Study on Worldwide Embodied Impacts of Construction: Analysis of WIOD Release 2016

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Abstract: Net-zero-energy buildings (ZEBs) that contribute to making annual energy consumption balances zero are effective measures for reducing greenhouse gas (GHG) emissions in the construction sector. As the application of ZEBs progresses, GHG emissions during the construction of buildings and the manufacturing of materials and products (called construction EG) account for a relatively large proportion of overall emissions. This study aimed to clarify construction EG as a means by which to formulate policies for the reduction of emissions in each country. The construction EGs of 43 countries from 2011 were analyzed. The 56-sector input/output table and CO2 emission data of the 2016 World Input/Output Database, published by the EU, were both used in this analysis. It was found that the construction sector accounted for the highest proportion of total CO2 emissions. Moreover, the fraction of construction EG tended to be higher in developing countries such as China and India, while developed countries tended to contribute a lower fraction of construction EG. Construction EGs were shown to be heavily influenced by the sectors that manufacture “cement”, “steel bars and steel frames”, and “energy sources”. Thus, it is very important to advance technological developments to reduce CO2 emissions within these sectors. The annual variation of construction EGs and CO2 emissions from 2000 to 2014 showed that the construction EGs and total CO2 emissions in developing countries were increasing, whereas emissions from developed countries have been decreasing slightly.

Keywords: input/output analysis; World Input/Output Database; embodied GHG emissions; construction EGs; developing countries; cement

1. Introduction

1.1. Background

It is known that greenhouse gas (GHG) emissions have been a cause of global warming in recent years. At the 21st Conference of the Parties in the United Nations Framework Convention on Climate Change in 2015, the Paris Agreement was adopted, which stipulates a framework for efforts to reduce greenhouse gas emissions beyond 2020. The Paris Agreement stipulates that its goal is to limit the increase in global average temperature to 2.0 °C or less—preferably to 1.5 °C—compared to preindustrial levels. In order to promote global warming countermeasures in each country, it is important to promote efforts to continuously reduce GHGs [1].

With an annual balance of primary energy consumption of zero, ZEBs (net-zero-energy buildings) and ZEHs (net-zero-energy houses) are effective measures in the construction sector. When ZEBs and ZEHs are achieved in the future, energy consumption and greenhouse gas emissions during building construction and the manufacturing of materials and products will account for a relatively large proportion of overall emissions. Energy consumption and GHG emissions during the construction of buildings and the manufacture of materials and products are known as embodied energy (EE) and embodied
GHG emissions (EGs), respectively, and both are collectively called the embodied impact or EEGs [2].

In order to promote EEG reduction, it is important for each country to formulate measures that are considered to be effective.

The purpose of this study was to analyze the EGs related to construction (hereafter referred to as “construction EGs”) in various countries and to clarify their components of construction EG and the differences between countries. The results of this research should provide valuable resources for effective measures to reduce construction EG for policymakers and engineers. For this analysis, the 2016 release of the World Input/Output Database (hereafter referred to as “WIOD (2016)”) published by the European Union (EU) was used [3]. The WIOD (2016) is suitable for a comparison of countries because the input/output (IO) tables for 43 countries in 56 sectors are created with the same specifications.

Prior to its most recent iteration, the World Input-Output Database 2013 Release (WIOD (2013)) was published. WIOD (2013) provides IO tables for 40 countries in 35 sectors. An analysis using the WIOD (2013) was conducted by Yokoyama [4] in Japanese. However, an analysis using the WIOD (2016), which includes increased number of sectors, as well as target countries, allows for a more precise analysis. Moreover, as the WIOD (2016) provides IO tables from 2000 to 2014, the latest trends can be understood.

1.2. Embodied Impact

The research on EEG was conducted by Annex 57, one of the research projects in the “EBC” (Energy in Buildings and Communities) of the IEA (International Energy Agency) [5].

In Annex 57, primary energy consumption intensity is classified as follows according to the type of energy source [2]:
1. Pef: Primary energy from fossil fuels only;
2. Penr: Primary energy from fossil fuels and nuclear power;
3. Pet: Total primary energy from fossil fuels, nuclear power, and renewable energy.

