Vol. 14, No. 1, 63-76, https://doi.org/10.22712/susb.20230006

INTERNATIONAL JOURNAL OF
SUSTAINABLE Building Technology and Urban Development

pISSN 2093-761X · eISSN 2093-7628

A Study on the derivation of carbon neutrality rates in the production stage through the application of construction materials with environmental product declaration in South Korea

Seongjo Wang[1], Sungho Tae[2*] and Daehong Kim[3]

[1]Ph.D, Department of Smart City Engineering, Hanyang University, Gyeonggi, Ansan, South Korea
[2]Professor, School of Architecture and Architectural Engineering, Hanyang University, Gyeonggi, Ansan, South Korea
[3]Reseacher, Archi green Co., Ltd, Gyeonggi, Ansan, South Korea

***Corresponding author:** jnb55@hanyang.ac.kr

Received: 22 February 2023
Accepted: 24 March 2023

A B S T R A C T

Reducing carbon emissions in the building sector is essential for achieving global carbon neutrality. To this end, it is necessary to evaluate the carbon emissions of materials used in actual buildings throughout the building lifecycle, quantify the amount of carbon reduction relative to standards, and derive carbon neutrality rates for the building sector. In Korea, carbon emissions during the operation stage account for approximately 65% of total emissions, and certification systems for zero-energy buildings and step-by-step roadmaps have been established to reduce carbon emissions in the operation stage. However, carbon emissions in the production stage account for approximately 29% of total emissions and are the second-highest, yet there is a lack of standards and management for carbon reduction in the production stage in Korea. In addition, the carbon emissions of materials used in actual buildings are not applied because Korea's Building LCA evaluates the carbon emissions in the production stage using data standardized by Korea's national LCI DB. This study constructed a carbon emissions database for 417 environmentally friendly construction materials produced by companies and used in buildings to derive the carbon neutrality rate in the production stage and established a reference building according to the classification system. Based on this, the amount of carbon reduction was derived in comparison to Korea's national LCI DB and the carbon neutrality rate, which is the ratio of carbon reduction to carbon emissions in the production stage. As a result, in the case of apartment houses, a maximum carbon reduction of 312 $kgCO_2$-eq per unit area (m^2) is possible, and the carbon neutrality rate in the production stage was 65.43%. For office facilities, a maximum carbon reduction of 327 $kgCO_2$-eq per unit area (m^2) is possible, and the carbon neutrality rate in the production stage was 69.22%. This study could potentially contribute to carbon neutrality in the building sector by deriving quantitative carbon neutrality rates, not only in the production stage but throughout the entire building process.

Keywords: carbon neutrality rate; environmentally friendly construction materials; production stage

Introduction

As awareness of the severity of the climate crisis has increased worldwide with the COVID-19 pandemic, major countries have officially declared a stepwise approach to carbon neutrality [1, 2]. Each country has set a target for

Table 1. Carbon neutrality plans of major countries

Country	Carbon Neutrality Plan for 2030	Carbon Neutrality Plan for 2050
EU	Reduce by 55% compared to 1990	Net-zero
United States	Reduce by 52% compared to 2005	Net-zero
Japan	Reduce by 46% compared to 2013	Net-zero
South Korea	Reduce by 26% compared to 2018	Net-zero

reducing carbon emissions by 2030 compared to the reference year and aims to achieve carbon neutrality (zero) by 2050 [3, 4]. South Korea has announced The 2050 Carbon Neutrality Scenario to reduce industrial carbon emissions by 40%, from 727.6 million tons in 2018 to 436.6 million tons, and then to achieve carbon neutrality by 2050. In the building sector, its goal is to reduce carbon emissions by 32.8% from 52.1 million tons and to reduce 88.1% by 2050 [5]. Any shortcomings are to be achieved through carbon capture, utilization, and storage (CCUS) and carbon sinks [4, 5]. Table 1 shows the stepwise carbon neutrality plans of major countries.

The carbon emissions of a building in its entire lifecycle are about 29% from the production stage and about 65% from the operational stage, and reducing emissions in the production and operational stages was found to be the most important [6].

In Korea, the carbon emissions in the operational stage are managed in stages through institutionalized measures, such as securing energy performance and the Zero Energy Building Certification, to achieve carbon neutrality targets for each building sector. However, the production stage has not yet been mandated institutionally [7, 8]. In Korea, the carbon emissions in the production stage are evaluated using standardized data of Korea's national LCI DB, which does not reflect the carbon emissions of materials used in actual buildings, and the emissions reduction in the production stage is not being evaluated [9].

Accordingly, this study aimed to derive the Carbon Neutrality Rate (CNR), which is the ratio of emissions reduction in the production stage, as follows. First, a carbon emissions database was created for construction materials with Environmental Product Declaration (EPD products) among construction materials actually produced and installed in Korea. In addition, the reference building was established by establishing a classification system based on region, building use, and structural type. Through this, the emissions reduction and CNR were derived by utilizing Korea's Building LCA evaluation technique and comparing the carbon emissions in the production stage applying Korea's national LCI DB with the carbon emissions in the production stage applying EPD products. Finally, the minimum and maximum CNR values in the production stage were derived according to the carbon emissions of each EPD product, and the major materials were identified from a carbon emissions perspective.

