting, and manufacturing the raw materials necessary for self-regeneration, which are then utilized in building construction. The construction phase (A4~A5) involves the resources and energy required to transport building materials from their origin and storage sites to the construction site and their assembly using various construction equipment. The building operation phase (B1~B7) accounts for the resources and energy consumed over the 50-year lifespan of the building as residents operate various equipment and machinery to maintain indoor comfort and perform repairs and maintenance on aging structures. The dismantling and disposal phases (C1–C4) cover the resources and energy used to dismantle the building with construction equipment and to transport and dispose of the construction waste at the disposal site [18].

The results of the six major EI factors of the B-LCA are derived by summarizing the assessment results of each categorized unit process. The six major EI factors of the B-LCA in Korea include GWP, ODP, ADP, AP, EP, and POCP.

2.3. Analyzing the GR-LCA Literature

Previous studies on the LCA of remodeled buildings have predominantly focused on LCA case analyses, the EIs of specific remodeling elements, and economic evaluations using a life cycle cost analysis (LCCA) from the LCA viewpoint [19–25]. Numerous investigations have also explored LCA evaluation criteria for remodeled buildings, including building life cycle, system boundary, evaluation unit, and climate [26–31]. Additional research has considered the carbon emission index of remodeled buildings and optimization studies concerning cost and carbon emissions [32–34].

In a methodological study analyzing criteria for LCA evaluation of buildings, Frischknecht R. et al. established that the life cycle of buildings, required evaluation system boundaries, and databases differ by country. They investigated the primary energy consumption, greenhouse gas (GHG) emissions, and EIs of the targeted buildings according to each criterion, and then compared and analyzed the results. Their findings indicated that annual GHG emission variations in analyzed buildings stemmed from differences in the GHG intensity of the building materials used and the evaluation period, asserting that the impact was predominately influenced by variations in the carbon footprint of the energy source and the embodied carbon in the building materials, rather than the evaluation period [26].

Brown et al. utilized the GWP as a metric to assess the EI of retrofitting and evaluated the GWP of a case building with a 50% reduction in operating energy through retrofitting.

The analysis demonstrated that the GWP of input materials contributed approximately 12% to the reduction in operating energy [27].

Roh et al. developed a life cycle carbon emission assessment model and a carbon emission index for remodeled buildings to fully assess the carbon emissions associated with remodeling. This study focused solely on the embedded carbon emissions from new building materials introduced during the remodeling process, excluding the carbon emissions of the input materials from the existing building's construction to provide a clear comparison of carbon emissions with and without remodeling. Additionally, the study evaluated embedded carbon emissions during the pre- and post-remodeling operation phases, omitting the service life. Embedded carbon emissions from the production, construction, and disposal phases of the new materials were also analyzed [28].

Dodoo et al. conducted an LCA analysis to assess the EI of retrofitting a wood-frame apartment building to meet Passive House standards, dividing it into passive and active components. Assuming a 50-year lifespan, the study evaluated the primary energy requirements of production, transportation, construction, and disposal for input materials and compared these to the LCA results of the original building. The analysis suggested that remodeling assessments should focus on primary energy and building life cycle rather than on final energy [29].

Luo et al. posited that climate change should be factored into life cycle assessments and conducted an optimization study to identify the optimal remodeling scenario for an office building considering climate change impacts. Their analysis revealed that the preferred remodeling scenario, based on existing weather data, yielded 54.7% lower carbon emissions under projected future weather conditions [30]. Pombo et al. evaluated criteria by categorizing the objectives of building LCA studies into three types: EIs, economic analysis, and multi-criteria. They argued that despite the consistent application of the LCA methodology, the detailed criteria differ according to the study's purpose and emphasized the importance of uniformly defining these criteria [31].

To determine the feasibility of applying the LCA methodology to GR projects and to define an appropriate scope, the evaluation periods and system boundaries from previous studies were summarized annually and are displayed in Table 1.

The evaluation periods identified in the literature were categorized into the total life of the building and its useful life, segmented into annual periods for analysis. System boundaries typically included material production (A1–A3) and construction (A4–A5), energy usage during the operational phase (B6), and optionally, operational maintenance and repair (B1–B4) as well as decommissioning and disposal (C1–C4). Nonetheless, many studies lacked a solid rationale for determining the evaluation period or system boundaries, and there is still a deficiency in establishing LCA methodology for evaluating remodeled buildings.

Therefore, the initial objective of this study was to develop a GR-LCA methodology that reflects the unique characteristics of GR projects in Korea, derived from an analysis of prior studies.

- Given that GR primarily targets older buildings, baseline documentation such as original drawings or statements of the building condition before GR is often unavailable.
- In Korea, most buildings are steel–concrete structures, and energy-efficiency retrofits typically occur 15 years after construction, with structural reinforcement seldom integrated into these retrofits.

Given that GR projects are implemented in older buildings, lacking detailed original specifications, this study omitted the EI assessment of materials used during initial construction and focused on evaluating the EI of new materials and operational energy pre- and post-GR projects. Moreover, the primary goal of GR projects is to enhance the energy

efficiency of existing buildings; structural reinforcement is infrequently simultaneous, and building lifespan is not considered extended without structural reinforcement in Korea [35]. Hence, building lifespan extension was not factored into the GR-LCA methodology. Finally, the system boundary included the entire area in the analysis range, including material production (A1–A3) and construction (A4–A5), operational stage energy use (B6), and maintenance, repair (B1–B4), dismantling and disposal (C1–C4). The evaluation unit was analyzed by including the six environmental impact factors, GWP, ODP, ADP, AP, EP, and POCP. Through this, we tried to differentiate the GR-LCA method of this study.

Table 1. Literature Analysis.

	Year	Study Name	Existing Building EI Evaluation	Incoming Material Assessment System Boundaries				Trial Period
				Production (A1–A3)	Construction (A4–A5)	Operations (B1–B5)	Discard (C1–C4)	
1	2010	Life cycle primary energy implications of retrofitting a wood-framed apartment building to passive house standard	O	O	O	O	O	Total lifetime
2	2011	Exergy analysis combined with LCA for energy-efficient retrofitting of building envelopes	-	O	-	-	-	Consider only certain steps
3	2012	Methods and concepts for sustainable renovation of buildings	-	O	O	-	-	Total lifetime
4	2013	Energy retrofit of a single-family house: Life cycle net energy savings and environmental benefits	-	O	O	-	-	Total lifetime
5	2014	A decision-making LCA for energy refurbishment of buildings: Comfort Conditions	-	O	O	O	O	Residual Lifetime
6	2015	Proposed life cycle carbon footprint assessment model for remodeled buildings	-	O	O (Transportation Only)	-	O	Residual Lifetime
7	2017	Evaluation of life cycle carbon impacts for higher education building redevelopment: a multiple case study approach	-	O	-	O	O	Total Lifetime
8	2017	Evaluation of life cycle carbon impacts for higher education building redevelopment: an archetype approach	-	O	O	O	O	Total Lifetime
9	2019	Comparison of the environmental assessment of an using national methods	-			-		Total Lifetime
10	2020	Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta	-	O	-	-	O	Consider only certain steps
11	2021	Green Remodeling Basic Research for Proposing Life Cycle Assessment (LCA) Certification Items in the Green Building Certification System	-	O	O	-	O	On an Annual Basis
12	2021	Life cycle analysis of GHG emissions from the building retrofitting: the case of a Norwegian office building	-	O	O	O	O	Total Lifetime
13	2022	Life cycle optimisation of building retrofitting considering climate change effects	-	O	O	O	O	Total Lifetime
14	2023	Optimization research on energy-saving and life-cycle decarbonization retrofitting of existing school buildings: A case study from a school in Nanjing	O	O	O	O	O	Total Lifetime
15	2023	Affordability assessment of passive retrofitting measure for residential buildings using life cycle assessment	O	O	O (Transportation Only)	O	-	Total Lifetime

"O": Stages included in the LCA analysis; "-": Stages not included in the LCA analysis.