In addition, four types of EEG boundaries are defined, as shown in Figure 1; A1 to C4 are called “Cradle-to-Grave”, A1 to A3 are called “Cradle-to-Gate”, A1 to A4 are called “Cradle-to-Site”, and A1 to A5 are called “Cradle-to-Handover”.

![Figure 1. Proposed model for system boundaries [2].](image-url)
1.3. Previous Research Using WIOD

Several studies on environmental load using the WIOD have been conducted. Cruz et al. [6] assessed the economy–ecology–environment interactions and CO2 emissions for EU countries. Zhang et al. [7] also analyzed the CO2 and energy flows associated with trade in BRICS countries. As a result, it was found that the amount of CO2 transferred to countries other than those in BRICS was large. In addition, it has been shown that China has a large impact on the world due to its sizeable economy. Jiborn et al. [8] used the WIOD (2016) to compare production-based, consumption-based, and technology-adjusted CO2 emissions for 44 countries and country groups from 2000 to 2014. The results showed that emissions were declining on a production and consumption basis in 20 European Union (EU) countries and the United States (US). The significant increase in global emissions that occurred during this period was due to increased consumption in China and developing countries. In addition, Fan et al. [9] used the WIOD (2013) to compare consumption-based (CBA) and production-based (PBA) CO2 emissions in 14 countries. As a result, it was shown that countries could be classified into four categories according to the difference in the ratio of CBA to PBA emissions. It was also confirmed that CBA CO2 emissions have a positive correlation with gross domestic product (GDP) per capita.

These studies were for all industries. There were not many studies focusing on the construction sector, except for the following.

Zhang et al. [10] used the WIOD (2013) to study of the global impact of the construction sector by means of a hypothetical extraction method (HEM), and they evaluated the impact of backward and forward CO2 emission linkages in the construction sector. On the other hand, Yokoyama [4] used the WIOD (2013) to analyze the construction EGs of each country. In this study, CO2 emission intensity was calculated for 35 sectors in 40 countries, and the construction EGs of each country and the composition of each sector’s input to construction were analyzed. The fraction of construction EG was found to be large in developing countries such as China and India, but small in developed countries. In addition, the annual change in construction EGs from 1995 to 2009 showed that the growth in developing countries was large, while that in developed countries was small.

In our study, construction EGs were analyzed using the latest version of the WIOD (2016) instead of the 2013 version described above.

2. Materials and Methods

2.1. Overview of the WIOD (2016)

The WIOD (2016) consists of the world IO table (WIOT), which is a collection of IO tables for all countries, IO tables for each country (national IO tables (NIOTs)), and environmental accounts [11].

Figure 2 shows the framework of the NIOTs. In NIOTs, items are divided into domestic and imported products, and prices are shown in USD. A conversion table with the local currency is provided for the list price.

The WIOD (2016) offers NIOTs of 56 sectors in 43 countries from 2000 to 2014. Table 1 shows the names of the 56 sectors in the NIOTs. In the figures that follow, sector names are represented by the numbers shown in Table 1.
Figure 2. National input/output (IO) table (NIOT) framework.

Table 1. List of sectors [3].

| No. | Item | Sectors |
|-----|------|---------|
| 1   | A01  | Crop and animal production, hunting and related service activities |
| 2   | A02  | Forestry and logging |
| 3   | A03  | Fishing and aquaculture |
| 4   | B    | Mining and quarrying |
| 5   | C10–C12 | Manufacture of food products, beverages and tobacco products |
| 6   | C13–C15 | Manufacture of textiles, wearing apparel and leather products |
| 7   | C16  | Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials |
| 8   | C17  | Manufacture of paper and paper products |
| 9   | C18  | Printing and reproduction of recorded media |
| 10  | C19  | Manufacture of coke and refined petroleum products |
| 11  | C20  | Manufacture of chemicals and chemical products |
| 12  | C21  | Manufacture of basic pharmaceutical products and pharmaceutical preparations |
| 13  | C22  | Manufacture of rubber and plastic products |
| 14  | C23  | Manufacture of other non-metallic mineral products |
| 15  | C24  | Manufacture of basic metals |
| 16  | C25  | Manufacture of fabricated metal products, except machinery and equipment |
| 17  | C26  | Manufacture of computer, electronic and optical products |
| 18  | C27  | Manufacture of electrical equipment |
| 19  | C28  | Manufacture of machinery and equipment n.e.c. |
| 20  | C29  | Manufacture of motor vehicles, trailers and semi-trailers |
| 21  | C30  | Manufacture of other transport equipment |
| 22  | C31–C32 | Manufacture of furniture; other manufacturing |
| 23  | C33  | Repair and installation of machinery and equipment |
| 24  | D35  | Electricity, gas, steam and air conditioning supply |
| 25  | E36  | Water collection, treatment and supply |
| 26  | E37–E39 | Sewage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services |
| 27  | F    | Construction |
| 28  | G45  | Wholesale and retail trade and repair of motor vehicles and motorcycles |
| 29  | G46  | Wholesale trade, except of motor vehicles and motorcycles |
2.2. Overview of Target Countries

