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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 CO_2 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 CO_2 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 CO_2 emissions within these sectors. The annual variation of construction EGs and CO_2 emissions from 2000 to 2014 showed that the construction EGs and total CO_2 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

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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".

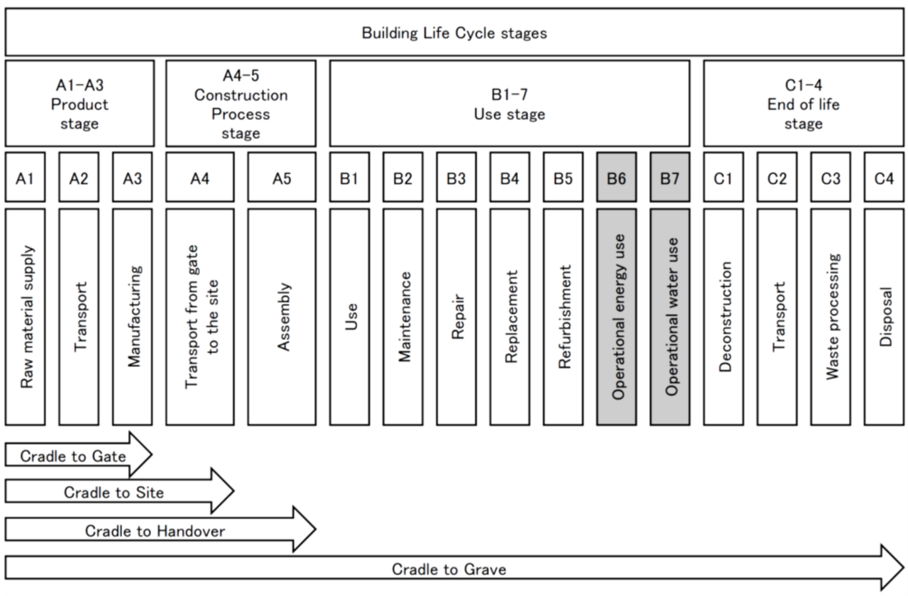


Figure 1. Proposed model for system boundaries [2].

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 CO_2 emissions for EU countries. Zhang et al. [7] also analyzed the CO_2 and energy flows associated with trade in

BRICS countries. As a result, it was found that the amount of CO_2 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 CO_2 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) CO_2 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 CO_2 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 CO_2 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, CO_2 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.

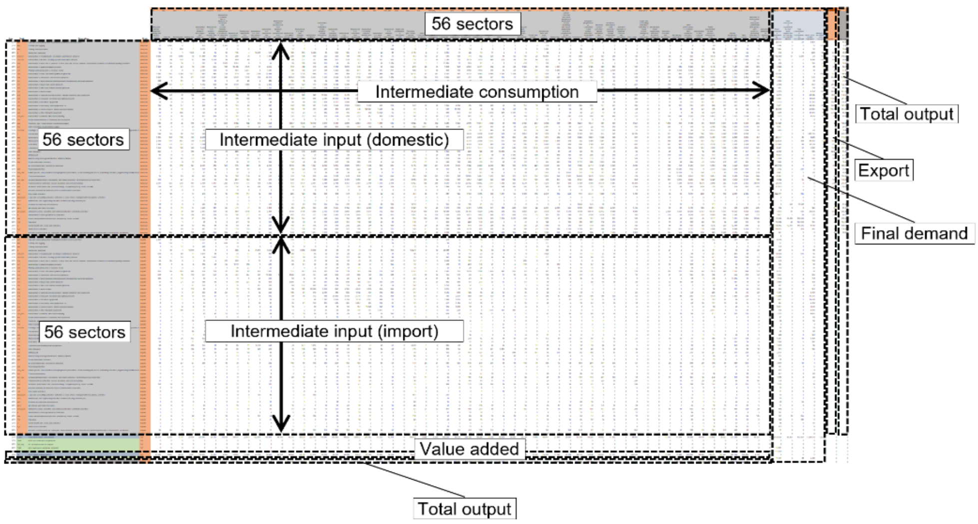


Figure 2. National input/output (IO) table (NIOT) framework.

