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A Study on Life Cycle CO_2 Emissions of Low-Carbon Building in South Korea

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Abstract: There have been much interest and many efforts to control global warming and reduce greenhouse gas (GHG) emissions throughout the world. Recently, the Republic of Korea has also increased its GHG reduction goal and searched for an implementation plan. In buildings, for example, there have been technology developments and deployment policies to reduce GHG emissions from a life cycle perspective, covering construction materials, building construction, use of buildings and waste disposal. In particular, Korea's Green Standard for Energy and Environmental Design is a certification of environmentally-friendly buildings for their energy saving and reduction of environmental pollution throughout their lives. In fact, the demand and adoption of the certification are rising every year. In construction materials and buildings, as a result, an environmentally-friendly aspect has become crucial. The importance of construction material and building development technologies that can reduce environmental load by diminishing GHG emissions in buildings has emerged. Moreover, there has been a rising necessity to verify the GHG reduction effects of buildings. To assess the reduction of carbon emissions in the buildings built with low-carbon construction technologies and materials, therefore, this study estimated life cycle carbon emissions in reference buildings in which general construction materials are used and in low-carbon buildings. For this, the carbon emissions and their reduction from construction materials (especially concrete) between conventional products and low-carbon materials were estimated, using Life Cycle Assessment (LCA). After estimating carbon emissions from a building life cycle perspective, their reduction in low-carbon buildings compared to the reference buildings was reviewed. The results found that compared to conventional buildings, low-carbon buildings revealed a 25% decrease in carbon emissions in terms of the reduction of Life Cycle CO_2 ($LCCO_2$) per unit area. If diverse production technologies and sales routes are further developed for low-carbon construction materials, carbon emission reduction effects would considerably increase.

Keywords: life cycle CO_2; Korea Life Cycle Inventory Database (KLCI DB); carbon reduction; low-carbon construction materials; building

1. Introduction

At the recent 2015 United Nations Climate Change Conference (COP 21), which was held in Paris, France, the 'Paris Agreement', a new framework convention on climate change, was adopted. It is the first consensus that is more binding than the Kyoto Protocol, keeping the efforts of advanced and developing countries. Therefore, there has been a rising interest in it for a proper response to a post-2020 climate framework around the world.

The Republic of Korea also announced a voluntary action plan to reduce greenhouse gas emissions by 37% from the business-as-usual (BAU) level of 851 million by 2030 [1]. For this, there have been many efforts to reduce GHG emissions throughout the industries. Businesses have operated a "GHG and energy target management system" and cap-and-trade to control GHG emissions. From a product standpoint, the product carbon footprint labeling has been run to encourage the use of low-carbon products. In buildings, the Green Standard for Energy and Environmental Design (G-SEED) has been applied to find ways for reducing GHG emissions considering the life cycle of the green buildings that have reduced GHG emissions with the use of environmental load-reduced materials.

In particular, Korea's construction industry accounts for 48% of the total material consumption and 40% of the national energy consumption. In terms of CO_2 emissions during the production of construction materials, in addition, the construction sector accounts for about 25% [2]. Therefore, there have been many efforts to develop and commercialize low-carbon construction materials that can satisfy the demand for environmentally-friendly buildings. As a result, there has been a rising necessity for the assessment of environmental loads by the life cycle of construction materials and environmental assessment and continuous management throughout the life of buildings.

Therefore, this study analyzed carbon emissions and reduction against the buildings built with low-carbon construction materials after reflecting the government's movement to reduce GHG emissions. For this, an assessment technique that can quantitatively assess carbon emissions in construction materials and buildings was chosen. Depending on the building life cycle, data by GHG the emission factor were collected. Then, Life Cycle CO_2 ($LCCO_2$) emissions were assessed according to the useful life of a building. As a result, GHG emission reduction key technologies were derived from construction materials and buildings. It appears that the study results would be useful data in developing a roadmap and implementation plan for the reduction of GHG emissions from a long-term perspective for low-carbon buildings.

2. Literature Review

2.1. Previous Studies Regarding Environmental Impact Assessment on Buildings Using LCA

According to previous studies, the environmental impact of buildings has been assessed in a more objective and quantitative manner, using LCA, which unveils environmental impact substances throughout the product and service processes and assesses environmental impact [3].

According to studies on energy consumption and carbon emissions throughout a building life cycle, in foreign countries, the environmental impact of energy consumption and greenhouse gas emissions was assessed. In particular, there have been studies targeted to analyze energy consumption patterns by building type in the operation phase [4], to design an energy-saving building and to develop an energy-saving solution through the analysis of diverse cases in foreign countries [5]. In terms of the characteristics of a building's operation phase, it accounted for up to 85% of total carbon emissions by building type due to the use of heating and cooling energy and electrical facilities [6,7].

In the study abroad, Wang *et al.* had found suggestions on improving the green building rating tools to encourage the GHG emission reduction performance of green buildings [8]. Additionally, Liu et al. reviewed the existing research and implementation examples to understand the development of carbon labeling [9]. Furthermore, Rogers *et al.* took an integrated analysis approach to explore the options available for a U.K. homeowner to reduce their domestic emissions [10]. Mahapatra analyzed the energy use of the buildings fulfilling the requirements of the Swedish building code and compared the primary energy use and CO_2 emissions from the operation of the building [11].

In other research work, some studies on green building certification, building materials and building life cycle greenhouse gas emissions were released [12,13]. Additionally, the renewable energy research, such as solar and biomass energy, were conducted [14–17].

Zhang *et al.* conducted the life cycle assessment of the air emissions by using a particular case to examine emissions during the construction stage [18]. Additionally, Baek *et al.* performed a study to identify the requisites for an $LCCO_2$ assessment program that can be used in the schematic design phase [19].

Furthermore, Bribián *et al.* presented the state-of-the-art regarding the application of life cycle assessment in the building sector [20]. Additionally, Verbeeck *et al.* outlined the goal and scope of the LCI and introduced several calculation methods for LCI of building. Then, they presented the results of a contribution analysis of the life cycle inventory of four typical Belgian residential buildings [21,22].