Table 2 shows gross national income (GNI) per capita according to the World Bank [12,13] and energy-derived CO2 emissions according to the International Energy Agency (IEA) [14] for the 43 countries. The total energy-derived CO2 emissions of the 43 countries analyzed account for approximately 80% of the world’s total emissions.

Table 2. List of countries, along with their gross national income (GNI) [12,13] and CO2 emissions [14] (2011).

| No. | Country Code | GNI (Billion USD) | GNI Per Capita (USD) | CO2 Emission \((\times10^6 \text{ t-CO}_2)\) | Ratio (%) |
|-----|--------------|------------------|----------------------|---------------------------------|-----------|
| 1   | CHN          | 7481.12          | 5565.77              | 8570.93                         | 27.3      |
| 2   | USA          | 15,832.21        | 50,816.43            | 5128.18                         | 16.3      |
| 3   | IND          | 1807.02          | 1445.28              | 1607.95                         | 5.1       |
| 4   | RUS          | 1985.53          | 13,888.60            | 1607.95                         | 5.1       |
| 5   | JPN          | 6331.88          | 49,532.44            | 1183.49                         | 3.8       |
| 6   | DEU          | 3840.29          | 47,839.23            | 731.22                          | 2.3       |
| 7   | KOR          | 1260.98          | 25,251.61            | 573.76                          | 1.8       |
| 8   | CAN          | 1161.74          | 51,223.17            | 541.16                          | 1.7       |
| 9   | MEX          | 2669.89          | 42,205.76            | 439.18                          | 1.4       |
| 10  | GBR          | 2548.97          | 12,905.24            | 391.09                          | 1.2       |
| 11  | BRA          | 868.24           | 3542.15              | 390.32                          | 1.2       |
2.3. Calculation of CO2 Emission Intensities

2.3.1. Summary of Calculation

The intensities of CO2 emissions were calculated using the NIOTs and environmental accounts from the WIOD (2016).

2.3.2. Calculation of CO2 Emission Intensities

As shown in Figure 2, the NIOTs distinguished between domestic products and imported products. Since this analysis targeted domestic CO2 emissions in each country and did not consider overseas spillover effects, the IO tables of domestic goods were used for this analysis. The calculation procedure according to Yokoyama [4] is described below.

The input coefficient $a_{ij}^d$ for domestic goods is expressed by the following equation [15]:

$$a_{ij}^d = \frac{x_{ij}^d}{X_i},$$

where $X_{ij}^d$ is the domestic product from sector $j$ to sector $i$ (million USD/year), $X_i$ is the gross domestic product (total output) (million USD/year), and $i$ (row) and $j$ (column) are sector numbers.