The detailed GR-LCA methodology is summarized in Section 3 as evaluation indicators and models.

3. GR-LCA Methodology

This study conducts a life cycle assessment of buildings guided by ISO 14040 (ISO 14040 and 14044) and ISO 21930, adopting the methodology established from prior analyses to perform a GR-LCA.

3.1. GR-LCA Analysis Scope

The LCA for buildings that have undergone a GR must specify the evaluation scope, which includes the evaluation period, system boundaries, and EI categories.

The building's total assumed lifespan is 50 years. This study focuses on evaluating buildings that have undergone GR projects, not new constructions. Therefore, the evaluation period is the remaining lifespan following the GR project, which, after accounting for 15 years of service, totals 35 years. Additionally, the evaluation scope was defined to include material production (A1~A3), transport during the construction phase (A4), operation phase (B4, B6), and dismantling and disposal phase (C1~C2, C4) (Figure 3).

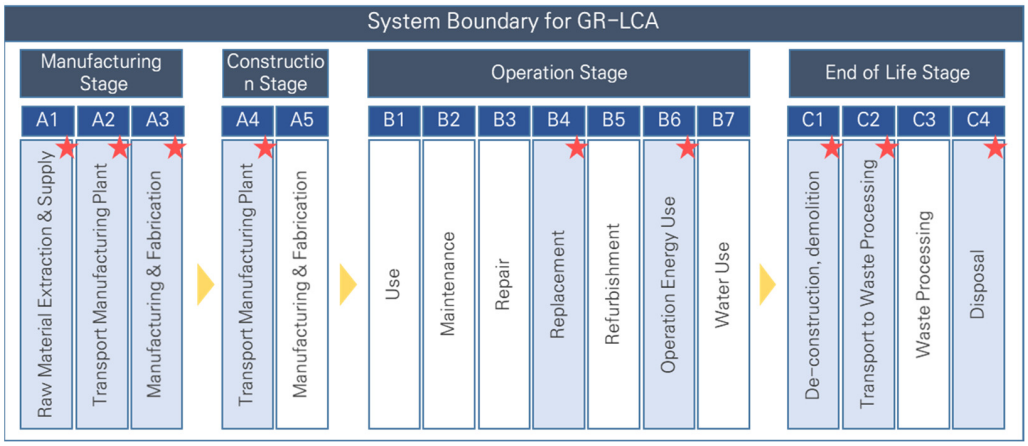


Figure 3. Setting system boundaries.

Except for the use of building operating energy (B6), all other steps were evaluated for new input materials, while B6 was assessed using the estimated value of the energy source based on primary energy consumption before and after GR, utilizing the ECO2 program. The assessment of construction materials (A5) during the construction phase is mandated in the life cycle assessment. However, due to the nature of the remodeling project, if the remodeling occurs in the office, it is challenging to distinguish the energy used for building operations from that used for construction equipment due to the simultaneous operation of the office during the GR project. Therefore, the EI assessment for this phase can be omitted.

The EI categories were defined as the six major EIs considered by the Ministry of Environment's environmental performance label: global warming (GWP), resource depletion (ADP), acidification (AP), eutrophication (EP), photochemical oxides (POCP), and ozone depletion (ODP). The evaluation program utilized the S-LCA program that satisfies the Building LCA Credit of G-SEED certification in Korea and LEED certification in the United States [13].

3.2. GR-LCA Metrics and Evaluation Model

This study aims to quantify the EI reduction effect of GR projects by considering the EI from new materials and the EI from operating energy, and to express the change in EI before and after GR holistically. Consequently, it employs $EIRE_{GR}$ as the evaluation indicator to demonstrate the EI reduction effect of the GR project, calculated as depicted in Equation (1).

$$EIRE_{GR} = \frac{EIm + OI_a}{OI_b} \quad (1)$$

where EIm represents the potential EI of the new input material over its entire lifecycle, OI_a represents the EI of the building's operating energy after the GR, and OI_b denotes the EI of the building's operating energy before the GR. If reducing the EI through the GR of a building is beneficial, $EIRE_{GR}$ will be less than 1; otherwise, it will be greater than 1. Furthermore, the evaluation model was devised by integrating the scope of evaluation and evaluation indicators for the subjects analyzed in this study, and is illustrated in Figure 4.

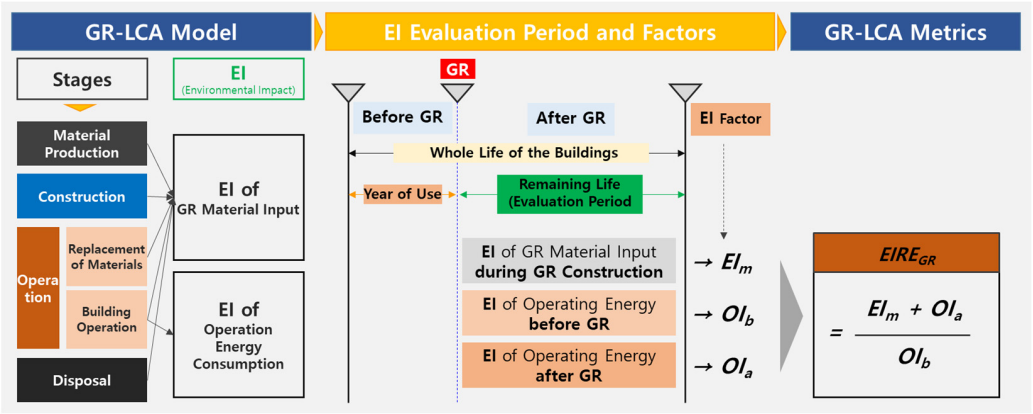


Figure 4. GR-LCA Model.

4. The GR-LCA of the Target Building

4.1. Target Building's GR Status

4.1.1. Target Building Overview

The subject of this study is a public office building constructed in 2003, enhanced according to the performance improvement standards for older public buildings in Korea; the building's details are displayed in Table 2. The GR project was executed from October 2017 to September 2018. This project exemplifies GR implementation under the public GR support project for aging public buildings to promote GR use. The study utilized pre- and post-GR design plans, building material specifications, and energy consumption data for GR-LCA analysis.

Table 2. Overview of analyzed buildings.