Furthermore, the paper did research about the status of low-carbon technologies in the building area and discussed the necessity and importance of reducing carbon emissions in the full life cycle of buildings [23].

In the Republic of Korea, there have been many environmental impact assessments on buildings using LCA. These studies can be divided into two categories: those [24–27] that suggested a method to assess the environmental impact using LCA and case studies on the building environment [28–30]. In addition, BIM template development studies [31] for the implementation of LCA on environmentally-friendly buildings and Life Cycle Inventory (LCI) DB development studies on construction materials have been very active [32].

Even though there have been many LCAs and studies on buildings, those that reflect the environmental impact of the latest low-carbon construction materials have not been enough.

Therefore, this study has derived the results that would be useful in estimating and analyzing the carbon emissions and reduction of low-carbon construction materials by carrying out environmental impact assessment on buildings using LCA.

2.2. The Status of the Development of Low-Carbon Construction Materials

The product carbon footprint labeling in the Republic of Korea issues measured carbon levels and low-carbon certification on all products and services. In particular, there has been a rising demand for certification on carbon emissions and reduction in construction materials and inventories [33]. At the same time, the development of carbon reduction technologies has been active, and diverse low-carbon products have been produced [34].

In terms of key technologies to reduce carbon emissions at a construction material production stage, it would be able to enhance the efficiency of input management and production processes by reducing the amount of input, using industrial byproducts or applying new materials and reducing carbon emissions during production through fuel switching [2]. In particular, regarding concrete, which is the most widely used for structures among construction materials, the products made of these latest carbon reduction technologies were chosen, and carbon emissions and reduction were measured. In terms of the selection of products, those that are same as conventional products in terms of specification, strength, physical property and test items were chosen, and same functions and functional units were applied [2].

Table 1 states the properties of low-carbon concrete products, while Table 2 reveals the reduction of carbon emissions in each product, compared to conventional products.

Table 1. Properties of low-carbon construction materials (ready-mixed concrete).

Categories	High Strength Ready-Mixed Concrete (A, B, C)	Non-Cement Concrete Panel (D)	Amorphous Steel Fiber Concrete (E, G)
End product	Ready-mixed concrete	Ready-mixed concrete	Ready-mixed concrete
Standard	25-50-600 (slump flow)	0.6 m × 3.0 m × 0.1 m	25-24-150
Function	To form structural frame of reinforced concrete building	To form structural frame of reinforced concrete building	To form structural frame of reinforced concrete building
Functional unit	50 MPa ready-mixed concrete 1-m^3 production	Ready-mixed concrete 1-m^3 production (Panel 1 unit module (46 kg))	24 MPa ready-mixed concrete 1-m^3 production

Table 1. *Cont.*

Categories	High Strength Ready-Mixed Concrete (A, B, C)	Non-Cement Concrete Panel (D)	Amorphous Steel Fiber Concrete (E, G)
CO_2 reduction technology	Resource recycling (use of industrial waste) Long life span (high strength)	Non-cement Use of industrial waste materials Long life span (high strength) Industrial waste reduction	Use of industrial waste materials Reduction of energy consumption for the production stage Increasing of the durability life by crack reducing
Reference product	50 MPa OPC concrete	Extrusion concrete panel	24 MPa OPC concrete
Division	Non-cement concrete for PC element (F)	Low energy curing concrete panel (H)	Carbon negative cement (I)
End product	Ready-mixed concrete	Ready-mixed concrete	Carbon negative cement
Standard	25-50-150	KS F 4735	-
Function	To form structural frame of reinforced concrete building	To form structural frame of reinforced concrete building	To use for construction in building and civil engineering
Functional unit	50 MPa ready-mixed concrete 1-m^3 production	Low energy curing concrete panel 1 kg production	Carbon negative cement 1-kg production
CO_2 reduction technology	Recycling materials 100%	Reduction of energy consumption for the production stageUse of industrial waste materials	Reduction of CO_2 emissions from raw materials Use of industrial waste materials
Reference product	Precast concrete	Extrusion concrete panel	Portland cement

OPC: Ordinary Portland Cement, PC: Precast Concrete, KS F: Korean Industrial Standards (F: Construction part)

Among the nine products for which carbon emission reduction and reduction rates were compared in Table 2, those with the same functions and functional units are alphabetically listed in Table 1.

Table 2. CO_2 emissions and reduction amounts of low-carbon products as compared to the baseline product (unit: kg CO_2 eq./unit).

No.	Low-Carbon Materials	CO_2 Emissions	Baseline CO_2 Emissions	Reduction Rate
A	HVMA Concrete	92.0	375.0	75%
B	HVMA SCC Concrete	145.0	417.0	65%
C	Non-cement Concrete	149.0	539.0	72%
D	Non-cement Concrete Panel	193.0	404.0	52%
E	Amorphous Steel Fiber Concrete	253.6	320.0	21%
F	High Thermal Insulation External Wall PC	345.0	559.0	38%
G	Fiber Reinforced High Strength Concrete	0.3	0.9	67%
H	Low Energy Curing Concrete Panel	0.3	0.4	25%
I	Carbon Negative Cement	0.6	0.9	44%

HVMA: High Volume Mineral Admixture, HVMA SCC: High Volume Mineral Admixture Self Compacting Conctete.

3. Research Methods

Among the assessment methods mostly used during LCA to assess the $LCCO_2$ emissions of buildings, process analysis [35] was adopted. A building is a composite structure comprised of construction materials. In addition, input and output data, which are produced through its life cycle are very complicated. Therefore, it was believed that the limitation on the scope of data collection considering the characteristics of a building's life cycle would derive the carbon emissions and reduction of a building in a clear manner.

3.1. Research Scope and Method

3.1.1. System Boundary

In general, a building consumes energy and resources and produces a variety of wastes through its life cycle, which include the design, production of construction materials, construction, building use and maintenance, demolition and recycling and reconstruction.

As shown in Figure 1, therefore, this study divided building life cycle stages and set the system boundary to define the scope of data collection in each stage and to perform $LCCO_2$ assessment.