Environmental Labeling

Environmental labeling granted to environmental-friendly products supports consumers in identifying and choosing products with excellent environmental performance and encourages companies to develop and produce environmentally friendly products [10]. The International Organization for Standardization (ISO) has established

Table 2. ISO standards for environmental labeling (ISO14020s)

Standard	Year (yyyy.mm)	Environmental Labeling
ISO 14020	2000.09	Environmental Labels and Declarations (General principle)
ISO 14021	1999.09	Type II (Self environmental claim)
ISO 14024	1999.04	Type I
ISO 14025	2006.07	Type III

international standards for environmental labeling according to ISO 14020s [11]. Type I environmental labels refer to products whose environmental impact has been evaluated by a third-party certification body throughout the entire process, including production, distribution, consumption, and disposal [12]. They were first used by Blue Angel, which was implemented in Germany in 1979 and have been introduced in developed countries like Japan, the United States, and the EU [13]. Type II environmental labels, defined in ISO 14021, refer to products that companies use in green marketing by indicating that their products have secured environmental performance without third-party verification using symbols and phrases. Due to the concern for excessive advertising or false information on environmentally friendly products, the governments of the United States, Canada, Japan, and Europe have established regulatory standards for Type II environmental labeling to prevent false and exaggerated advertising [14]. Type III environmental labels refer to products that companies disclose the overall environmental impact of their products voluntarily [12]. Since its initial introduction by the Scientific Certification System, a private American organization, in 1992, Type III has been implemented in countries like Korea, Sweden, and Japan. The information disclosed is verified by a third party and analyzed through the Life Cycle Assessment (LCA) method, and it is difficult for general consumers to interpret the information and judge environmental friendliness compared to Type I. Therefore, the Global Type III Environmental Product Declarations Network (GEDnet) was founded as an international non-profit organization to promote cooperation and information exchange among parties [10, 15]. The ISO international standards for environmental labeling are shown in Table 2.

Environmental Labeling in South Korea

Environmentally friendly construction materials in Korea are mainly operated by the Korea Environmental Industry & Technology Institute, and they are classified into three levels based on the carbon emissions of each material [16]. Products with Environmental Declaration correspond to level 1 certification, and level 1 is a certification granted to products after quantitatively evaluating the seven environmental impact categories (Carbon Footprint, Ozone Depletion, Resource Footprint, Photochemical Smog, Eutrophication, Acidification, Water Footprint) according to the scenario set for each product based on the collection, production, distribution, use, and disposal of raw materials [17]. Low-carbon products correspond to level 2 certification, which is granted to products that have a carbon footprint lower than the maximum allowable standard for carbon emissions or higher than the minimum carbon emissions rate. The maximum allowable carbon emissions refer to emissions that are

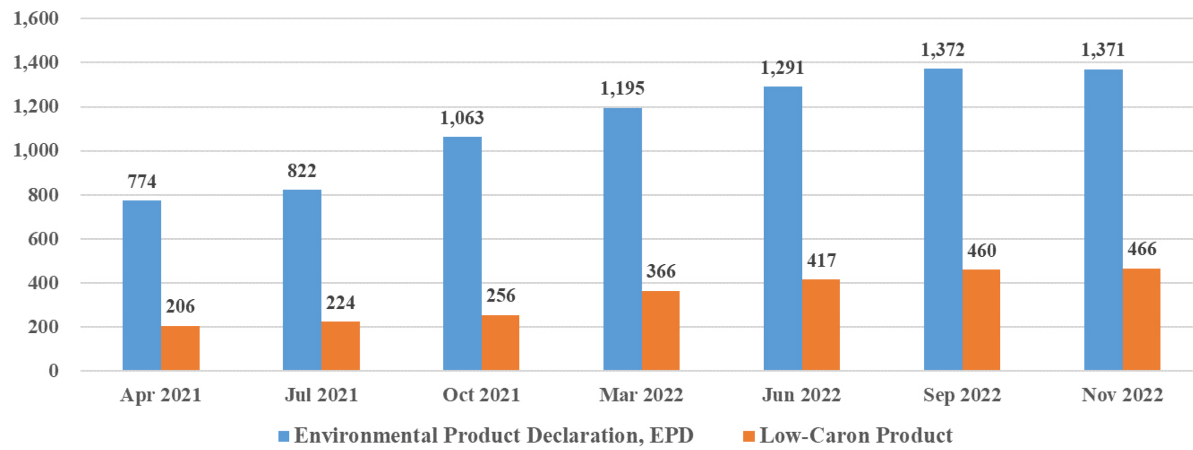

Figure 1. Current status of Environmental Declaration and low-carbon construction materials certified in Korea.

lower than the average carbon emissions of the same product group, and the minimum carbon reduction rate corresponds to a product that has reduced carbon emissions by at least 3.3% compared to the comparison product. Lastly, level 3 certification is granted to products that attained zero carbon emissions in the entire lifecycle through the purchase of carbon credits or other reduction activities [18]. In this study, products with Environmental Declaration and low-carbon products are abbreviated as EPD products and utilized in calculating the CNR in the production stage.