### Table 1: CO2 Emission Intensities (million ton per million USD/year)

| Country | $x_{ij}^d$ | $X_i$ | $a_{ij}^d$ |
|---------|-------------|-------|-------------|
| ITA | 2286.19 | 38,501.44 | 0.12 |
| AUS | 1340.59 | 60,008.33 | 0.12 |
| FRA | 2937.48 | 44,954.91 | 0.13 |
| POL | 511.68 | 13,442.95 | 0.12 |
| TUR | 825.27 | 11,236.81 | 0.09 |
| ESP | 1452.68 | 31,078.16 | 0.08 |
| TWN | - | - | - |
| NLD | 916.73 | 54,917.08 | 0.05 |
| CZE | 210.69 | 20,072.81 | 0.03 |
| BEL | 523.48 | 47,424.28 | 0.03 |
| GRC | 279.94 | 25,208.71 | 0.03 |
| ROU | 181.11 | 8989.08 | 0.03 |
| AUT | 432.57 | 51,548.18 | 0.03 |
| FIN | 276.30 | 51,277.56 | 0.03 |
| BGR | 351.26 | 60,008.33 | 0.02 |
| PRT | 240.83 | 22,811.21 | 0.02 |
| HUN | 134.32 | 13,442.95 | 0.02 |
| SWE | 584.48 | 61,855.31 | 0.02 |
| DNK | 351.26 | 63,055.84 | 0.02 |
| CHE | 707.65 | 89,435.44 | 0.02 |
| NOR | 503.52 | 101,657.40 | 0.02 |
| IRL | 192.53 | 42,036.42 | 0.02 |
| SVK | 95.59 | 17,706.25 | 0.02 |
| HRV | 60.31 | 14,089.97 | 0.02 |
| EST | 22.21 | 16,732.11 | 0.01 |
| SVN | 50.82 | 24,754.46 | 0.01 |
| LTU | 42.19 | 13,933.23 | 0.01 |
| LUX | 41.43 | 79,927.99 | 0.01 |
| LVA | 28.46 | 13,818.00 | 0.01 |
| CYP | 28.29 | 25,151.79 | 0.01 |
| MLT | 9.21 | 79,927.99 | 0.01 |

Other countries | 6406.16 | 20.4
All of the world | 31,392.58 | 100.0

USD represents current prices in United States (US) dollars.
The gross domestic product vector $X$ is expressed by the following equation [15]:

$$X = A^d X + (F^d + F^e),$$  \hspace{1cm} (2)

Solving Equation (2) for $X$ gives the following equation [15]:

$$X = (I - A^d)^{-1} 	imes (F^d + F^e),$$  \hspace{1cm} (3)

where $X$ is the gross domestic product vector, with $X_i$ as an element (million USD/year); $(I - A^d)^{-1}$ is the Leontief inverse matrix; $I$ is the unit matrix; $A^d$ is the activity matrix of the gross domestic product with $a^d_{ij}$ as an element, $F^d$ is the final demand vector of domestic goods (million USD/year); and $F^e$ is the export vector (exports) (million USD/year).

CO$_2$ emission intensity ($ICO_2$), including the spillover effect is calculated by multiplying the direct CO$_2$ emissions per million USD of the producer price by the Leontief inverse matrix of Equation (3), as shown in Equation (4):

$$ICO_2 = CO_2 (I - A^d)^{-1},$$  \hspace{1cm} (4)

where $ICO_2$ is the CO$_2$ emission basic unit vector, with spillover effects per manufacturer price of 1 million USD in each industry (kg-CO$_2$/million USD), and $CO_2$ is the direct CO$_2$ emission row vector per manufacturer price of 1 million USD in each industry (kg-CO$_2$/million USD).

Direct CO$_2$ emissions ($CO_2$) per million USD of producer price in Equation (4) are expressed as follows on the basis of emission data:

$$CO_2 = \frac{SCO_2}{X_i},$$  \hspace{1cm} (5)

where $CO_2$ represents the direct CO$_2$ emissions per manufacturer price of 1 million USD in sector $i$ (kg-CO$_2$/million USD), $X_i$ is the gross domestic product value in sector $i$ (million USD/year), and $SCO_2$ represents the total CO$_2$ emissions in sector $i$ (kg-CO$_2$/year).

Therefore, the induced CO$_2$ emissions ($SCO_2$) due to the final demand for each sector are expressed by the following equation from Equations (3)–(5):

$$SCO_2 = ICO_2 \times F_i,$$  \hspace{1cm} (6)

where $SCO_2$ represents the induced CO$_2$ emissions from the final demand of sector $i$ (kg-CO$_2$/year), $ICO_2$ is the CO$_2$ emission intensity of sector $i$ (kg-CO$_2$/million USD), and $F_i$ is the final demand of sector $i$ (million USD/year).