Architectural Overview		Before GR	After GR
Location	Daegu, Republic of Korea		
Completion of Building	26 June 2003		
Building Uses	Public Office Building		
Land Area	11,032.0 m^2		
Gross Floor Area	3099.7 m^2		
Number of Floors	B1/5F		
Structure	Reinforced Concrete		

4.1.2. Performance Improvement Factors by GR

Regarding GR improvements, the architectural updates included enhanced exterior wall finishes (existing: porcelain tiles; after: terracotta and aluminum panels), upgraded exterior wall insulation (+50 mm PF Board) and ceiling insulation (+100 mm PF Board), window replacements (Triple-Low-E + double glazing, PVC frames), and the addition of EVBs on the east and west sides as well as horizontal awnings on the south side. The mechanical and electrical systems were upgraded with new air conditioning and heating systems, a constant-temperature-and-humidity humidifier, electric heat exchange ventilation, and LEDs.

4.2. GR-LCA Analysis

Using the GR-LCA methodology in Section 3.2, the study first calculated the environmental impact EI_m from new input materials during the GR project. Subsequently, the environmental impacts OI_a, associated with the operational energy of the building post-GR, and OI_b, related to the operational energy pre-GR, were calculated. This process aims to derive $EIRE_{gr}$ and assess the environmental impact of GR.

4.2.1. First GR-LCA Analysis

(1) EI_m Calculations and analysis

Newly introduced materials in the GR project were assessed based on a cumulative mass contribution cut-off of 99% for the remaining building materials, excluding lighter interior materials like wallpaper. Figure 5 summarizes the materials and their weights included in the analysis. The analysis revealed that glass/fenestration, exterior wall finishes, and insulation are the primary contributors to a building's GR by volume, reflecting efforts to address common issues in aging structures such as deteriorating wall finishes, inadequate insulation, leaks, and condensation.

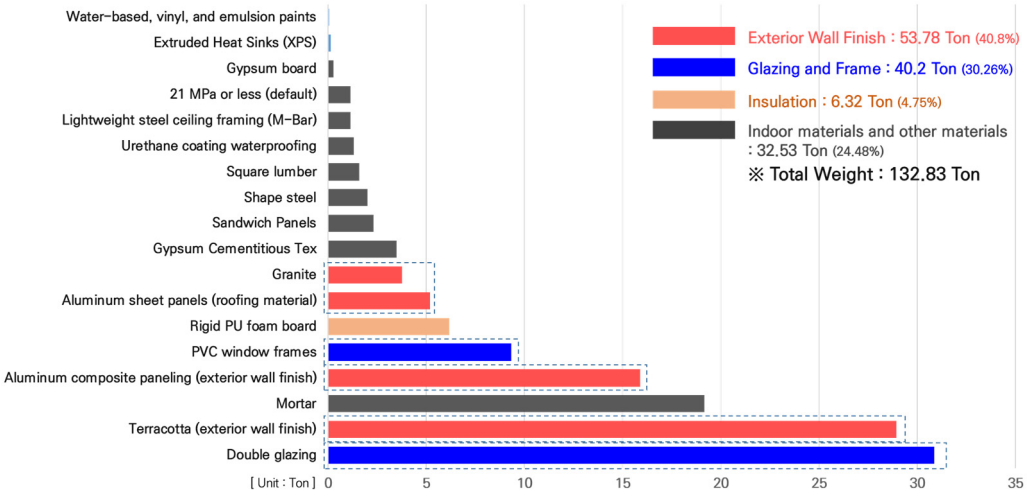


Figure 5. GR building new input materials list.

Table 3 illustrates the results of calculating EI_m using new materials. When analyzing the EI by stage, the production stage of most materials accounted for the most significant proportions as follows: global warming potential (GWP), about 91.3%; ozone depletion potential (ODP), about 97.6%; resource depletion potential (ADP), about 98.8%; acidification potential (AP), about 65.7%; eutrophication potential (EP), about 90.3%; and photochemical oxides creation potential (POCP), about 99.7%.

Table 3. EI_m assessment results for new material inputs by stage.

	Separation		GWP [tCO_2-eq]	ODP [tCFC-11-eq]	ADP [tSb-eq]	AP [tSO_2-eq]	EP [tPO_4^3-eq]	POCP [tC_2H_4-eq]
Material Production	A1 to A3	Materialization	4.898×10^2 91.3%	9.247×10^{-5} 97.6%	1.111×10 98.8%	2.338 65.7%	3.123×10^{-1} 90.3%	1.053×10 99.7%
Construction	A4	Material Handling	2.036 0.4%	7.371×10^{-7} 0.8%	1.383×10^{-2} 0.1%	1.009×10^{-2} 0.3%	1.654×10^{-3} 0.5%	4.873×10^{-3} 0.0%
Operations	B4	Replacement Materials	3.126×10 5.8%	4.989×10^{-7} 0.5%	8.494×10^{-2} 0.8%	1.230×10^{-1} 3.5%	2.243×10^{-2} 6.5%	2.210×10^{-2} 0.2%
Deconstruction Discard Steps	C1	Deconstruction	1.279 0.2%	5.017×10^{-11} 0.0%	8.553×10^{-3} 0.1%	1.035 29.1%	4.459×10^{-4} 0.1%	9.230×10^{-5} 0.0%
	C2	Transportation	1.988 0.4%	7.435×10^{-7} 0.8%	1.351×10^{-2} 0.1%	9.685×10^{-3} 0.3%	1.577×10^{-3} 0.5%	4.718×10^{-3} 0.0%
	C4	Disposal	9.826 1.8%	3.160×10^{-7} 0.3%	1.391×10^{-2} 0.1%	4.270×10^{-2} 1.2%	7.573×10^{-3} 2.2%	3.299×10^{-3} 0.0%
	The total (EI_m)		5.361×10^{-2}	9.477×10^{-5}	1.125×10	3.559	3.459×10^{-1}	1.057×10

(2) ECO2-based OI_a, OI_b Calculation and analysis

The OI_a and OI_b calculations show that by using the ECO2 program, the operating energy use (B6) of buildings was estimated similarly to the B-LCA under the Korean Green Building Certification. Table 4 displays the results of analyzing building operating energy before and after the GR project using the ECO2 program. It is evident that the primary energy source prior to the GR project was electricity, whereas following the GR project, city gas has been incorporated into the heating and cooling energy mix due to the gas heat pump (GHP) installation.

Table 4. Energy usage in the GR project analyzed using ECO2, and the energy (B6) EI assessment results.

Separation			Primary Energy Consumption per Unit Area (kWh/m^2, Year)						
			Heating	**Cooling**	**Lighting**	**Hot Water**	**Ventilation**	**Subtotal**	**Total**
ECO2	Before GR	Power	91.50	214.90	86.20	27.30	5.60	389.90	389.90
		Gas	-.	-.	-.	-.	-.	-.	
	After GR	Power	41.31	154.17	64.10	27.30	16.30	303.48	314.30
		Gas	2.26	8.53	-.	-.	-.	10.82	

The following table data display the energy (B6) EI assessment results for the building operations phase, based on ECO2.