In Korea, with the emphasis on the importance of carbon neutrality in the building sector, construction materials obtaining environmentally friendly certification continue to increase due to the increasing demand for reduced carbon emissions of construction materials [10]. Among construction materials in Korea, the number of products with Environmental Declaration, level 1 certification, has increased by about 1.8 times from 774 in April 2021 to 1,371 in November 2022. The number of low-carbon products with level 2 certification that additionally reduced carbon emissions increased by 2.3 times from 206 in April 2021 to 466 in November 2022 [19]. Figure 1 shows the current status of the Environmental Declaration and low-carbon construction materials recently certified in Korea.

Building LCA

Building Life Cycle Assessment (Building LCA) is a technique for identifying the environmental load generated throughout the lifecycle of products and systems as per ISO 14040s and evaluating, reducing, and improving the environmental impact of the environmental load [20]. The evaluation categories include global warming potential (GWP), abiotic depletion potential (ADP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical oxidant creation potential (POCP), and the Building LCA evaluation scope is classified into the production, construction, operational, and disposal stages [21].

This study utilizes Korea's Building LCA evaluation technique and targets the production stage. Carbon emissions in the production stage are calculated based on the amount of materials used in buildings and the basic

Table 3. Carbon emissions of major materials in Korea's national LCI DB

Major Material	Detail	Unit	Emissions ($kgCO_2$-eq)	Major Material	Detail	Unit	Emissions ($kgCO_2$-eq)
Ready-mixed concrete	18 Mpa	m^3	4.09E+02	Insulation	EPS	kg	1.96E+00
	24 Mpa	m^3	4.14E+02		XPS	kg	3.28E+00
Brick	Concrete brick	kg	1.23E-01	Cement	Cement	ton	1.06E+03
	ALC block	kg	6.57E-01		Cement mortar	kg	4.31E-01
Rebar	-	kg	4.38E-01	Gypsum board	-	ton	1.38E+02

environmental unit of each material [22]. The basic environmental unit of each material includes all the environmental impacts that occur in all processes for producing construction materials used to construct the evaluated building, including the extraction of raw materials, transportation, and manufacturing process. In Korea, the basic environmental unit of each material applied to the current carbon emissions in the production stage is calculated using the standardized data of Korea's national LCI DB [21, 22]. However, as carbon emissions differ among products within the same product group depending on the product characteristics, it is necessary to evaluate the carbon emissions of actual EPD products produced by companies and installed in buildings instead of Korea's standardized national LCI DB.

The amount of materials used in buildings needed to calculate the carbon emissions in the production stage refers to the amount of major construction materials used per unit area (m^2) [23]. Major materials used per unit area (m^2) are construction materials that belong to the top 99% by weight, including ready-mixed concrete, rebar, cement, brick, insulation, glass, and tile [22]. The carbon emissions of major materials in Korea's national LCI DB are as shown in Table 3 [24].

Material and Methodology

Establishing DB of construction materials with Environmental Product Declaration (EPD)

In this study, a database was established for 417 EPD products that acquired level 1 and level 2 carbon emissions certifications to derive carbon reduction and CNR in the production stage. They include 328 EPD products, 89 low-carbon products, 390 ready-mixed concrete, 2 rebars, 4 brick, 11 insulation, 7 cement, and 3 gypsum board [19]. The established DB of EPD products converted weight units according to the Building LCA Guidelines, and the specifications of each product were classified according to the detailed specifications of Korea's national LCI DB [22]. Through this, the amount of carbon reduction, which is the difference between the carbon emissions standardized by Korea's national LCI DB and the carbon emissions of the DB of each EPD product produced by companies and installed in buildings, can be calculated. In addition, the CNR, which is the ratio of carbon reduction in the production stage, can be derived. The list of EPD product DB of major materials established in this study is shown in Table 4.

Table 4. Current status of EPD product DB of major materials (as of September 30, 2022)

Major Materials	Unit	Total	Environmental Declaration	Low Carbon
Ready-mixed concrete	ton	390	306	84
Rebar	ton	2	2	0
Brick	ton	4	4	0
Insulation	ton	11	8	3
Cement	ton	7	7	0
Gypsum board	ton	3	1	2

Table 5. Classification system set to establish reference building

Analyzed Data	Classification System	Details
G-SEED certification cases	Region	· Capital area (Seoul, Gyeonggi, Incheon): 65% of all cases
	Building use	· Residential sector: Apartment houses: 28% of all cases · Non-residential sector: Office facilities: 32% of all cases
Building LCA evaluation cases	Structural type	· Reinforced concrete structures: 75% of all cases

Establishing Reference Building

The classification system set to establish the reference building was classified according to region, building use, and structural type, which can affect carbon emissions in the production stage. The Building LCA in Korea is operated as an additional item in the innovative design field within the G-SEED, and it is commonly performed to obtain G-SEED scores [25]. Accordingly, this study utilized the Building LCA evaluation method of Korea and established a classification system based on G-SEED certification cases and Building LCA evaluation cases. As a result of analyzing G-SEED certification cases according to the classification system, over 65% of all certification cases were located in Seoul, Gyeonggi, and Incheon in the capital area. In terms of building use, apartment houses accounted for about 28% of the residential sector, and office facilities accounted for about 32% of the non-residential sector [26]. Based on the analysis of Building LCA evaluation cases, reinforced concrete structures accounted for about 75% of all structural types [23]. Accordingly, the classification system of this study classified apartment houses and office facilities with reinforced concrete structures in the capital area. The classification system set to establish the reference building is presented in Table 5.