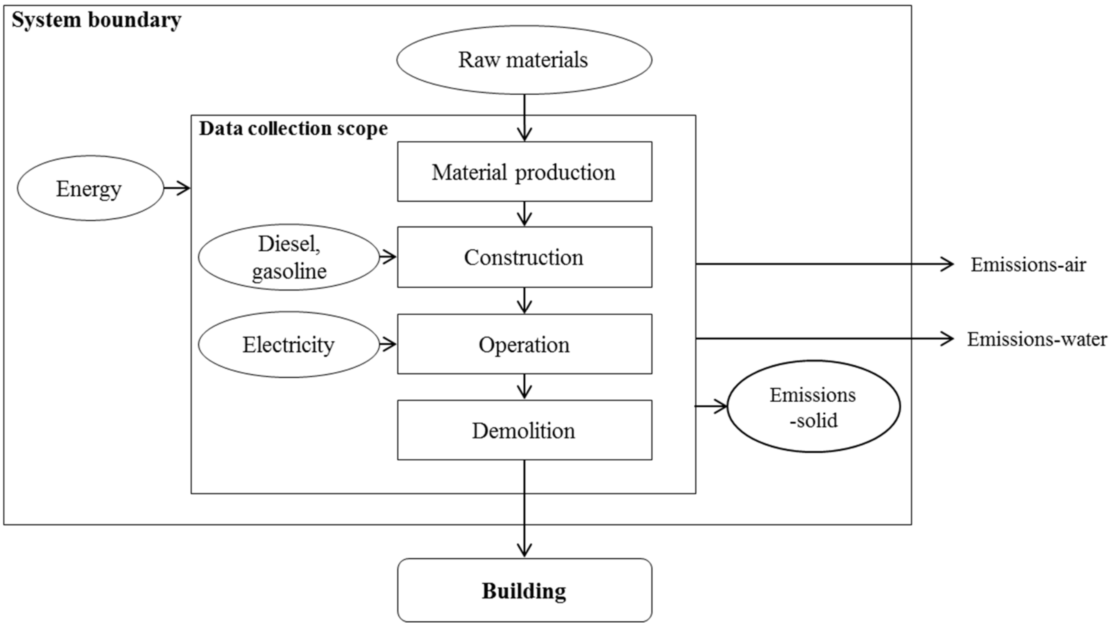


Figure 1. System boundary for $LCCO_2$ assessment of a building.

3.1.2. Environmental Load Assessment Plan by Life Cycle

Considering a building's life cycle, the scope of data collection was divided into four stages: construction material production (manufacture) phase, construction phase, operation and maintenance phase and demolition phase.

Table 3 states the matters that should be considered at LCA depending on a building's life cycle phase.

Table 3. Description of the unit process for the building $LCCO_2$ assessment.

Division	Unit process	Description
Material production phase	Construction material production	The process of the manufacturing and processing of raw materials; the building materials to be charged into the building consume resources and the energy required for production, such as the production of products
Construction phase	Material transport	The process of transporting the material to be put into the building from the dealer or store to construction sites
	Construction activities	The transported material on site, using a variety of construction equipment; the process of applying the building

Table 3. *Cont.*

Division	Unit process	Description
Operation and maintenance phase	Use	The process that residents maintain a comfortable life by using various equipment during their life time
	Maintenance	The process of maintaining the building as the initial conditions by repairing works
Demolition phase	Destruction	The process of the building by using the construction machinery demolition
	Waste material transport	The process of transporting the waste materials to a treatment plant in accordance with the disposal method after the destruction process
	Recycling	The process of converting recyclable waste materials to new raw materials or manufacturing new products through crushing and screening work
	Waste landfill/incineration	The process of burying or burning the non-reusable residue waste

3.2. Utilization of the LCI Database of the Construction Materials

The environmental information of the construction materials that can be used to perform LCA on the environmental impact of buildings was collected. For this, the results of national LCI DB and conventional LCI DB development-related studies were referenced. In case of construction materials in which KLCI DB [36,37] is not found, a foreign LCI DB [38] was used or LCI results were calculated in person in accordance with international standards (See Table 4.).

Table 4. List of LCI DB for construction materials.

Division	Input Materials	Unit	Environmental Impact Database (GWP) (kg-CO_2 eq./unit *)	Resources
Material production phase	Ready-mixed concrete (25-24-15)	m^3	4.29×10^2 kg-CO_2 eq./m^3	KLCI DB
	Ready-mixed concrete (25-18-8)	m^3	4.29×10^2 kg-CO_2 eq./m^3	KLCI DB
	Ready-mixed concrete (25-50-600)	m^3	3.75×10^2 kg-CO_2 eq./m^3	CFF (Korea)
	Ready-mixed concrete (25-18-12)	m^3	3.20×10^2 kg-CO_2 eq./m^3	CFF (Korea)
	Ready-mixed concrete (K product)	kg	3.54×10^2 kg-CO_2 eq./kg	CFF (Korea)
	Ready-mixed concrete (E product)	kg	9.20×10 kg-CO_2 eq./kg	CFF (Korea)
	Ready-mixed concrete (D product)	kg	1.45×10^2 kg-CO_2 eq./kg	CFF (Korea)
	Ready-mixed concrete (R product)	kg	2.54×10^2 kg-CO_2 eq./kg	CFF (Korea)
	Lightweight wall panel (K Lab product)	kg	1.93×10^2 kg-CO_2 eq./kg	CFF (Korea)
	LEC panel (KH product)	kg	2.90×10^{-1} kg-CO_2 eq./kg	CFF (Korea)
	Dry mortar (P product)	m^3	6.76×10^{-1} kg-CO_2 eq./m^3	CFF (Korea)
	High thermal insulation PC (H product)	m^3	3.45×10^2 kg-CO_2 eq./m^3	CFF (Korea)
	Lumber	m^3	5.21×10 kg-CO_2 eq./m^3	KLCI DB
	Steel and pipe	kg	3.96×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Concrete brick	kg	1.23×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Brick masonry	kg	3.98×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Tile	kg	3.53×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Granite	kg	1.13×10 kg-CO_2 eq./kg	KLCI DB
	Scagliola	kg	1.34×10 kg-CO_2 eq./kg	KLCI DB
	Aluminum panel	kg	2.11 kg-CO_2 eq./kg	KLCI DB
	Thermopane	m^2	2.24×10 kg-CO_2 eq./m^2	KLCI DB
	Gypsum board	kg	2.15×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Foam polystyrene insulation	kg	1.90×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Cement	kg	9.44×10^{-1} kg-CO_2 eq./kg	KLCI DB
	Sand	kg	3.87 kg-CO_2 eq./kg	KLCI DB
	Gravel	kg	1.13×10 kg-CO_2 eq./kg	KLCI DB
Construction Phase	Diesel	kg	6.82×10^{-2} kg-CO_2 eq./kg	KLCI DB
	Gasoline	kg	8.32×10^{-2} kg-CO_2 eq./kg	KLCI DB
	Electricity (production)	kwh	4.95×10^{-1} kg-CO_2 eq./kwh	KLCI DB
Operation and maintenance phase	Electricity(production)	kwh	4.95×10^{-1} kg-CO_2 eq./kwh	KLCI DB
	Gas (production)	Nm^3	4.81×10^{-1} kg-CO_2 eq./Nm^3	KLCI DB
	Gas (combustion)	Nm^3	2.30 kg-CO_2 eq./Nm^3	KLCI DB