Separation	**GWP [tCO_2-eq]**	**ODP [tCFC-11-eq]**	**ADP [tSb-eq]**	**AP [tSO_2-eq]**	**EP [tPO_4^3-eq]**	**POCP [tC_2H_4-eq]**
OI_b (Before GR)	6.05×10^3	1.67×10^{-7}	3.82×10	1.02×10	1.90	4.31×10^{-2}
OI_a (After GR)	4.54×10^3	9.96×10^{-6}	2.87×10	8.30	1.48	2.03×10^{-1}
Increase/Decrease	1.50×10^3 reduction	9.80×10^{-6} increase	9.55 reduction	1.92 reduction	4.20×10^{-1} reduction	1.60×10^{-1} increase
Increase/Decrease Ratio	25% reduction	5.96% increase	25% reduction	19% reduction	22% reduction	472% increase

These results indicate that, following the analysis, OI_a and OI_b reveal reductions in the EI of global warming (GWP), resource depletion (ADP), acidification (AP), and eutrophication (EP) due to the GR project. However, the impacts on ozone depletion (ODP) and photochemical oxides (POCP) increased, presumably influenced by the addition of the city gas energy source via the newly installed GHP facility.

4.2.2. $EIRE_{GR}$ Calculation and Analysis

Based on the previous analyses, $EIRE_{GR}$ is detailed in Table 5. The analysis indicates that the overall EI value (EI_{m}) increased due to new input materials. Additionally, compared to the impact on operating energy (B6) in Table 4, the assessment results show that the impacts of resource depletion (ADP) and acidification (AP) have shifted from decreasing to increasing.

Table 5. GR-LCA results based on ECO2 analysis.

Separation				**GWP [tCO_2-eq]**	**ODP [tCFC-11-eq]**	**ADP [tSb-eq]**	**AP [tSO_2-eq]**	**EP [tPO_4^3-eq]**	**POCP [tC_2H_4-eq]**
Before GR	OI_b	B6	Operational Energy	6.05×10^3 100.0%	1.67×10^{-7} 100.0%	3.82×10 100.0%	1.02×10 100.0%	1.90 100.0%	4.31×10^{-2} 100.0%
After GR	EI_m	A1 to A3	Materialization	4.90×10^2 9.6%	9.25×10^{-5} 88.3%	1.11×10 27.8%	2.34 19.7%	3.12×10^{-1} 17.1%	1.05×10 97.8%
		A4	Material Handling	2.04 0.0%	7.37×10^{-7} 0.7%	1.38×10^{-2} 0.0%	1.01×10^{-2} 0.1%	1.65×10^{-3} 0.1%	4.87×10^{-3} 0.0%
		B4	Replacement materials	3.13×10 0.6%	4.99×10^{-7} 0.5%	8.49×10^{-2} 0.2%	1.23×10^{-1} 1.0%	2.24×10^{-2} 1.2%	2.21×10^{-2} 0.2%
		C1	Deconstruction	1.28 0.0%	5.02×10^{-11} 0.0%	8.55×10^{-3} 0.0%	1.04 8.7%	4.46×10^{-4} 0.0%	9.23×10^{-5} 0.0%
		C2	Transportation	1.99 0.0%	7.44×10^{-7} 0.7%	1.35×10^{-2} 0.0%	9.69×10^{-3} 0.1%	1.58×10^{-3} 0.1%	4.72×10^{-3} 0.0%
		C4	Disposal	9.83×10^0 0.2%	3.16×10^{-7} 0.3%	1.39×10^{-2} 0.0%	4.27×10^{-2} 0.4%	7.57×10^{-3} 0.4%	3.30×10^{-3} 0.0%
	OI_a	B6	Operational Energy	4.54×10^3 89.4%	9.96×10^{-6} 9.5%	2.87×10 71.8%	8.30 70.0%	1.48 81.1%	2.03×10^{-1} 1.9%
		Subtotal ($EI_m + OI_a$)		5.08×10^3 100.0%	5.08×10^3 100.0%	1.05×10^{-4} 100.0%	3.99×10 100.0%	1.19×10 100.0%	1.83 100.0%
	$EIRE_{GR}$			0.84	626.76	1.04	1.16	0.96	250.09

To understand the EI from new input materials, we compared and reviewed the EI from operational energy (OI_a) and the combined EI from materials and operational energy ($OI_a + EI_m$). The $EIRE_{GR}$ values for global warming potential (GWP) and eutrophication (EP) were less than 1, indicating a reduction in the EI via the GR project. Conversely, values for ozone layer destruction (ODP), resource depletion (ADP), acidification (AP), and photochemical oxide (POCP) were greater than 1, suggesting an increase in EI through the GR project.

Figure 6 demonstrates the carbon reduction effect in terms of operational energy before and after GR, as well as the carbon reduction effect including the embodied carbon of GR. While many countries, including Korea, assess the GR effect by focusing solely on operational energy, doing so results in a carbon reduction of 24.9%. However, when including embodied carbon in GR-LCA, the reduction effect is 16.1%. This outcome indicates that the embodied carbon significantly offsets the reduction in operational energy, underscoring the importance of including embodied carbon in GR-LCA evaluations for carbon-neutral policy.

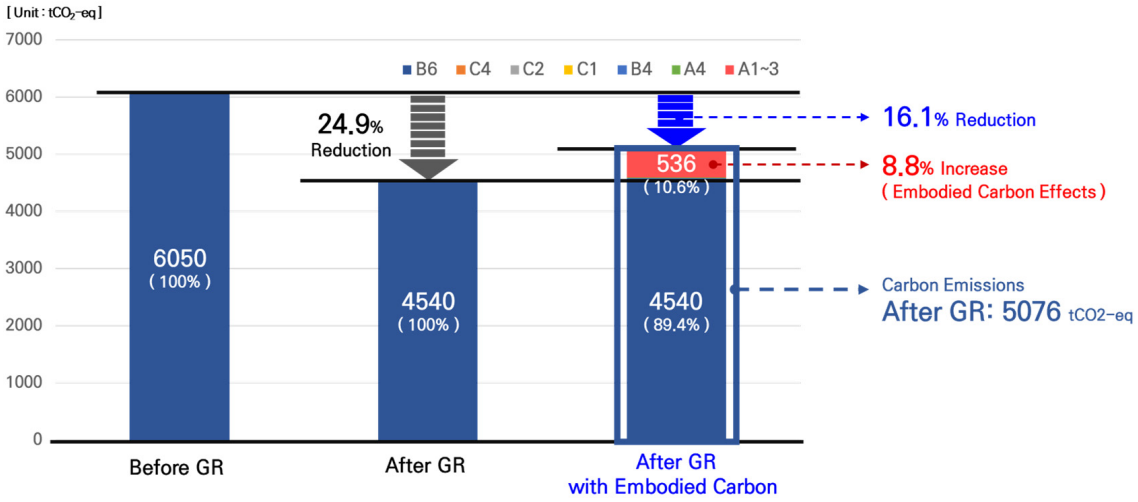


Figure 6. The carbon reduction impact of GR including embodied carbon.

Previous studies report an embodied carbon ratio of 25 to 35% in new building evaluations using B-LCA [13], whereas this study finds the embodied carbon ratio in GR to be around 10% when evaluating GR-LCA. The difference stems from approximately 60% of the embodied carbon in new constructions being attributed to the frame (building structural material), while in GR, the frame is retained and the main material changes involve internal and external finishes, and the replacement of materials to enhance energy performance.