Setting Amount of Major Materials Per Unit Area

According to the Building LCA Guidelines in Korea, carbon emissions in the production stage are calculated using the amount of materials used in buildings and the basic environmental unit of each material [22]. Since the amount of materials used in buildings can vary largely according to the characteristics and design techniques of each project, a standard amount needs to be set [23]. In this study, the input amount of major materials was set by utilizing existing studies that derived the standard amount of major materials [27]. According to the literature, there

Table 6. Standard quantities of major construction materials per unit area for RC-structured apartment houses

Standard quantities per unit area (kg/m^2)			
Major construction materials	Apartment houses RC	Major construction materials	Apartment houses RC
Ready-mixed concrete	2,184.72	Cement	50.88
Rebar	63.64	Stone	2.43
Section steel	0.00	Aggregate	43.46
Glass	8.22	Wood	1.36
Brick	88.49	Paint	2.77
Insulation	2.22	Iron	0.50
Gypsum board	7.75	Tile	7.13

are 14 major materials, including ready-mixed concrete, rebar, brick, insulation, and cement. The weight (kg) per unit area (m^2) was derived for major materials in the construction sector, and the standard amount was set for materials that are in the top 99% by weight according to Korea's Building LCA Guidelines. The standard quantities of major construction materials per unit area for RC-structured apartment houses taken from the literature in this study are shown in Table 6 [28].

Deriving Formula for Carbon Neutrality Rate in Production Stage

Carbon reduction in the production stage proposed in this study refers to the difference between carbon emissions in Korea's national LCI DB and carbon emissions of the EPD product DB performed according to Korea's Building LCA Guidelines. CNR in the production stage refers to the ratio of carbon reduction to carbon emissions of Korea's national LCI DB. Carbon reduction in the production stage proposed in this study is calculated as Eq. (1), and CNR in the production stage is as Eq. (2).

$$\text{Amount of Carbon Reduction } (kgCO_2\text{-}eq/m^2) = CE_{LCI\ DB} - CE_{EPD\ DB} \tag{1}$$

$CE_{LCI\ DB}$: Carbon emissions in the production stage through Korea's national LCI DB ($kgCO_2$-eq/m^2)

$CE_{EPD\ DB}$: Carbon emissions in the production stage through Korea's EPD product DB ($kgCO_2$-eq/m^2)

$${}_{A1\text{-}A3}CNR(\%) = \Sigma(CE_{LCI\ DB} - CE_{EPD\ DB}) \div CE_{LCI\ DB} \times 100 \tag{2}$$

${}_{A1\text{-}A3}CNR$: Carbon neutrality rate in the production stage (A1-A3) (%)

$CE_{LCI\ DB}$: Carbon emissions in the production stage through Korea's national LCI DB ($kgCO_2$-eq/m^2)

$CE_{EPD\ DB}$: Carbon emissions in the production stage through Korea's EPD product DB ($kgCO_2$-eq/m^2)

Result and Discussions

Deriving Carbon Neutrality Rate in Production Stage for Apartment Houses

As carbon emissions of EPD products differ according to producing companies and product characteristics, CNR in the production stage was comparatively analyzed through the minimum, average, and maximum values. CNR in the production stage was derived by classifying apartment houses and office facilities of the RC structure in the capital area according to the classification.

Production stage carbon emissions of apartment houses based on Korea's national LCI DB were 4.76E+02 ($kgCO_2$-eq/m^2), and the EPD product group with the lowest carbon emissions was 1.65E+02 ($kgCO_2$-eq/m^2). Carbon emissions can be reduced by 3.15E+02 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 65.43%. Carbon emissions of the EPD product group with the average emissions were 2.95E+02 ($kgCO_2$-eq/m^2), reduced by 1.81E+02 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 38.02%. Carbon emissions of the EPD product group with the highest carbon emissions were 4.34E+02 ($kgCO_2$-eq/m^2), reduced by 4.28E+01 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 8.99%.

As a result of comparing the minimum and maximum carbon emissions among EPD products, carbon emissions ranged from the minimum of 4.28E+01 ($kgCO_2$-eq/m^2) to the maximum of 3.12E+02 ($kgCO_2$-eq/m^2). Applying any EPD product resulted in a reduction in carbon emissions compared to the results of Korea's national LCI DB evaluation carried out in Korea's Building LCA.

However, the carbon emissions of EPD products were higher than the carbon emissions of Korea's national LCI DB in the case of rebar. Concrete brick, extruded insulation, and sand were included in major materials, but there

Table 7. Analysis of carbon reduction and CNR in production stage of apartment houses according to application of EPD products (Unit: $kgCO_2$-eq/m^2)

Division			Carbon Emissions of Reference Building Through National LCI DB (ⓐ)	Minimum Carbon Emissions of EPD DB	Average Carbon Emissions of EPD DB	Maximum Carbon Emissions of EPD DB
Production stage	Carbon emissions (ⓑ)	Major construction materials	4.76E+02	1.65E+02	2.95E+02	4.34E+02
		Ready-mixed concrete	3.93E+02	9.58E+01	2.25E+02	3.60E+02
	Carbon reduction (ⓒ=ⓐ-ⓑ)	Major construction materials	-	3.12E+02	1.81E+02	4.28E+01
		Ready-mixed concrete	-	2.97E+02	1.68E+02	3.26E+01
	Carbon neutrality rate (ⓒ/ⓐ×100)	Major construction materials	-	65.43%	38.02%	8.99%
		Ready-mixed concrete	-	62.86%	35.59%	6.82%