3. Results
3.1. CO$_2$ Emission Intensity and CO$_2$ Emissions by Sector

From the abovementioned step in Section 2.3.2., 2011 CO$_2$ emission intensities by sector, as well as CO$_2$ emissions by sector and their ratios, were calculated for 43 countries. Table 3 shows the calculation results for Japan.
Table 3. CO2 emission intensities (JPN, 2011).

| No. | Sectors                                                                 | CO2 Emission Intensity (t-CO2/Million USD) | CO2 Emission by Sector (t-CO2) | Ratio (%) |
|-----|-------------------------------------------------------------------------|-------------------------------------------|--------------------------------|-----------|
| 1   | Crop and animal production, hunting and related service activities       | 135                                       | 4,919,168                      | 0.44      |
| 2   | Forestry and logging                                                     | 107                                       | 116,275                        | 0.01      |
| 3   | Fishing and aquaculture                                                  | 213                                       | 541,109                        | 0.05      |
| 4   | Mining and quarrying                                                     | 651                                       | 444,719                        | 0.04      |
| 5   | Manufacture of food products, beverages and tobacco products             | 157                                       | 40,997,531                     | 3.67      |
| 6   | Manufacture of textiles, wearing apparel and leather products            | 268                                       | 4,162,533                      | 0.37      |
| 7   | Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials | 135                                       | 32,947                         | 0.00      |
| 8   | Manufacture of paper and paper products                                  | 393                                       | 3,158,788                      | 0.28      |
| 9   | Printing and reproduction of recorded media                             | 152                                       | 207,932                        | 0.02      |
| 10  | Manufacture of coke and refined petroleum products                       | 269                                       | 21,557,835                     | 1.93      |
| 11  | Manufacture of chemicals and chemical products                          | 497                                       | 42,722,640                     | 3.83      |
| 12  | Manufacture of basic pharmaceutical products and pharmaceutical preparations | 131                                       | 1,406,607                      | 0.13      |
| 13  | Manufacture of rubber and plastic products                              | 274                                       | 9,628,872                      | 0.86      |
| 14  | Manufacture of other non-metallic mineral products                       | 982                                       | 14,135,752                     | 1.27      |
| 15  | Manufacture of basic metals                                             | 895                                       | 70,290,173                     | 6.30      |
| 16  | Manufacture of fabricated metal products, except machinery and equipment | 323                                       | 26,602,346                     | 2.38      |
| 17  | Manufacture of computer, electronic and optical products                 | 178                                       | 31,547,894                     | 2.83      |
| 18  | Manufacture of electrical equipment                                     | 248                                       | 30,793,610                     | 2.76      |
| 19  | Manufacture of machinery and equipment n.e.c.                           | 198                                       | 34,171,918                     | 3.06      |
| 20  | Manufacture of motor vehicles, trailers and semi-trailers               | 211                                       | 50,125,125                     | 4.49      |
| 21  | Manufacture of other transport equipment                                | 230                                       | 11,692,167                     | 1.05      |
| 22  | Manufacture of furniture; other manufacturing                           | 248                                       | 5,639,812                      | 0.51      |
| 23  | Repair and installation of machinery and equipment                       | 0                                         | 0                              | 0.00      |
| 24  | Electricity, gas, steam and air conditioning supply                     | 2009                                      | 151,250,059                    | 13.55     |
| 25  | Water collection, treatment and supply                                  | 91                                        | 1,100,709                      | 0.10      |
| 26  | Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services | 398                                       | 770,038                        | 0.07      |
| 27  | Construction                                                             | 167                                       | 104,337,632                    | 9.35      |
| 28  | Wholesale and retail trade and repair of motor vehicles and motorcycles  | 137                                       | 5,022,185                      | 0.45      |
| 29  | Wholesale trade, except of motor vehicles and motorcycles               | 68                                        | 22,968,291                     | 2.06      |
| 30  | Retail trade, except of motor vehicles and motorcycles                  | 142                                       | 48,340,521                     | 4.33      |
| 31  | Land transport and transport via pipelines                              | 228                                       | 29,826,951                     | 2.67      |
| 32  | Water transport                                                          | 1569                                      | 58,658,307                     | 5.26      |
| 33  | Air transport                                                            | 409                                       | 10,734,638                     | 0.96      |
| 34  | Warehousing and support activities for transportation                   | 142                                       | 4,134,704                      | 0.37      |
| 35  | Postal and courier activities                                            | 120                                       | 334,482                        | 0.03      |
| 36  | Accommodation and food service activities                               | 159                                       | 43,740,026                     | 3.92      |
| 37  | Publishing activities                                                    | 131                                       | 1,275,492                      | 0.11      |
3.2. Impact by Sectors

Figure 3 shows the results of CO₂ emissions of 56 sectors in 43 countries for each sector, as well as the ratio of each sector to total CO₂ emissions (56 sectors and a total of 43 countries). The sector with the highest share of total CO₂ emissions was “27: construction (19%)”, followed by “24: electricity, gas, steam, and air-conditioning supply (12%)”.