5. Second GR-LCA Analysis Applying Low-Carbon and EPD Materials

Furthermore, we analyzed the EI of new materials used in GR across different life cycle stages and found that the material production stage contributes most significantly to the EI across all six impact categories. Therefore, in this section, we consider the use of low-carbon and EPD-certified materials as a strategy to further reduce the EI of GR, and we will examine how the application of these materials affects the increase and decrease in EI.

5.1. Defining EPD Materials

EPD materials are products that have been evaluated and quantified for their EI throughout their life cycle, including raw material extraction, production, transportation, use, and disposal. For building materials, the environmental performance is determined by following guidelines for environmental labeling, and the system boundary encompasses

production stages (A1~A4), and may include the construction stage (B), disposal stage (C), and additional information (D) depending on the specific use scenario or guidelines [36]. In this study, the boundary conditions for EPD-certified materials are confined to the production phase. Among these, products with global warming potential (GWP) values below the maximum allowable emissions or above the minimum carbon reduction rate are granted low-carbon certification [37].

Hence, materials meeting the low-carbon certification were prioritized for GR materials that can substitute low-carbon versions, while other materials were chosen based on their EPD certification.

5.2. Analyze the EI of Applying Low-Carbon and EPD Materials

5.2.1. EI of Materials

The GR-LCA was performed by selecting GR materials that could be replaced by EPD-certified and low-carbon-certified products, with the resultant replacements shown in Figure 7. From 18 types of materials, 7 were substituted, amounting to 39.72 tons out of a total of 132.8 tons. Among these, extruded polystyrene (XPS) insulation was substituted with EPD-certified materials, while other materials were chosen and utilized as low-carbon certified products.

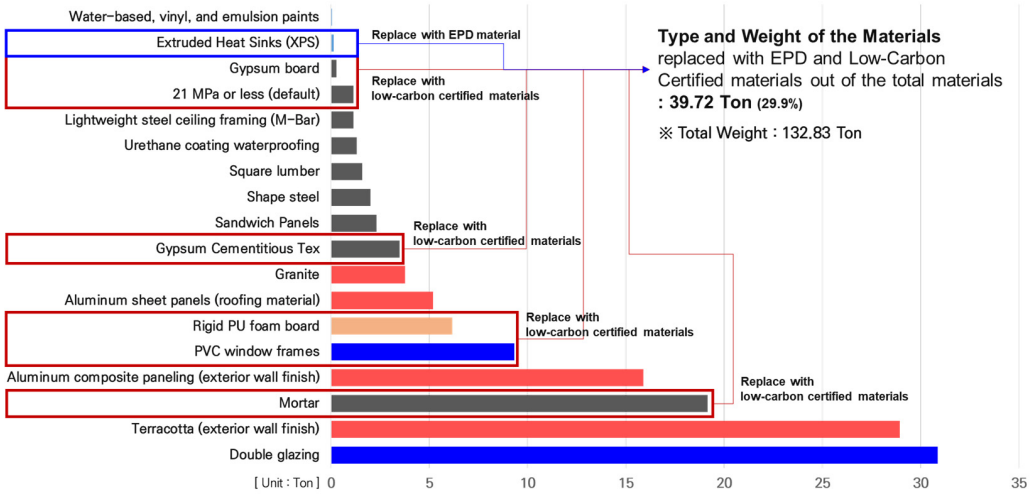


Figure 7. Application of low-carbon and EPD materials.

Figure 8 demonstrates the carbon reduction effect by replacing existing materials with low-carbon- and EPD-certified materials. Although the reduction ratio varies by material, most exhibit a significant reduction. However, as indicated in Figure 7, the construction market faces limitations due to a lack of alternative low-carbon and EPD products for exterior wall finishes and glass, which are materials with significant weight.

The EI of material substitution is displayed in Table 6. All global warming potential (GWP) impacts were reduced through the use of low-carbon and EPD materials. However, for certain materials, there was a significant increase in EI across other categories besides GWP. In particular, ozone depletion potential (ODP) rose in four out of seven materials, showing an average increase of 90.963%. This is attributable to the fact that low-carbon certification evaluations focus primarily on GWP, leading to increased EI in other impact categories when compared to standard materials. In addition, to alleviate this problem, it is expected that improvement will be possible by replacing the insulation and indoor gypsum board and cement-based tex, which had a high ODP effect, with wood materials. It is believed that additional GWP and ODP can be reduced by replacing the insulation with wood fiber insulation, and the indoor tex and board with OSB and engineering wood.

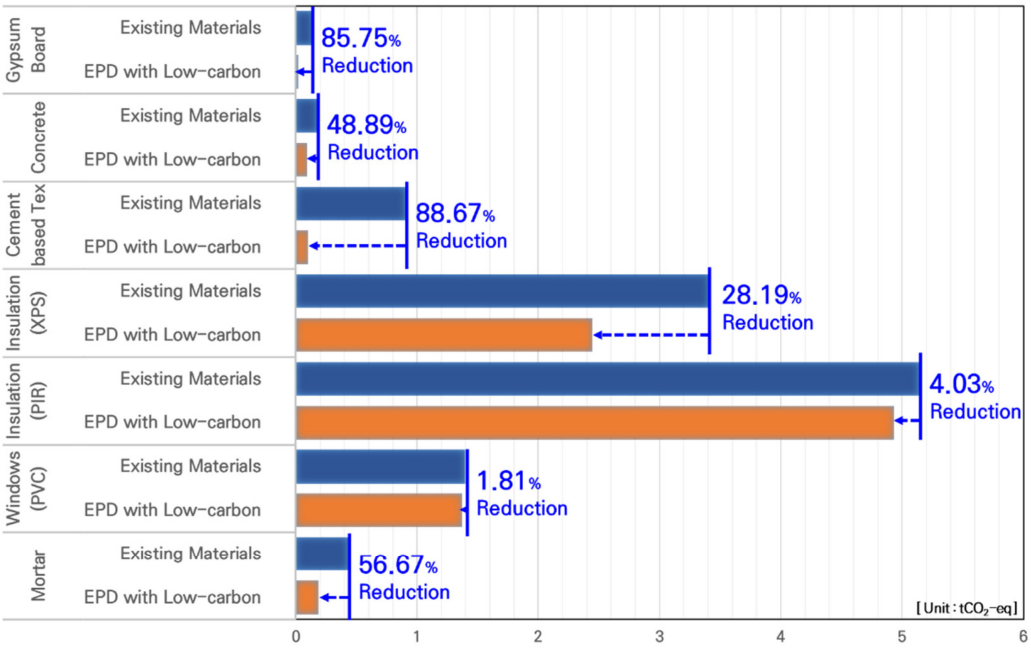


Figure 8. Carbon reduction effect by replacing low-carbon and EPD materials.

Table 6. Results of EI from material substitution.