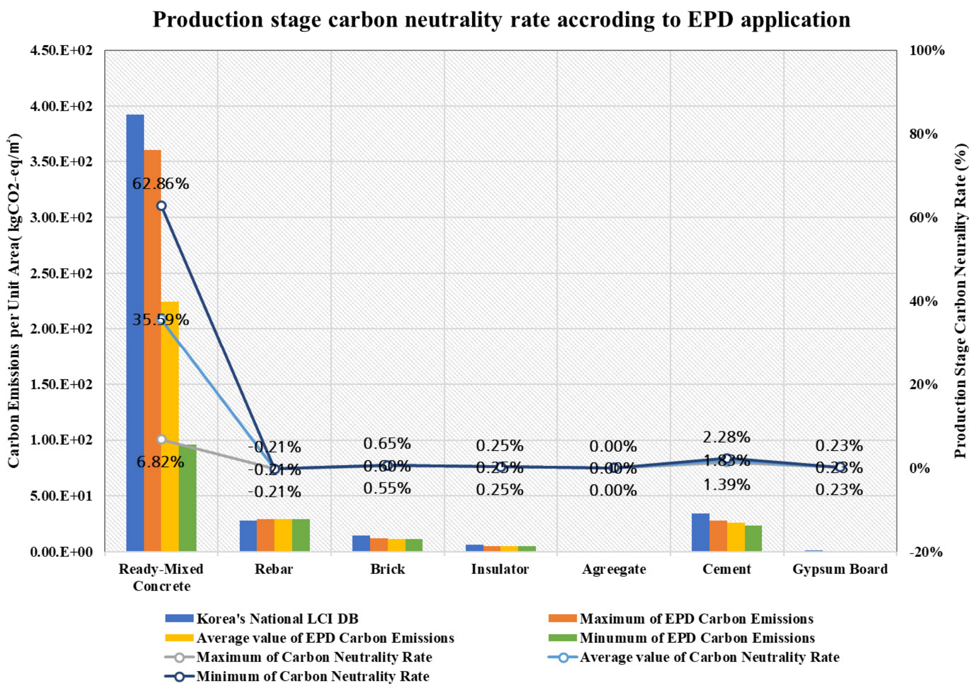

Figure 2. Carbon neutrality rate in production stage according to application of EPD (apartment houses).

were no environmental label products that corresponded to EDP products [19]. Therefore, the diversification of EPD products is necessary, in which case additional CNR can be secured in the building sector. The results of deriving CNR of apartment houses and graphs are shown in Table 7 and Figure 2.

Deriving Carbon Neutrality Rate in Production Stage of Office Facilities

Carbon reduction and CNR of office facilities in the production stage were derived through the minimum, average, and maximum carbon emissions of EPD products, as done for apartment houses.

Production stage carbon emissions of office facilities based on Korea's national LCI DB were 4.72E+02 ($kgCO_2$-eq/m^2), and the EPD product group with the lowest carbon emissions was 1.45E+02 ($kgCO_2$-eq/m^2). Carbon emissions can be reduced by 3.27E+02 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 69.22%. Carbon emissions of the EPD product group with the average emissions were 3.18E+02 ($kgCO_2$-eq/m^2), reduced by 1.54E+02 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 32.69%. Carbon emissions of the EPD product group with the highest carbon emissions were 4.35E+02 ($kgCO_2$-eq/m^2), reduced by 3.70E+01 ($kgCO_2$-eq) per unit area (m^2), and CNR in the production stage was found to be 7.83%.

As a result of comparing the minimum and maximum carbon emissions among EPD products, carbon emissions ranged from the minimum of 3.70E+01 ($kgCO_2$-eq/m^2) to the maximum of 3.27E+02 ($kgCO_2$-eq/m^2). Applying any EPD product resulted in a reduction in carbon emissions compared to the results of Korea's national LCI DB evaluation carried out in Korea's Building LCA.

However, the carbon emissions of EPD products were higher than the carbon emissions of Korea's national LCI DB in the case of rebar. Concrete brick, sand, gravel, and granite were included in major materials, but there were

Table 8. Analysis of carbon reduction and CNR in production stage of office facilities according to application of EPD products (Unit: $kgCO_2\text{-}eq/m^2$)

Division			Carbon Emissions of Reference Building Through National LCI DB (ⓐ)	Minimum Carbon Emissions of EPD DB	Average Carbon Emissions of EPD DB	Maximum Carbon Emissions of EPD DB
Production stage	Carbon emissions (ⓑ)	Major construction materials	4.72E+02	1.45E+02	3.18E+02	4.35E+02
		Ready-mixed concrete	3.86E+02	6.90E+01	2.43E+02	3.56E+02
	Carbon reduction (ⓒ=ⓐ-ⓑ)	Major construction materials	-	3.27E+02	1.54E+02	3.70E+01
		Ready-mixed concrete	-	3.17E+02	1.43E+02	2.93E+01
	Carbon neutrality rate (ⓒ/ⓐ×100)	Major construction materials	-	69.22%	32.69%	7.83%
		Ready-mixed concrete	-	67.13%	30.35%	6.29%