Therefore, it was confirmed that a reduction in emissions in the construction sector would be effective in reducing overall CO₂ emissions.
3.3. Construction EGs

Figure 4 shows the relationship between the fraction of construction EG in each country and the fraction of global CO₂ emissions. The vertical axis is the fraction of construction EG and the horizontal axis is the fraction of global CO₂ emissions. The magnitude of the absolute value of construction EG is indicated by the size of the area of the quadrangle. The fraction of construction EG refers to the fraction of CO₂ emissions of “27: construction” to domestic emissions, and it is the value shown in the “ratio” column in Table 3.

In China, as the fractions of both construction EG and the fraction of CO₂ emissions are large, the country’s construction EG is the largest globally. China is followed by India, Russia, the United States, and Japan, in that order. Accordingly, it should be considered that activities to reduce CO₂ emissions related to construction in China and India can contribute to a global reduction in CO₂ emissions.

Figure 4. Fraction of construction EG and total CO₂ emissions.
Figure 5 shows the relationship between GNI per capita and the fraction of construction EG. The income of 43 countries was classified by referring to the standard of income classification by GNI per capita published by the World Bank in 2012 [16].

According to Figure 5, construction EG tends to be higher in developing countries such as China and India.

3.4. Composition of Construction EGs

It was found that construction EGs account for a large part of CO2 emissions. In order to reduce construction EGs, an analysis of the sectors contributing to construction EGs is required. The main materials for construction and the corresponding WIOD (2016) sector names are shown in Figure 6.

Figure 7 shows the calculation results for CO2 emissions by the construction sector in Japan, the United States, China, India, and Germany, according to Equation (6). However, Fi is the amount of i-sector which has been invested in the construction sector.

The sectoral linkages on the construction sector can be evaluated by the traditional method of analyzing the column elements of the Leontief inverse matrix. In addition, a method called hypothetical extraction method (HEM) [17] is used. This is a method to evaluate the sectoral linkages by comparing the state with and without the target sector. However, in this study, since the CO2 emission intensity for each industrial sector was calculated in Section 3.2, the CO2 emissions of the sectors that contribute the construction EG can be calculated by multiplying the amount of sector that that is put into the construction sector by the intensity. This method is equivalent to the traditional method of analyzing the column elements of the Leontief inverse matrix.

According to Figure 7, sectors 14, 15, 16, and 24 are large contributors. These are the sectors that manufacture “cement”, “steel bars and steel frames”, and “energy sources”. The proportion of CO2 emissions from these three materials accounts for around 60–80% of the construction EGs in each country.

Considering each construction-related material, “cement” tends to have a high ratio of CO2 emissions by sector in all countries, particularly in China and Germany, where it exceeds 40%. In addition, “steel bars and steel frames” tend to have high contributions in Japan, India, and China, especially in the former, where they exceed 30%. “Energy sources” tend to have high contributions in India, the United States, and Germany, especially in the latter pair, where they account for nearly 20%.
In all countries, CO₂ emissions in cement production, steel production, and energy supply were found to have a significant impact on construction EGs. Thus, it is very important to advance technological development to reduce CO₂ emissions within these sectors.

### Figure 6. Sector-specific construction materials.

| Main materials for construction | Sector name (WIOD Release 2016) |
|---------------------------------|----------------------------------|
| Gravel and crushed stone        | 4: Mining and Quarrying          |
| Steel bar and steel frame       | 15: Manufacture of basic metals   |
| Cement                          | 16: Manufacture of fabricated metal products, except machinery and equipment |
| Mechanical and electrical equipment | 14: Manufacture of other non-metallic mineral products |
| Wood                            | 18: Manufacture of electrical equipment |
| Energy source                   | 19: Manufacture of machinery and equipment n.e.c. |

| 7: Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials |
| 10: Manufacture of coke and refined petroleum products |
| 24: Electricity, gas, steam and air conditioning supply |

### Figure 7. CO₂ emissions by sectors comprising construction EGs.

#### 3.5. Relationship with Cement Production

In the previous section, the sector of cement production was identified as having a large impact on construction EG. Figure 8 shows the relationship between CO₂ emissions by cement production and construction EG in each country, according to statistical data on carbon emissions from the Carbon Dioxide Information Analysis Center (CDIAC) [18].