The Six Impact Assessments		GWP [tCO_2-eq]	ODP [tCFC11-eq]	ADP [tSb-eq]	AP [tSO_2-eq]	EP [tPO_4^3-eq]	POCP [tC_2H^4-eq]
Cement Mortar (Remittal)	Existing Materials	4.310×10^{-1}	1.460×10^{-8}	1.780×10^{-3}	7.370×10^{-4}	1.140×10^{-4}	2.370×10^{-4}
	EPD With Low-Carbon	1.867×10^{-1}	6.365×10^{-9}	8.017×10^{-4}	3.009×10^{-4}	3.704×10^{-5}	1.736×10^{-4}
	Ratio (%)	−56.67%	−56.40%	−54.96%	−59.17%	−67.51%	−26.77%
Windows	Existing Materials	1.398	3.093×10^{-8}	1.675×10^{-2}	3.073×10^{-3}	6.387×10^{-4}	1.734×10^{-3}
	EPD With Low-Carbon	1.373	7.561×10^{-5}	1.593×10^{-2}	2.784×10^{-3}	6.933×10^{-4}	6.459×10^{-3}
	Ratio (%)	−1.81%	244,327.4%	−4.92%	−9.42%	8.53%	272.49%
Insulation (PIR)	Existing Materials	5.138	1.383×10^{-5}	4.000×10^{-2}	2.725×10^{-2}	2.224×10^{-2}	1.105×10^{-2}
	EPD With Low-Carbon	4.931	6.297×10^{-7}	4.062×10^{-2}	2.452×10^{-2}	1.233×10^{-2}	5.104×10^{-3}
	Ratio (%)	−4.03%	−95.45%	1.54%	−10.01%	−44.57%	−53.81%
Board-Tex/ Gypsum-Cement-Based Tex	Existing Materials	9.063×10^{-1}	1.176×10^{-7}	4.534×10^{-3}	3.401×10^{-3}	6.528×10^{-4}	9.616×10^{-4}
	EPD With Low-Carbon	1.027×10^{-1}	4.203×10^{-6}	7.768×10^{-4}	3.469×10^{-4}	4.631×10^{-5}	3.100×10^{-5}
	Ratio (%)	−88.67%	3475.54%	−82.87%	−89.80%	−92.91%	−96.78%
Concrete/ 21 MPa or less	Existing Materials	1.780×10^{-1}	2.023×10^{-8}	8.757×10^{-4}	2.965×10^{-4}	3.460×10^{-5}	5.135×10^{-4}
	EPD With Low-Carbon	9.098×10^{-2}	3.891×10^{-9}	3.635×10^{-4}	1.354×10^{-4}	1.729×10^{-5}	7.644×10^{-5}
	Ratio (%)	−48.89%	−80.77%	−58.49%	−54.34%	−50.02%	−85.11%
Board-Tex/ Gypsum Board	Existing Materials	1.378×10^{-1}	1.418×10^{-8}	1.035×10^{-3}	7.823×10^{-4}	1.319×10^{-4}	2.718×10^{-4}
	EPD With Low-Carbon	1.964×10^{-2}	4.237×10^{-6}	1.413×10^{-4}	7.419×10^{-5}	1.170×10^{-5}	1.579×10^{-5}
	Ratio (%)	−85.75%	29778.42%	−86.35%	−90.52%	−91.13%	−94.19%
Insulation (XPS)	Existing Materials	3.405	1.412×10^{-7}	5.459×10^{-6}	1.930×10^{-2}	1.075×10^{-3}	5.262×10^{-3}
	EPD Materials	2.445	1.220×10^{-4}	2.225×10^{-2}	5.587×10^{-3}	7.155×10^{-4}	8.763×10^{-3}
	Ratio (%)	−28.19%	86,273.90%	407,532.3%	−71.05%	−33.43%	66.54%

5.2.2. Second GR-LCA Results and Effects Analysis (Comparison with First GR-LCA Results)

The second GR-LCA, which utilized low-carbon and EPD materials, was conducted based on the analysis previously carried out. The EI of the original draft (first GR-LCA)

without EPD materials and the EI of the proposed draft (second GR-LCA) with low-carbon and EPD materials were compared and analyzed. Table 7 presents the findings, showing reduced EIs in all impact categories except ozone depletion (ODP) and photochemical oxides (POCP) during the material production stage (A1~A3) and all categories except ozone depletion (ODP) during the material replacement stage (B4).

Table 7. Post-GR, result comparison of proposed draft vs. original draft EI assessment.

EI Assessment		GWP [tCO_2-eq]	ODP [tCFC-eq]	ADP [tSb-eq]	AP [tSO_2-eq]	EP [tPO_4^3-eq]	POCP [tC_2H^4-eq]
Material Production [A1–A3]	Original	4.898×10^2	9.247×10^{-5}	1.111×10	2.338	3.123×10^{-1}	1.053×10
	Proposed	4.805×10^2	7.485×10^{-4}	1.108×10	2.297	2.478×10^{-1}	1.054×10^{-2}
	Ratio (%)	−1.89	709.44	−0.30	−1.75	−20.64	0.03
Construction [A4]	Original	2.036	7.371×10^{-7}	1.383×10^{-2}	1.009×10^{-2}	1.654×10^{-3}	4.873×10^{-3}
	Proposed	Same as original draft					
	Ratio (%)	-.					
Operational (material replacement) [B4]	Draft	3.126×10	4.989×10^{-7}	8.494×10^{-2}	1.230×10^{-1}	2.243×10^{-2}	2.210×10^{-2}
	Suggestion	2.979×10	1.856×10^{-5}	7.794×10^{-2}	1.174×10^{-1}	2.133×10^{-2}	2.105×10^{-2}
	Ratio (%)	−4.72	3619.88	−8.24	−4.58	−4.92	−4.72
Operational [B6]	Original	4.541×10^3	9.964×10^{-6}	2.867×10	8.296	1.483	2.033×10^{-1}
	Proposed	Same as original draft					
	Ratio (%)	-.					
Disposal [C1~C2,C4]	Original	1.309×10	1.060×10^{-6}	3.597×10^{-2}	1.087	9.596×10^{-3}	8.109×10^{-3}
	Proposed	Same as original draft					
	Ratio (%)	-.					
Total	Original	5.077×10^3	1.047×10^{-4}	3.992×10	1.185×10	1.829	1.077×10
	Proposed	5.066×10^3	7.788×10^{-4}	3.988×10	1.181×10	1.763	1.077×10
	Ratio (%)	−0.21	643.64	−0.10	−0.39	−3.58	0.02

Additionally, an analysis of the GR-LCA results revealed that although the EI for ozone depletion (ODP) and photochemical oxides (POCP) increased when using low-carbon and EPD materials compared to the original draft, reductions were seen across other impact categories. Ozone depletion (ODP) saw an increase of approximately 643.64%, and photochemical oxides (POCP) increased by about 0.02% when using low-carbon and EPD materials relative to traditional materials. In other categories, EI reductions were achieved with the application of low-carbon and EPD materials compared to the original proposal, with a maximum reduction rate analyzed at 3.58%.