Table 4. *Cont.*

Division	Input Materials		Unit	Environmental Impact Database (GWP) (kg-CO_2 eq./unit *)	Resources
Demolition phase	Recycling	Waste wood	kg	1.39×10^{-2} kg-CO_2 eq./kg	KLCI DB
		Waste glass	kg	9.76×10^{-3} kg-CO_2 eq./kg	KLCI DB
		Waste concrete	kg	1.38×10^{-2} kg-CO_2 eq./kg	KLCI DB
		Waste steel	kg	3.79×10^{-3} kg-CO_2 eq./kg	KLCI DB
	Landfill	Waste wood	kg	6.07×10^{-2} kg-CO_2 eq./kg	KLCI DB
		Waste glass	kg	7.00×10^{-3} kg-CO_2 eq./kg	KLCI DB
		Waste concrete	kg	7.00×10^{-3} kg-CO_2 eq./kg	KLCI DB
		Waste steel	kg	7.00×10^{-3} kg-CO_2 eq./kg	KLCI DB
	Incineration	Waste wood	kg	1.17×10^{-2} kg-CO_2 eq./kg	KLCI DB
		Waste glass	kg	2.42×10^{-2} kg-CO_2 eq./kg	KLCI DB
		Waste steel	kg	1.70×10^{-2} kg-CO_2 eq./kg	KLCI DB

GWP: Global Warming Potential. Resources: (1) KLCI DB: Korea life cycle inventory database, (2) CFF: Carbon Emission Factor in the development of carbon reducing concrete structural materials and energy-saving building materials.

3.3. Assumptions and Restrictions

To analyze subjects with many variables, it is needed to restrict the subjects and scope of data collection to permit LCA based on process analysis. Therefore, the factors having considerable environmental impact by the life cycle of buildings were extracted and used in preparing a data collection scenario and setting assumptions.

At the operation and maintenance and demolition phases, it is able to estimate environmental load by assuming the factors with significant environmental impact and setting a scenario depending on certain conditions.

4. LCCO_2 Assessment of a Low-Carbon Building

4.1. Overview of LCA-Targeted Building

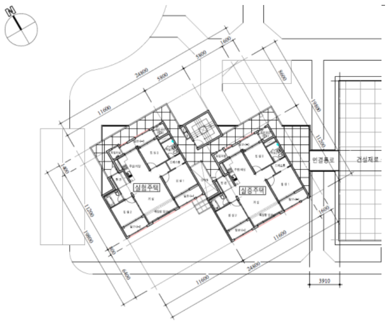
The target building is a building aimed to verify the effects through the development of carbon-reduction construction materials. It features a PR (publicrelations) hall on the first floor, a monitoring space on the second floor and empirical and reference spaces on the third and fourth floors. As a result, the area apart from the empirical and reference spaces was set as a "common space" and divided into common space, empirical house and reference house for building analysis.

As indicated in Table 5, among the gross floor area (1078 m^2), the common space accounted for 738 m^2, while empirical and reference houses were 170 m^2 each (85 m^2/floor).

Table 5. Overview of the building.

	Division		Description
	Building		Low-carbon material building
	Site		Goyang-Si, Gyeonggi-do, Korea
	Lot area		372 m^2
	Gross floor area		1078 m^2
	Structure		Reinforced concrete structure
	Parking		5 cars
	Division	**Area (m^2)**	**Use**
	1st floor	335	Common space (PR (publicrelations) hall, monitoring space)
	2nd floor	302	
	3rd floor	220 (House 170)	Reference house (85 m^2), empirical house (85 m^2)
	4th floor	220 (House 170)	Reference (85 m^2), empirical house (85 m^2)
	Roof floor	13	(Excluded from the GFA (Gross Floor Area))
	Total	**1078**	

Table 5. *Cont.*

Division	Description
	

As shown in Table 6, for the evaluation of building $LCCO_2$, a building was divided into office and residential spaces by reflecting the target building's spatial characteristics, and functional units were selected. In terms of service life setting for a building, 30 years were set for a reinforced concrete structure in accordance with the Corporate Tax Act (No. 40 of the References).

Table 6. Overview of the $LCCO_2$ assessment.

Division		1st, 2nd Floor Common Space	3rd, 4th Floor Reference House	3rd, 4th Floor Empirical House (Low-Carbon Materials)
Assessment scope	Temporal	Life cycle of 30 years		
	Spatial	Resources and energy, which is input and output into the building life cycle (production of building materials, construction, use, disposal)		
Function		The function of the support for a variety of business activities	The function of household-dwelling	
Functional unit		The office building for 30 years	A residential building for one household during 30 years	
Reference flow		Resources and energy, which are put into the office buildings for 30 years	Resources and energy input to a building for a household during 30 years	
Reference flow unit		$kgCO_2$ eq./m^2.30 years		

4.2. Material Production Phase

This phase includes the processes from the collection of raw materials needed to manufacture construction materials to their production.