From Figure 8, since the approximate curve is an upward-sloping equation, a strong positive correlation between cement production and construction EGs was considered. It was found that CO₂ emissions from cement production account for approximately 31% of construction EG in many countries.
Figure 8. CO$_2$ emissions from cement production and construction EGs.

3.6. Annual Variation of Construction EGs

Figure 9 shows the relationship between total CO$_2$ emissions from 2000 to 2014 and construction EGs, and cement production in Japan, the United States, China, India, and Germany.

Total CO$_2$ emissions in Japan have not changed significantly, with the lowest value recorded in 2009. Construction EGs were on a downward trend until 2011, with no significant changes recorded since 2011. CO$_2$ emissions from cement production have not changed significantly.

Total CO$_2$ emissions in the United States were on a downward trend until 2009, with no significant changes recorded since 2010, but a slight upward trend has been observed since 2013. Construction EGs were on a downward trend until 2012, but they have been on an increasing trend since 2012. CO$_2$ emissions from cement production also showed almost the same tendency as construction EGs.

Total CO$_2$ emissions in China have been on the rise, being 2.9 times higher in 2014 than in 2000. Similarly, construction EGs and CO$_2$ emissions from cement production have also increased significantly (4.7 times and 4.2 times, respectively).

Total CO$_2$ emissions in India have been on the rise, being 2.2 times higher in 2014 than in 2000. Construction EGs and CO$_2$ emissions from cement production have also increased (2.4 times and 2.9 times, respectively).

Total CO$_2$ emissions in Germany have been on a downward trend. Construction EGs were on a downward trend until 2005; however, since 2006, no major fluctuations have been observed, and a similar trend can be seen in CO$_2$ emissions from cement production.

In China and India, total CO$_2$ emissions, construction EGs, and CO$_2$ emissions from cement production have all increased. This was due to increased investment in the construction sector. This is considered to be a characteristic of developing countries. On the other hand, in Japan, the United States, and Germany, total CO$_2$ emissions and construction EGs have decreased. However, in recent years, there has been no significant change in construction EGs and CO$_2$ emissions from cement production. This is considered to be a characteristic of developed countries.

There was a clear trend for developing countries (India and China). By contrast, for developed countries (the United States, Japan, and Germany), the trend was not so clear.
Figure 9. Annual variations in total CO2 emissions, construction EGs, and CO2 emissions from cement production.

Figure 10 shows the annual variation in the fraction of construction EG. Compared to India, China has the largest fraction of construction EG demonstrating a strong increasing trend. On the other hand, India changed from 17% (2000) to 19% (2014), with only a slight increase. In both cases, construction EGs have increased, which is a characteristic of developing countries, but it can also be seen that there was a clear difference in the increasing trend.

Germany has remained at around 4%, while the United States has remained at around 5%. Among the five countries, Germany and the United States are characterized by a low fraction of construction EG and small fluctuations. However, the fraction of construction EG in Japan has been intermediate among the five countries, showing a gradual downward trend from 14% (2000) to 10% (2014).
From the above, it can be noted that the fraction of construction EG in developing countries is large and rising, whereas it is small and stable in developed countries.

Compared with the 2013 analysis results [4], the construction EG values from 2000 to 2009 are slightly different; however, their trends are almost the same.

Figure 10. Annual variations in fraction of construction EGs. The fraction of construction EG of WIOD (2013) is cited from Reference [4].

4. Discussion

This study aimed to clarify the characteristic of construction EG as a material for formulating policies for reducing emissions in each country.

In this study, the construction EGs of 43 countries from 2011 were analyzed. The 56-sector input/output table and CO2 emission data of the 2016 World Input/Output Database, published by the EU were used in this analysis. The CO2 emissions intensities in 56 sectors in 43 countries were obtained.