Based on the results of the analysis, we calculated each EI category $EIRE_{GR}$ value of the first GR-LCA (original) and second GR-LCA (proposed). Table 8 summarizes the proportion of EI for each stage and the $EIRE_{GR}$ values. According to the analysis results, comparing the proposed $EIRE_{GR}$ value with the original $EIRE_{GR}$ value showed a decrease in the global warming potential (GWP), resource depletion (ADP), acidification (AP), and eutrophication (EP) values, whereas the ozone layer destruction (ODP) and photochemical oxidant creation (POCP) values increased. These findings align with Table 6, which provides an assessment of the environmental impact of materials and shows that while alternative low-carbon and EPD materials reduced GWP, ADP, AP, and EP, they conversely increased ODP and POCP when used in window and XPS insulation. This confirms that the application of commonly used eco-friendly materials can still elevate certain EIs like ODP and POCP. Despite the challenges, this outcome is consistent with the goal of using GR-LCA as a means towards carbon neutrality. However, the potential adverse effects on other environmental impacts highlight a need for further research.

Table 8. Comparison and analysis of first (original) and second (proposed) GR-LCA results.

Separation				GWP [tCO_2-eq]	ODP [tCFC-11-eq]	ADP [tSb-eq]	AP [tSO_2-eq]	EP [tPO_4^3-eq]	POCP [tC_2H_4-eq]
Original (First GR-LCA)	Before GR	OI_b	B6	6.05×10^3 100.00%	1.67×10^{-7} 100.00%	3.82×10 100.00%	1.02×10 100.00%	1.90 100.00%	4.31×10^{-2} 100.00%
	After GR	EI_m	A1 to A3	4.90×10^2 9.60%	9.25×10^{-5} 88.30%	1.11×10 27.80%	2.34 19.70%	3.12×10^{-1} 17.10%	1.05×10 97.80%
			A4	2.04 0.00%	7.37×10^{-7} 0.70%	1.38×10^{-2} 0.00%	1.01×10^{-2} 0.10%	1.65×10^{-3} 0.10%	4.87×10^{-3} 0.00%
			B4	3.13×10 0.60%	4.99×10^{-7} 0.50%	8.49×10^{-2} 0.20%	1.23×10^{-1} 1.00%	2.24×10^{-2} 1.20%	2.21×10^{-2} 0.20%
			C1	1.28 0.00%	5.02×10^{-11} 0.00%	8.55×10^{-3} 0.00%	1.04×10^0 8.70%	4.46×10^{-4} 0.00%	9.23×10^{-5} 0.00%
			C2	1.99 0.00%	7.44×10^{-7} 0.70%	1.35×10^{-2} 0.00%	9.69×10^{-3} 0.10%	1.58×10^{-3} 0.10%	4.72×10^{-3} 0.00%
			C4	9.83 0.20%	3.16×10^{-7} 0.30%	1.39×10^{-2} 0.00%	4.27×10^{-2} 0.40%	7.57×10^{-3} 0.40%	3.30×10^{-3} 0.00%
		OI_a	B6	4.54×10^3 89.40%	9.96×10^{-6} 9.50%	2.87×10 71.80%	8.30×10^0 70.00%	1.48 81.10%	2.03×10^{-1} 1.90%
		Subtotal ($EI_m + OI_a$)		5.08×10^3 100.00%	1.05×10^{-4} 100.00%	3.99×10 100.00%	1.19×10 100.00%	1.83 100.00%	1.08×10 100.00%
		$EIRE_{GR}$		0.840	626.764	1.044	1.160	0.961	250.090
Proposed (Second GR-LCA)	Before GR	OI_b	B6	6.05×10^3 100.00%	1.67×10^{-7} 100.00%	3.82×10 100.00%	1.02×10 100.00%	1.90 100.00%	4.31×10^{-2} 100.00%
	After GR	EI_m	A1 to A3	4.80×10^2 9.50%	7.49×10^{-4} 96.10%	1.11×10 27.80%	2.30×10^0 19.50%	2.48×10^{-1} 14.10%	1.05×10 97.80%
			A4	2.04 0.00%	7.37×10^{-7} 0.10%	1.38×10^{-2} 0.00%	1.01×10^{-2} 0.10%	1.65×10^{-3} 0.10%	4.87×10^3 0.00%
			B4	2.98×10 0.60%	1.86×10^{-5} 2.40%	7.79×10^{-2} 0.20%	1.17×10^{-1} 1.00%	2.13×10^{-2} 1.20%	2.11×10^{-2} 0.20%
			C1	1.28 0.00%	5.02×10^{-11} 0.00%	8.55×10^{-3} 0.00%	1.04×10^0 8.80%	4.46×10^{-4} 0.00%	9.23×10^{-5} 0.00%
			C2	1.99 0.00%	7.44×10^{-7} 0.10%	1.35×10^{-2} 0.00%	9.69×10^{-3} 0.10%	1.58×10^{-3} 0.10%	4.72×10^{-3} 0.00%
			C4	9.83 0.20%	3.16×10^{-7} 0.00%	1.39×10^{-2} 0.00%	4.27×10^{-2} 0.40%	7.57×10^{-3} 0.40%	3.30×10^{-3} 0.00%
		OI_a	B6	4.54×10^3 89.60%	9.96×10^{-6} 1.30%	2.87×10 71.90%	8.30×10^0 70.30%	1.48 84.10%	2.03×10^{-1} 1.90%
		Subtotal ($EI_m + OI_a$)		5.07×10^3 100.00%	7.79×10^{-4} 100.00%	3.99×10 100.00%	1.18×1 100.00%	1.76 100.00%	1.08×10 100.00%
		$EIRE_{GR}$		0.838	4660.892	1.043	1.155	0.927	250.131
Original vs. Proposal $EIRE_{GR}$ Percentage Increase or Decrease				−0.21	643.64	−0.10	−0.39	−3.58	0.02

Figure 9 illustrates the carbon reduction effect, including embodied carbon, of the GR before and after comparison with the initial GR-LCA analysis. In various countries, such as Korea, the GR effect is typically assessed solely on its energy implications. Analyzing only the energy aspect reveals a 24.9% carbon reduction, while including embodied carbon lowers this effect to 16.1%. Despite incorporating alternative low-carbon and EPD materials, the second GR-LCA analysis showed a 16.7% reduction. This contrasts with Kim et al.'s (2023) findings of an 11.9% reduction from applying these materials in 29 new buildings, indicating only a 0.6% additional reduction from using low-carbon and EPD materials in GR, which is unfortunate [13].

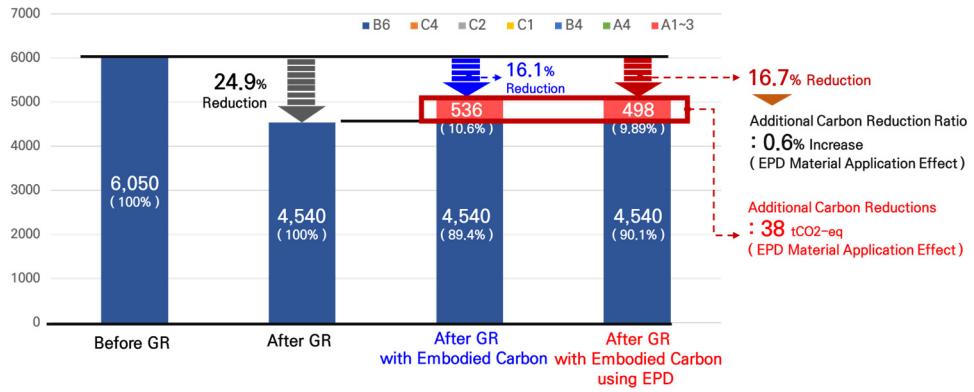


Figure 9. Additional carbon reduction effect of low-carbon and EPD material application.