The total mass of inventories used for the construction of the target building was 3172 tons (2.9 tons/unit area). Considering the characteristics of a reinforced concrete structure, ready-mixed concrete, sand and gravel, cement and precast concrete accounted for about 95% of the total input.

In this study, 99.7% of the cumulative contribution was applied for the "cut-off" based on the total construction material input, including the common area of the building and empirical and reference houses (See Table 7 and Figure 2.).

Table 7. The cumulative mass contribution analysis.

Materials	Inputs (kg)	Contribution Rate (%)	Cumulative Contribution Rate (%)
Ready-mixed concrete	2,379,155	75.0	75.0
Sand and gravel	459,200	14.5	89.5
Steel and pipe	127,696	4.0	93.5
Cement	47,090	1.5	95.0

Table 7. *Cont.*

Materials	Inputs (kg)	Contribution Rate (%)	Cumulative Contribution Rate (%)
Lumber	40,347	1.3	96.3
Wooden product	38,731	1.2	97.5
PC panel	24,700	0.8	98.3
Glass product	16,451	0.5	98.8
Clay product	11,862	0.4	99.2
Asbestos product	10,853	0.3	99.5
Concrete production	4124	0.1	99.6
Gypsum production	2829	0.1	99.7
Paint	2291	0.1	99.8
Adhesive	1813	0.1	99.9
Steel pipe	1787	0.1	100.0
Stone	1004	0.0	100.0
Steel wire	668	0.0	100.0
Rolled steel materials	662	0.0	100.0
etc.	1024	0.0	100.0
Total	**3,172,285**	**100**	**100.0**

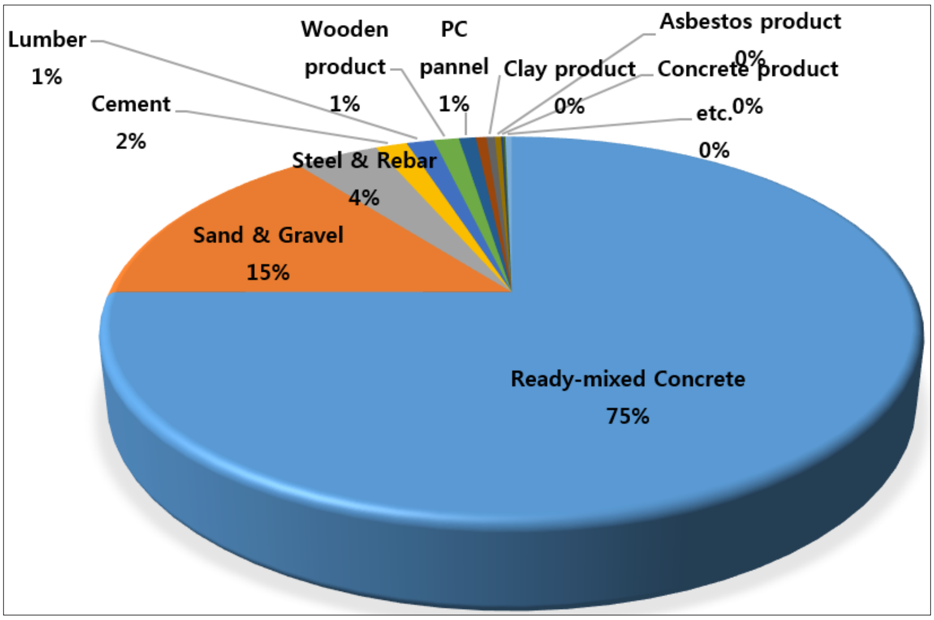


Figure 2. The cumulative mass contribution of input materials.

4.3. Construction Phase

The construction phase refers to the stage in which a building is being built with various equipment and facilities, since the transportation stage is where construction materials are brought to the construction site.

In this phase, CO_2 is mostly emitted by construction machines and equipment and transportation vehicles. Therefore, the data on these transportation vehicles and transportation distance are collected. Furthermore, this is calculated based on fuel and power consumption at the construction site. In the building, the construction equipment was mostly used for earthwork, reinforced concrete work and plaster work.

4.4. Operation and Maintenance Phase

This phase is to use and repair and manage the building until it is demolished. Among energy consumption and building maintenance, in this study, the former was only considered for carbon emissions. Based on previous studies on building energy consumption [31], annual power consumption (41.7 kwh/m^2) and annual city gas consumption (16.1 Nm^3/m^2) were considered. In terms of the useful life of the building, 30 years [39,40] were set according to a standard repair cycle.

4.5. Demolition Phase

This phase is to deconstruct a building and dispose of or recycle the materials when it becomes useless after the expiry of its social and physical lives.

This study did not consider CO_2 emissions, which occur during the demolition of the low-carbon building or transportation of the wastes, because assessment was conducted, focusing on CO_2 emissions among total construction material input. In addition, CO_2 emissions were considered according to the waste estimation and disposal methods. Depending on the treatment method by the type of construction wastes, therefore, 97.5% of recycling rates, 1.8% of landfill and 0.7% of incineration were applied, using statistical values [37].

5. Results of Carbon Emissions by the Life Cycle Phase of Low-Carbon Buildings

5.1. Material Production Phase

As shown in Table 8 and Figure 3, the CO_2 emissions of input materials were 495,802 kg CO_2 eq. Regarding environmental impact by the construction material, ready-mixed concrete was the highest with 72.7%, followed by reinforcing bar and steel bar (10.1%) and cement (8.6%) in terms of CO_2 emissions.

Table 8. CO_2 emissions by input material during the material production phase.