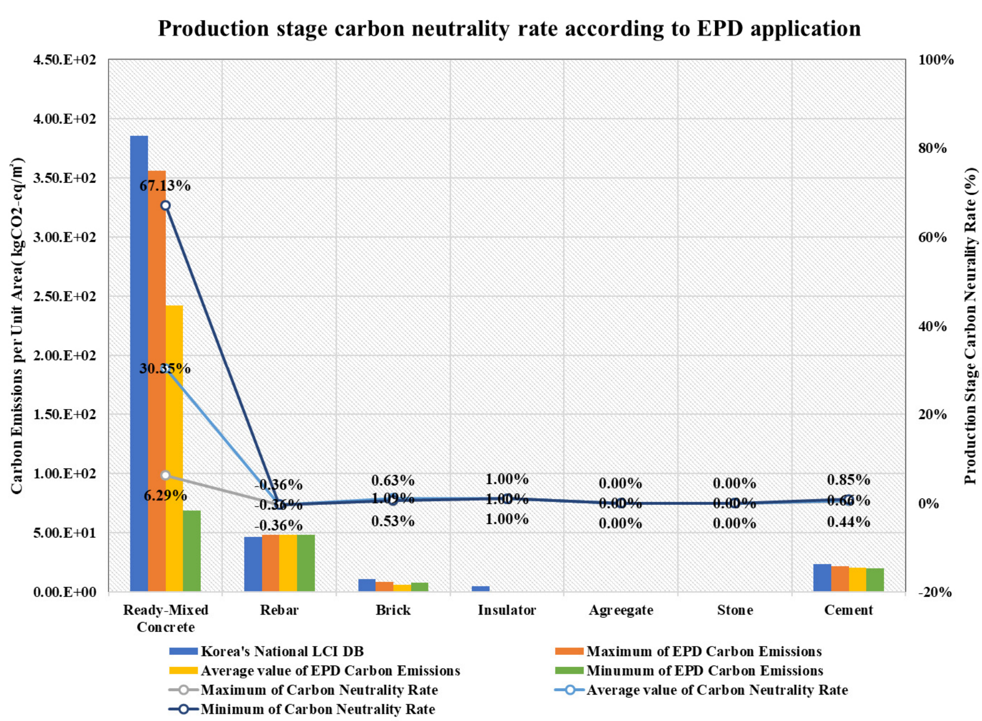

Figure 3. Carbon neutrality rate in production stage according to application of EPD products (office facilities).

no environmental label products that corresponded to EDP products [19]. Therefore, the diversification of EPD products is necessary, in which case additional CNR can be secured in the building sector. The results of deriving CNR of office facilities and graphs are shown in Table 8 and Figure 3.

Deriving Major Carbon Emission Materials

Products with the top 99% cumulative carbon emissions in the production stage were selected to derive major materials based on carbon emissions in the production stage. Major materials corresponding to the top 99% of cumulative carbon emissions in the production stage were ready-mixed concrete, rebar, cement, and brick, both for apartment houses and office facilities. Insulation, aggregate, stone, and gypsum board correspond to the top 99% cumulative weight contribution and are classified as major materials, but they are excluded from major materials from a carbon emissions perspective because the amount of materials used is small and the basic environmental unit is not high.

Ready-mixed concrete was found to be the first major material, accounting for 70% or more of carbon emissions in the production stage, as its amount in weight was over 80% of all major materials. Rebar was the second major material, and their contribution to carbon emissions in the production stage was about 10% in apartment houses and about 17% in office facilities. Cement was the third major material, and contribution was about 9% in apartment houses and about 7% in office facilities. Lastly, brick showed a carbon emissions contribution of about 4% in apartment houses and about 3% in office facilities.

As a result of analyzing carbon reduction and CNR of EPD products of ready-mixed concrete, rebar, cement, and brick with a cumulative contribution of 99% or above through the minimum, average, and maximum carbon emissions, the carbon reduction per unit area was from 3.00E+01 ($kgCO_2$-eq/m^2) to 2.97E+02 ($kgCO_2$-eq/m^2) and the CNR was from 6.21% to 67.16% for ready-mixed concrete. Ready-mixed concrete accounted for 76.95% to 96.94% of carbon emissions in the production stage shown by all major materials and was found to be the material most important for reducing carbon emissions in the production stage.

As of September 30, 2022, the product of Company H is the only rebar product. The carbon emissions of the EPD product were slightly higher than those of Korea's national LCI DB. The carbon emissions increased by 1 ($kgCO_2$-eq/m^2) by applying the EPD product. Since rebars are used in large amounts and have a high basic environmental unit, they account for over 10% of carbon emissions in the production stage, and it is necessary to diversify EPD products with low carbon emissions to contribute to carbon reduction in the production stage.

In the case of cement, the carbon reduction was from 2.13E+00 ($kgCO_2$-eq/m^2) to 1.08E+01 ($kgCO_2$-eq/m^2), and the CNR was from 0.45% to 2.25%. Although cement accounts for over 7% of total carbon emissions in the production stage, there are only seven EPD products. Accordingly, EPD products must be invigorated to contribute to carbon reduction in the production stage and secure additional CNR.