Figure 10 presents the analysis results; in terms of GWP, it was found that the GWP contributions from four materials—aluminum composite panels (56.6%), aluminum sheet panels (16.6%), double-layer glass (11.6%), and rigid urethane foam board (6.6%)—amounted to more than 90%. Among these, only rigid urethane foam board (PIR) could be replaced with EPD-certified materials, as double-layer glass, aluminum composite panels, and aluminum sheet panels had no suitable low-carbon alternatives. Consequently, the reduction rate of EI in the material production stages (A1 to A3) was minimal.

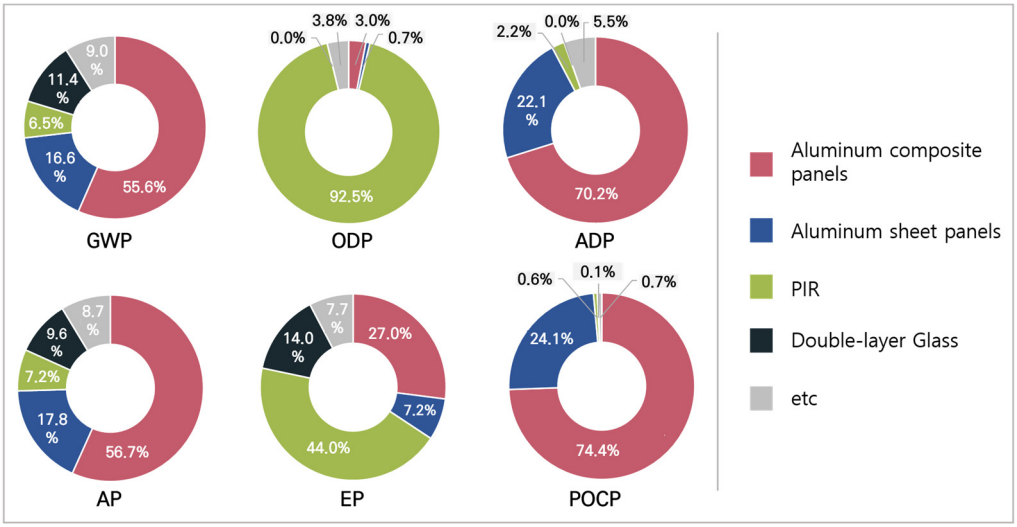


Figure 10. EI contribution by materials.

6. Discussion and Conclusions

6.1. Limitations and Improvement Direction on Embodied Carbon Reduction in GR

Research on carbon neutrality in the building sector highlights limitations in reducing operational energy due to continuous improvements in building energy performance since the 2000s, alongside the increased adoption of Passive House Certification and Zero Energy Building standards [13,38–42]. Various studies have thus been initiated to explore the potential for reducing embodied carbon in buildings using B-LCA [43,44].

Therefore, it is essential to consider implementing low-carbon and EPD materials based on the EI of the total volume of each material to further reduce the carbon footprint of buildings. In GR projects, a high proportion of the materials used are internal and external finishing materials, excluding structural components like concrete, due to the nature of GR construction. In new constructions, structural materials such as concrete and steel, which have high weight ratios, contain a significant portion of the embodied carbon. These materials are readily available in low-carbon- and EPD-certified versions due to the diverse manufacturers of steel and ready-mixed concrete. Hence, the impact of structural components on the embodied carbon in new buildings accounts for about 60% to 65%, making it relatively easier to reduce embodied carbon [13].

However, in the case of GR, it is essential to retain the existing framework while considering the use of low-carbon and EPD materials for various components as opposed to new constructions, which can benefit from enhanced internal and external finishes, insulation, and windows. Furthermore, in Korea, the diversity of finishing materials for both interior and exterior of buildings combined with the limited availability of low-carbon and EPD materials from manufacturers due to design constraints necessitates national-level efforts to promote the certification of these materials, which are commonly used in GR, to enhance the carbon reduction effectiveness of GR. Finally, for embodied carbon reduction, there have been recent studies dealing with the possibility of reduction using

wood materials or pre-fabrication materials [45,46]. In future studies, research using various reduction materials in addition to the EPD materials covered in this study will be needed.

6.2. Discussion on the Results of Analyzing the Six Major Environmental Impacts

The assessment of the six major EIs of the target building before and after GR demonstrated that the values for global warming potential (GWP) and eutrophication (EP) $EIRE_{GR}$ were less than 1, signifying a reduction in EI through GR. Conversely, ozone depletion (ODP), resource depletion (ADP), acidification (AP), and photochemical oxides (POCP) exhibited values exceeding 1. Notably, there was a significant increase in the impact categories of ozone depletion (ODP) and photochemical smog (POCP), which are predominantly associated with the material production stage of EI.

Based on these results, alternative low-carbon and EPD materials were implemented to diminish the EI at the material production stage, and a second GR-LCA analysis was executed. The analysis indicated that in comparison with $EIRE_{GR}$, the first GR-LCA, and $EIRE_{GR}$, the second GR-LCA, there was a modest decrease in global warming (GWP), resource depletion (ADP), acidification (AP), and eutrophication (EP), while increases were observed in ozone depletion (ODP) and photochemical oxides (POCP). This finding, relative to the material environmental impact analysis in Table 6, suggests that although alternative low-carbon and EPD materials, including windows and XPS insulation, decreased GWP, ADP, AP, and EP, they conversely raised ODP and POCP. To alleviate this problem, it is expected that improvements will be possible by replacing the insulation and indoor gypsum board and cement-based tex, which had a high ODP and POCP effect, with wood materials. It is believed that additional GWP and ODP can be reduced by replacing the insulation with wood fiber insulation, and the indoor tex and board with OSB and engineering wood.

Thus, although GR reduced operating energy, the EI analysis revealed increases in ODP and POCP due to shifts in energy sources and the impact of new input materials. This underscores the importance of analyzing the embedded carbon content of new input materials alongside operating energy and considering EI factors beyond carbon emissions to enhance the reliability of GR projects as a carbon-neutral strategy.

To effectively reduce the EI of the entire building process, it is crucial to identify and replace materials that contribute significantly to the EI at the production stage with low-impact alternatives through the use of EPD and low-carbon certifications. Moreover, there is a pressing need to develop and implement a comparable certification system for other EI categories beyond the GWP for commonly used materials such as interior and exterior finishes at the national level.

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Abbreviations

The following abbreviations are used in this manuscript:

GR	Green remodeling
ZEB	Zero energy building
LCA	Life cycle assessment
EPD	Environmental product declaration
B-LCA	Building life cycle assessment
GR-LCA	Green remodeling life cycle assessment
MP Stage	Material production stage
EC	Embodied carbon
EI	Environmental impacts
EIm	Environmental impacts of materials
OI_b	Environmental impacts before GR
OI_a	Environmental impacts after GR
$EIRE_{GR}$	EI reduction efficiency of GR
GWP	Global warming potential
ODP	Ozone layer depletion potential
ADP	Abiotic resource depletion potential
AP	Acidification potential
EP	Eutrophication potential
POCP	Photochemical oxidants creation potential

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