Division	Inputs (kg)	CO_2 Emissions (kg CO_2 eq.)	Percentage (%)
Ready-mixed concrete	2,379,155	360,577	72.7
Sand and gravel	459,200	2647	0.5
Steel and pipe	127,696	50,247	10.1
Cement	47,090	42,404	8.6
PC panel	24,700	4485	0.9
Glass product	16,451	7959	1.6
Wooden product	15,284	7063	1.4
Lumber	14,580	1356	0.3
Clay product	11,862	4486	0.9
Asbestos product	10,853	2062	0.4
Concrete production	4124	508	0.1
Gypsum production	2829	608	0.1
Construction stone	1004	11,400	2.3
Total	3,114,828	495,802	100

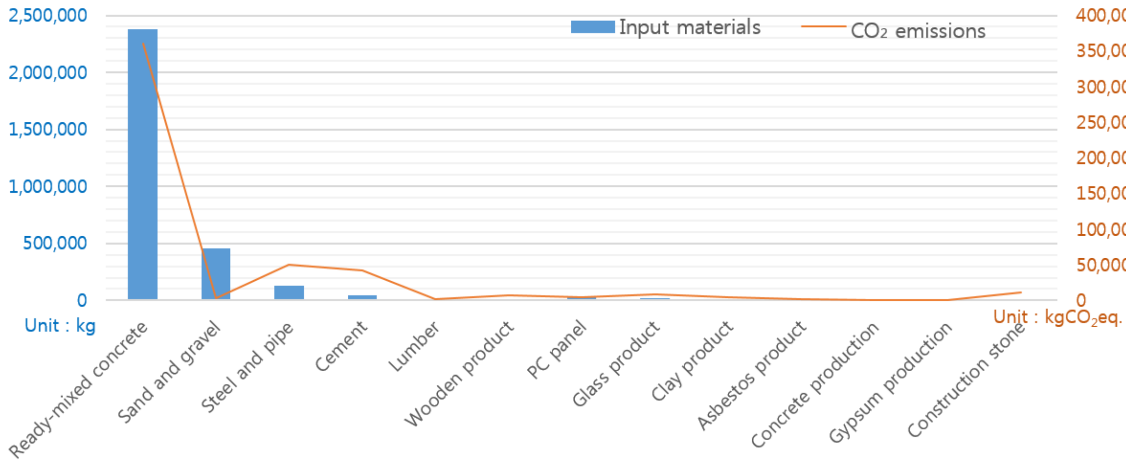


Figure 3. CO_2 emission distribution of the whole building during the material production phase

The CO_2 emissions by common area, residential house and empirical house are estimated as shown in Table 9 and Figure 4.

Table 9. Material inputs and CO_2 emissions by building sector.

Division		Ready-Mixed Concrete	Sand and Gravel	Steel and Pipe	Cement	PC Panel	Glass Product	Wooden Product	Lumber	Clay Product	Asbestos Product	Concrete Production	Gypsum Production	Construction Stone	Total
Inputs (kg)	Whole building	2,379,155	459,200	127,696	47,090	24,700	16,451	15,284	14,580	11,862	10,853	4124	2829	1004	3,114,828
	Common space	1,957,600	411,136	97,521	30,422	-	9722	15,284	14,580	8315	3612	4124	119	988	2,553,423
	Reference House	256,450	24,029	15,088	8335	-	3987			1774	3622	-	1354	8	314,647
	Empirical house	165,381	24,036	15,084	8333	24,700	2742			1774	3619	-	1355	8	247,032
CO_2 emissions (kg CO_2 eq.)	Whole building	360,577	2647	50,247	42,404	4485	7959	7063	1356	4486	2062	508	608	11,400	495,802
	Common space	277,967	2531	38,309	28,025	-	3997			3236	686	508	26	11,198	366,483
	Reference House	42,632	58	5969	7190	-	2347			625	688	-	291	101	59,901
	Empirical house	39,978	58	5969	7190	4485	1614			625	688	-	291	101	60,999

Among total input for the building, the largest amount of construction materials was used during the foundation and frame works for the common space. Therefore, CO_2 emissions were the greatest in the common space. In addition, even though reference and empirical houses were the same in terms of area, there was a difference in the amount of input to the empirical house because of the use of low-carbon ready-mixed concrete, PC panel and insulated products.

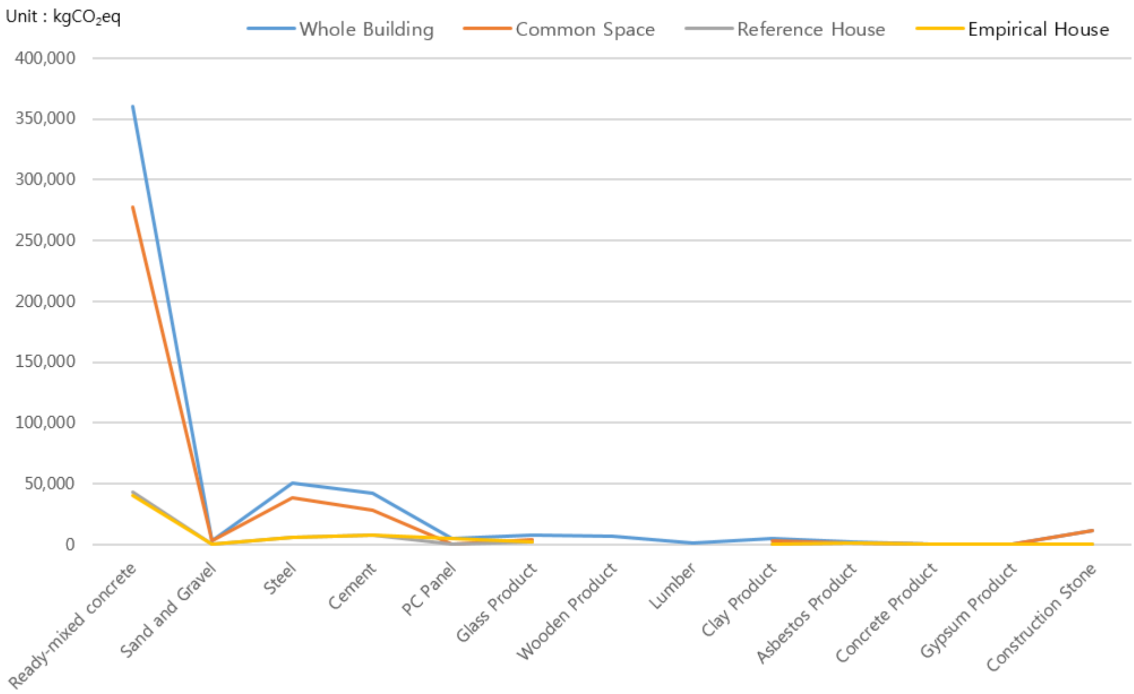


Figure 4. CO_2 emissions by construction material input in the building sectors.