In the case of brick, there was no EPD product for concrete brick with large input amounts as of September 30, 2022, and carbon reduction was evaluated for ALC blocks. For ALC blocks, the carbon reduction was from 2.51E+00 ($kgCO_2$-eq/m^2) to 3.06E+00 ($kgCO_2$-eq/m^2), and the CNR was from 0.53% to 0.59%. Although concrete brick accounts for over 3% of all carbon emissions in the production stage, there are no EPD products. Accordingly, EPD products must be invigorated to contribute to carbon reduction in the production stage and secure additional CNR. The results of analyzing cumulative carbon emissions contribution are shown in Table 9.

Table 9. Carbon reduction and carbon neutrality rate in production stage of major materials with top 99% cumulative carbon emissions (Unit: $kgCO_2$-eq/m^2)

Use	Major Material	Cumulative Carbon Emissions Contribution	EPD Product Carbon Emissions Minimum		EPD Product Carbon Emissions Average		EPD Product Carbon Emissions Maximum	
			Carbon Reduction	CNR in Production Stage	Carbon Reduction	CNR in Production Stage	Carbon Reduction	CNR in Production Stage
Apartment houses	Ready-mixed concrete	74.98%	2.97E+02	62.27%	1.68E+02	35.35%	3.25E+01	6.83%
	Rebar	10.48%	-1.00E+00	-0.21%	-1.00E+00	-0.21%	-1.00E+00	-0.21%
	Cement	9.00%	1.08E+01	2.25%	8.62E+00	1.81%	6.50E+00	1.36%
	Brick	4.59%	3.06E+00	0.64%	2.85E+00	0.60%	2.58E+00	0.54%
	Total	99.08%	3.10E+02	64.95%	1.78E+02	37.55%	4.06E+01	8.52%
Office facilities	Ready-mixed concrete	71.70%	3.17E+02	67.10%	1.43E+02	30.31%	3.00E+01	6.21%
	Rebar	17.36%	-1.70E+00	-0.36%	-1.70E+00	-0.36%	-1.70E+00	-0.36%
	Cement	7.53%	4.00E+00	0.84%	3.05E+00	0.65%	2.13E+00	0.45%
	Brick	3.12%	2.98E+00	0.63%	2.78E+00	0.59%	2.51E+00	3.84%
	Total	99.71%	3.22E+02	68.21%	1.47E+02	31.19%	3.29E+01	10.14%

Korea's 2030 carbon emission reduction target in the building sector is 32.8% from 52.1 million tons in 2018, which requires a reduction of about 17 million tons. The maximum carbon reduction of major construction materials in the production stage was 3.10E+02 ($kgCO_2$-eq/m^2) for apartment houses and 3.22E+02 ($kgCO_2$-eq/m^2) for business facilities. In order to achieve the carbon emission reduction target in the building sector, it is considered that additional carbon reduction efforts are required for the life cycle of buildings as well as the use of EPD products in the production stage [29, 30].

Conclusions

The purpose of this study was to derive the carbon neutrality rate in the production stage during the lifecycle of buildings, and the following conclusions were drawn.

1. The production stage carbon reduction proposed in this study refers to the difference between the production stage carbon emissions based on Korea's standardized national LCI DB and the production stage carbon emissions from actual environmentally friendly construction materials (EPD products). In addition, the CNR in the production stage proposed in this study refers to the ratio of carbon reduction to the production stage carbon emissions based on Korea's standardized national LCI DB.
2. An EPD product DB was established for 417 cases of eight major construction materials to evaluate carbon reduction in the production stage. All EPD products of the established DB are actual products produced by

companies. The carbon emissions of each product were included, and the DB was established by weight units according to Korea's Building LCA Guidelines.

3. A reference building was established for apartment houses and office facilities according to the classification system to evaluate the production stage carbon emissions, and the production stage carbon emissions were derived.
4. The production stage carbon reduction and CNR were derived by classifying carbon emissions into the minimum, average, and maximum values for each product based on the EPD product DB. As a result, the production stage carbon reduction was from 4.28E+01 ($kgCO_2$-eq/m^2) to 3.12E+02 ($kgCO_2$-eq/m^2) for apartment houses, and the production stage CNR was from 8.99% to 65.43%. In the case of office facilities, the production stage carbon reduction was from 3.70E+01 ($kgCO_2$-eq/m^2) to 3.27E+02 ($kgCO_2$-eq/m^2), and the production stage CNR was from 7.83% to 69.22%.
5. As a result of deriving major construction materials with the top 99% cumulative carbon emissions contribution, major materials in terms of carbon emissions were ready-mixed concrete, rebar, cement, and brick for both apartment houses and office facilities.

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021R1A2C2095630).

References

[1] J. Rogelj, M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen, *Paris Agreement climate proposals need a boost to keep warming well below 2 ℃*. Nature. 534 (2016), pp. 631-639.

[2] The Energy Information Administration (EIA), *Annual Energy Outlook—Fossil Fuels Remain Dominant Through 2040*, EIA: Washington, DC, USA, 2014.

[3] Korea Energy Agency, *2020 Energy Policy Reports of Major Countries*. 2020.

[4] Ministry of Land, Infrastructure and Transport (MOLIT), *Korean New Deal*. 2020.