The total CO2 emissions of the 43 countries included in this analysis account for about 80% of the world’s total energy-derived CO2 emissions. In addition, the sector with the highest share of total CO2 emissions in the 43 countries was “27: construction”, which was shown to be the highest in the following order of countries: China, India, Russia, the United States, and Japan.

It was found that developing countries tend to have higher construction EGs. The large fraction of construction EG in developing countries is thought to be due to the construction of many facilities such as buildings, roads, and railroads for economic development. Therefore, it is important to promote methods for reducing construction EGs.

CO2 emissions by construction sectors in Japan, the United States, China, India, and Germany were analyzed. As a result of this analysis, the sectors manufacturing “cement”, “steel bars and steel frames”, and “energy sources” were found to be large contributors, and the fraction of CO2 emissions by these three sources is around 60–80% of the construction EGs in the five countries.

In addition, annual variation from 2000 to 2014 in total CO2 emissions, construction EGs, CO2 emissions from cement production in five countries as above were compared. In China and India, total CO2 emissions, construction EGs, and CO2 emissions of cement production have all increased, which could be due to a sharp increase in investment in the construction sector. This is a characteristic of developing countries. On the other hand, in Japan, the United States, and Germany, total CO2 emissions, construction EGs, and CO2 emissions from cement production have been on a downward trend; however, in recent years, there has been no significant change in construction EGs and CO2 emissions from
cement production. This is considered to be a characteristic of developed countries. The fraction of construction EG was around 4% each year in Germany and around 5% each year in the United States, both of which show a flat trend. The fraction of construction EG in Japan was intermediate among the five countries, showing a gradual downward trend.

Compared with the WIOD (2013) analysis results [4], it was confirmed that the construction EG values were slightly different, but the trends were similar to those mentioned above.

CO₂ emissions from cement production, steel production, and energy supply heavily affect construction EG. Therefore, measures to reduce these CO₂ emissions are important in terms of reducing construction EGs. Construction EGs in developing countries are expected to continue increasing in the future; therefore, countermeasures are urgently needed. To shrink carbon emissions, resource-recycling manufacturing methods should be considered. These could include cement production without CO₂ emissions, recycling cement from used concrete, and the utilization of renewable energy. All of these are effective as countermeasures. Furthermore, in addition to the efforts of each country, it is desirable for developed countries to provide their proven CO₂ emission reduction technologies to developing countries.

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Nomenclature

Abbreviations

ZEBs net-zero-energy buildings
ZEHs net-zero-energy houses
EU European Union
GNI Gross National Product
GHG greenhouse gas
EE embodied energy
EGs embodied GHG emissions
EEGs embodied energy and GHG emissions
WIOD World Input-Output Database
IEA International Energy Agency
EBC Energy in Building and Communities
PEf primary energy from fossil fuels only
PEnr primary energy from fossil fuels and nuclear power
PET total primary energy from fossil fuels, nuclear power, and renewable energy
WIOT world IO table
NIOT national IO tables
USD US dollars

Symbols

\( a_{ij}^d \) the input coefficient for domestic goods
\( X_{ij}^d \) the domestic product from sector j to sector i, million USD/year
\( X_i \) the gross domestic product (total output), million USD/year
\( X \) the gross domestic product vector, million USD/year
\((I - A^d)^{-1}\) the Leontief inverse matrix
\( I \) the unit matrix
\( A^d \) the activity matrix of the gross domestic product with \( a_{ij}^d \) as an element
\( F^d \) the final demand vector of domestic goods, million USD/year
\( F^e \) the export vector, million USD/year
ICO
the CO₂ emission basic unit vector with spillover effects per manufacturer price of 1 million USD in each industry, kg-CO₂/million USD

CO₂
the direct CO₂ emission row vector per manufacturer price of 1 million USD in each industry, kg-CO₂/million USD

CO₂i
the direct CO₂ emissions per manufacturer price of 1 million USD in sector i, kg-CO₂/million USD

SCO₂i
the induced CO₂ emissions from the final demand of sector i, kg-CO₂/year

ICO₂i
the CO₂ emission intensity of sector i, kg-CO₂/million USD/year

Subscripts

d domestic
E export
i sector numbers of row
j sector numbers of column

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