5.2. Construction Phase

In this phase, CO_2 emissions were assessed by classifying emission effects by the transportation of construction materials and construction. In terms of CO_2 emissions generated in transporting construction materials to a construction site, ready-mixed concrete was 67.3%, while other materials were 32.7% (See Table 10.).

Table 10. CO_2 emissions by material transport.

Equipment	Distance (km)	Inputs	Unit	CO_2 Emission Unit		CO_2 Emissions (kg CO_2 eq.)
Truck (2.5 ton)	30	784,887	kg	1.46×10^{-1}	$kgCO_2/ton \cdot km$	3437.8
Concrete mixer truck	10	1051	m^3	6.74×10^{-1}	$kgCO_2/m^3 \cdot km$	7083.7
		Total				**10,521.5**

As indicated in Table 11, in terms of CO_2 emissions generated by the use of construction equipment, the use of diesel oil during earthwork and concrete pouring was 68.1%, while power consumption for other works, such as plaster work, was 31.4%.

Table 11. CO_2 emissions by construction activity.

Energy Sources	Inputs	Unit	CO_2 Emission Unit		CO_2 Emissions (kg CO_2 eq.)
Diesel	1180	kg	4.80E-01	$kgCO_2/kg$	566.4
Gasoline	40	kg	8.32E-02	$kgCO_2/kg$	3.3
Electricity	529	kwh	4.95E-01	$kgCO_2/kwh$	261.9
		Total			**831.6**

The CO_2 emissions generated during the construction phase were 11,353.1 kg CO_2 eq. Among them, 92.7% was created during transportation, while 7.3% was generated by construction. In terms of CO_2 emissions during transportation, ready-mixed concrete was the highest with 62.4%, while other materials were 30.3%.

5.3. Operation and Maintenance Phase

In this phase, assessment is conducted based on the energy consumption [31] of apartment houses. For the consumption of heating energy by empirical houses (third floor and fourth floor: one apartment unit each), the simulation data from the manufacturer of input materials were used.

For the two apartment units, 170 m^2 (85 m^2/unit) was applied. For reference and common spaces, in contrast, 908 m^2 was adopted. Then, LCA was performed with the assumption that the building's useful life was 30 years.

As shown in Table 12, the total CO_2 emissions for 30 years are 1,890,282 kg CO_2 eq. In the case of the empirical houses (third floor and fourth floor: one apartment unit each), which were built with low-carbon ready-mixed concrete and concrete products, it was able to reduce heating energy consumption by 37%.

Table 12. CO_2 emissions during the operation and maintenance phase.

Division	Electricity		LNG		Yearly CO_2 Emissions (kg CO_2 eq./y)	30 Years CO_2 Emissions (kg CO_2 eq./30 y)
	Consumption ($kwh/y{\cdot}m^2$)	CO_2 Emissions (kg CO_2 eq./$y{\cdot}m^2$)	Consumption ($Nm^3/y{\cdot}m^2$)	CO_2 Emissions (kg CO_2 eq./$y{\cdot}m^2$)		
Consumption per unit of empirical house	41.7	18	10.0	27.9	7803	234,090
Consumption per unit (except empirical house)	41.7	18	16.1	42.8	55,206	1,656,192
Total	83.4	36	26.1	70.7	63,009	1,890,282

5.4. Demolition Phase

In this phase, CO_2 emissions were analyzed from waste concrete, waste metal, waste wood and waste glass. The disposal method was classified into recycling, burying and incineration steps. Assessment was performed after applying the three methods as follows: recycling (97.5%), landfill (1.8%) and incineration (0.7%) [35].

The CO_2 emissions generated during the demolition phase are 33,412 kg CO_2 eq. In particular, waste concrete accounts for 96.7% with 32,311 kg CO_2 eq (See Table 13.).

Table 13. CO_2 emissions by demolishing the building.

Division		Waste Concrete	Waste Steel	Waste Wood	Waste Glass	Total Emissions
Disposal volumes (kg)	Total	2,379,155	127,696	29,602	16,451	2,552,904
	Common space	1,957,600	97,521	19,340	9722	2,084,183
	Reference house	256,450	15,088	132	3987	275,657
	Empirical house	165,381	15,084	130	2742	183,337

Table 13. *Cont.*

Division		Waste Concrete	Waste Steel	Waste Wood	Waste Glass	Total Emissions
CO_2 emissions (kg CO_2 eq.)	Total	32,311	503	436	161	33,984
	Common space	26,586	384	285	95	27,350
	Reference house	3483	59	2	39	3583
	Empirical house	2963	59	2	27	3051

5.5. The Results of the LCCO$_2$ Assessment of the Low-Carbon Building

According to estimation on the LCCO$_2$ emissions of the building, a total of 595 tons CO_2 eq./m^2 is produced annually. As shown in Table 14 and Figure 5, in terms of CO_2 emissions by life cycle, the material production (manufacture) phase (81.8%) was the highest, followed by the construction phase (1.9%), the operation and maintenance phase (10.6%) and the demolition phase (5.7%).

Table 14. The results of LCCO$_2$ assessment (unit: kg CO_2 eq./m^2).