[5] Ministry of Environment (ME), *National Greenhouse Gas Reduction Target Discussion*. 2050 Carbon Neutrality Promotion Committee. 2021 .

[6] Bank of Korea, *Industry Association Analysis Commentary*. 2014.

[7] H.J. Lim and S.H. Tae, *Analysis of the environmental impact emissions for the office building based on analysis of major building materials of life cycle assessment of G-SEED*. International Journal of Sustainable Building Technology and Urban Development (IJSTUD). 9 (2018), pp. 170-182.

[8] Ministry of Land, Infrastructure and Transport (MOLIT), *Building Energy Efficiency Rating Certification and Zero Energy Building Certification Criteria*. Ministry of Government Legislation: Sejong, Korea, 2020.

[9] S.K. Ha, S.H. Tae, and R.H. Kim, *A Study on the Limitations of South Korea's National Roadmap for Greenhouse Gas Reduction by 2030 and Suggestions for Improvement*. Sustainability. 11 (2019), 3969.

[10] S.W. Lee, S.H. Tae, S.J. Roh, and T.H. Kim, *Green Template for Life Cycle Assessment of Buildings Based on*

Building Information Modeling: Focus on Embodied Environmental Impact. Sustainability. 7(12) (2015), pp. 16498-16512.

[11] S.J. Wang, S.H. Tae, and R.H. Kim, *Development of a Green Building Materials Integrated Platform Based on Materials and Resources in G-SEED in South Korea*. Sustainability. 11 (2019), 6532.

[12] M. Nikolay, B. Vanessa, and F.Matthias, *Characterization of the Cradle to Cradle Certified. Products Program in the Context of Eco-labels and Environmental Declarations*. Sustainability. 10 (2018), 738.

[13] N. Minkov, A. Lehmann, L. Winter, and M. Finkbeiner, *Characterization of environmental labels beyond the criteria of ISO 14020-series*. Int. J. Life Cycle Assess. 24 (2019), pp. 1-16.

[14] International Organization for Standardization (ISO), *Environmental Labels and Declarations-General Principles (ISO 14020:2000)*, ISO: Geneva, Switzerland, 2000.

[15] International Organization for Standardization (ISO). *Environmental Labels and Declarations-Type I Environmental Labelling-Principles and Procedures (ISO 14024:1999)*, ISO: Geneva, Switzerland, 1999.

[16] N.R. Lee, *A Study on the Improvement Plan of Type II Environmental Labelling*. Master's Thesis, Sejong University, Seoul, Korea, 2017.

[17] Korea Environmental Industry and Technology Institute (KEITI), *Characterization Factors by Impact Category*. In Environmental Labelling Certification Guide; Ministry of Environment: Sejong, Korea, 2019, Volume 1, pp. 1-188.

[18] Korea Environmental Industry and Technology Institute (KEITI), Environmental Product Declaration [Online], 2022. Available at: http://www.greenproduct.go.kr [Accessed 30/01/2023].

[19] Korea Environmental Industry and Technology Institute (KEITI), Low Carbon Products [Online], 2022. Available at: https://www.pps.go.kr [Accessed 30/01/2023].

[20] Korea Environmental Industry and Technology Institute (KEITI), Environmental Product Declaration [Online], 2022. Available at: https://www.greenproduct.go.kr/epd/carbon/productStatusList.do?bbsCode=18 [Accessed 01/2023].

[21] S.J. Roh, S.H. Tae, S.J. Suk, and G. Ford, *Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea*. Renewable and Sustainable Energy. 73 (2017), pp. 135-144.

[22] Korea Institute of Civil Engineering and Building Technology (KICT), *G-SEED Criteria Commentary 2016-6.* 2021.

[23] Korea Institute of Civil Engineering and Building Technology (KICT), *Building Life Cycle Assessment Guidelines*. 2017.

[24] H.J. Jang, *A study of the green building certification system to achieve the carbon neutral goal in the building sector*. Ph.D. Thesis, Hanyang University, 2022.

[25] Korea Environmental Industry and Technology Institute (KEITI), Korea National LCI DB [Online], 2022. Available at: https://www.greenproduct.go.kr/epd/lci/lciDb.do [Accessed 01/2023].

[26] Ministry of Land, Infrastructure and Transport (MOLIT), *Green Building Certification Criteria.* Ministry of Government Legislation: Sejong, Korea, 2016, Article 3.

[27] Korea Institute of Civil Engineering and Building Technology (KICT), G-SEED Certification Status [Online], 2022. Available at: http://www.gseed.or.kr/greenCerti.do [Accessed 01/2023].

[28] H.S. Kim, *Proposal of a methodology for evaluating the Life Cycle Assessment using the standard quantity of building materials based on probabilistic analysis techniques*. M. Thesis, Hanyang University, 2022.

[29] S.W. Lee, S.H. Tae, S.K. Ha, and Y.J. Bok, *The greenhouse gas evaluation methodology based on building energy cases*. International Journal of Sustainable Building Technology and Urban Development (IJSTUD) 11 (2020), pp. 78-93.

[30] Z. Oliveira, V. David, S. Serra, and D. Barreto, *Decision making process assisted by life cycle assessment: greenhouse gas emission*. International Journal of Sustainable Building Technology and Urban Development (IJSTUD), 8 (2017), pp. 244-252.