Division	Manufacture	Construction	Operation	Demolition	Yearly CO_2 Emissions	Emissions per Unit Area
Consumption per unit of empirical house	60,999	1790	7803	3051	73,643	433
Consumption per unit (except empirical house)	426,384	9562	55,206	30,933	522,085	575
Yearly total emissions (%)	487,383 81.8%	11,352 1.9%	63,009 10.6%	33,984 5.7%	595,728 100.0%	552.6
30 years total emissions (%)	487,383 20.1%	11,352 0.5%	1,890,285 78.0%	33,984 1.4%	2,423,004 100.0%	2248

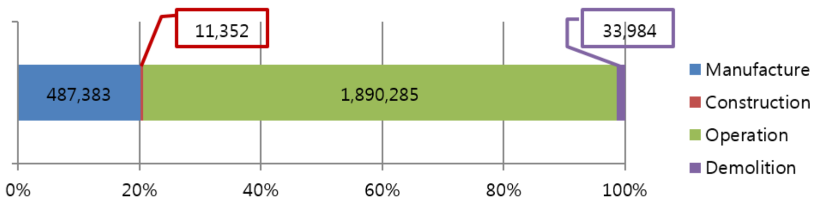


Figure 5. LCCO$_2$ emissions throughout the life cycle phases for 30 years (unit: kg CO_2 eq./m^2).

In particular, as shown in Figure 6, empirical houses revealed a decrease in CO_2 emissions by 141.8 kg CO_2 eq./m^2 annually, compared to the common and reference spaces. Furthermore, the sources of CO_2 emissions in each stage were as follows: ready-mixed concrete (manufacture phase), transportation of ready-mixed concrete (construction phase), consumption of heating energy (LNG) (operation and maintenance phase) and concrete disposal (demolition phase).

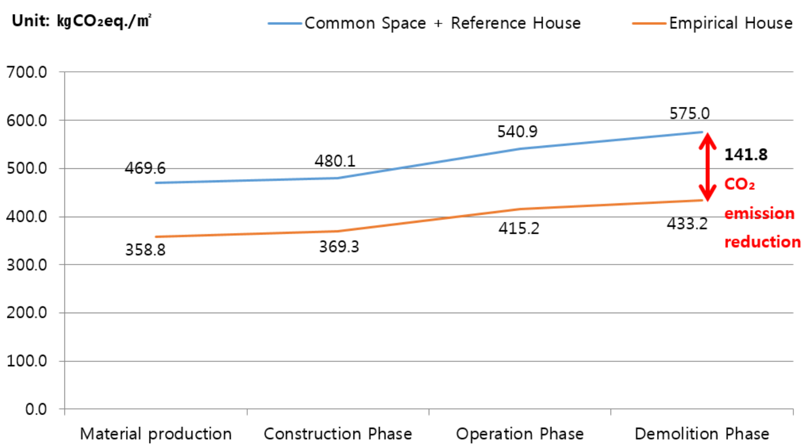


Figure 6. LCCO$_2$ emission reduction of low-carbon building.

6. Discussion and Limitation

This study aimed to comparatively analyze the effects of the construction materials (concrete, cement, *etc.*) manufactured with carbon emission reduction technology on the carbon emissions of a reinforced concrete structure throughout its life cycle.

For this, car emissions and the reduction amount by construction material were estimated, and the results were applied to the target building. Then, its life cycle carbon emissions were estimated.

There are two types of products: a product that reduced carbon emissions during the production of construction materials; and an insulated product that reduces energy consumption during the operation of a building. Therefore, the reduction of energy consumption in the operation phase was expected.

However, no effective values on energy simulation in the target building were applied. In addition, there were limitations in individually analyzing the $LCCO_2$ emissions of the various concrete products that were applied to each building area.

Hence, it is needed to improve the carbon emission estimation results by energy resumption after monitoring energy consumption at the operation phase. Furthermore, there should be studies to analyze the effects of CO_2 reduction in each construction material on a building through diverse influential factors, for example, input of construction materials, life cycle, energy source, *etc.*

7. Conclusions

This study estimated $LCCO_2$ emissions against the buildings built with low-carbon concrete and energy-saving materials, using Korea's LCI DB for construction materials. The $LCCO_2$ assessment and analysis on low-carbon construction materials and buildings found the following:

(1) The carbon-reduction technologies for construction materials include: the reduction of resource consumption by using recycled materials or industrial byproducts (manufacture phase); the decrease in CO_2 emissions by shortening the production processes or changing fuels; the decrease in resource consumption throughout the life of buildings by reducing the consumption of materials for repair with construction materials that reduce energy consumption and have a long lifespan (operation and maintenance phase).

(2) A low-carbon building refers to one built with low-carbon construction materials and conventional ones. A total of 3115 tons of construction materials were added. Among them, those for a building frame (ex: ready-mixed concrete, sand and gravel, reinforcing bar, pipe, *etc.*) accounted for over 80%.

(3) According to the analysis on CO_2 emissions by input material, ready-mixed concrete, wood, reinforcing bar and cement were the major sources of CO_2 emissions. They accounted for 92.8% of total annual CO_2 emissions.

(4) Total CO_2 emissions generated throughout the life (30 years) of low-carbon buildings are 2,423,004 kg CO_2 eq. In terms of CO_2 emissions by stage, the operation and maintenance phase (78.0%) was the highest, followed by the manufacture phase (20.1%), the demolition phase (1.4%) and the construction phase (0.5%). When compared to the studies (domestic papers) under simulation conditions [41], the results were similar to this study in terms of emission ratio in the order of operation stage (81.39%–86.45%), production stage (11.66%–15.85%), construction stage (1.49%–2.15%) and disposal stage (0.4%–0.61%). In overseas studies, as well [42], the operation stage (77%–85%) was the highest, followed by the production and construction stages (14%–21%) in terms of emission ratio. These results reveal that energy-saving and carbon emission reduction effects would increase during building maintenance.

(5) Regarding $LCCO_2$ emissions, carbon emissions were the highest in the manufacture of ready-mixed concrete for which heating energy, electricity and input materials were mostly used. This kind of result stems from the input of the materials for low-carbon concrete and energy-saving ones.

(6) Compared to common and reference areas, empirical houses reduced CO_2 emissions by about 25% (141.8 kg CO_2 eq./m^2 per year).
(7) To reduce CO_2 emissions throughout the life of buildings, it is needed to consider the embodied energy of construction materials and embodied CO_2 emissions at the construction material manufacture phase, as well as at the operation and maintenance phase. There should be an in-depth study on carbon-reduction of construction materials in empirical houses.

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