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.

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	Sewerage; 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
30	G47	Retail trade, except of motor vehicles and motorcycles
31	H49	Land transport and transport via pipelines
32	H50	Water transport
33	H51	Air transport
34	H52	Warehousing and support activities for transportation
35	H53	Postal and courier activities
36	I	Accommodation and food service activities
37	J58	Publishing activities
38	J59–J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
39	J61	Telecommunications
40	J62–J63	Computer programming, consultancy and related activities; information service activities
41	K64	Financial service activities, except insurance and pension funding
42	K65	Insurance, reinsurance and pension funding, except compulsory social security
43	K66	Activities auxiliary to financial services and insurance activities
44	L68	Real estate activities
45	M69–M70	Legal and accounting activities; activities of head offices; management consultancy activities
46	M71	Architectural and engineering activities; technical testing and analysis
47	M72	Scientific research and development
48	M73	Advertising and market research
49	M74–M75	Other professional, scientific and technical activities; veterinary activities
50	N	Administrative and support service activities
51	O84	Public administration and defence; compulsory social security
52	P85	Education
53	Q	Human health and social work activities
54	R–S	Other service activities
55	T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
56	U	Activities of extraterritorial organizations and bodies

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 CO_2 emissions according to the International Energy Agency (IEA) [14] for the 43 countries. The total energy-derived CO_2 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 CO_2 emissions [14] (2011).

No.	Country Code	GNI (Billion USD)	GNI per Capita (USD)	CO_2 Emission ($\times 10^6$ 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	1667.76	5.3
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	1758.97	51,223.17	541.16	1.7
9	MEX	1161.74	10,041.39	456.46	1.5
10	GBR	2669.89	42,205.76	439.18	1.4
11	BRA	2548.97	12,905.24	391.09	1.2
12	IDN	868.24	3542.15	390.32	1.2
13	ITA	2286.19	38,501.44	384.11	1.2
14	AUS	1340.59	60,008.33	382.11	1.2
15	FRA	2937.48	44,954.91	322.27	1.0
16	POL	511.68	13,442.95	303.19	1.0
17	TUR	825.27	11,236.81	287.20	0.9
18	ESP	1452.68	31,078.16	264.87	0.8
19	TWN	-	-	255.46	0.8
20	NLD	916.73	54,917.08	158.41	0.5
21	CZE	210.69	20,072.81	109.32	0.3
22	BEL	523.48	47,424.28	92.81	0.3
23	GRC	279.94	25,208.71	82.12	0.3
24	ROU	181.11	8989.08	80.86	0.3
25	AUT	432.57	51,548.18	67.01	0.2
26	FIN	276.30	51,277.56	54.56	0.2
27	BGR	55.56	7560.80	49.17	0.2
28	PRT	240.83	22,811.21	47.05	0.1
29	HUN	134.32	13,470.15	46.34	0.1
30	SWE	584.48	61,855.31	42.35	0.1
31	DNK	351.26	63,055.84	42.06	0.1
32	CHE	707.65	89,435.44	39.23	0.1
33	NOR	503.52	101,657.40	36.22	0.1
34	IRL	192.53	42,036.42	35.38	0.1
35	SVK	95.59	17,706.25	32.85	0.1
36	HRV	60.31	14,089.97	17.95	0.1
37	EST	22.21	16,732.11	17.63	0.1
38	SVN	50.82	24,754.46	15.43	0.0
39	LTU	42.19	13,933.23	11.53	0.0
40	LUX	41.43	79,927.99	10.51	0.0
41	LVA	28.46	13,818.00	7.34	0.0
42	CYP	28.29	25,151.79	7.00	0.0
43	MLT	9.21	22,117.24	2.57	0.0
		Other countries		6406.16	20.4
		All of the world		31,392.58	100.0

USD represents current prices in United States (US) dollars.

2.3. Calculation of CO_2 Emission Intensities

2.3.1. Summary of Calculation

The intensities of CO_2 emissions were calculated using the NIOTs and environmental accounts from the WIOD (2016).

2.3.2. Calculation of CO_2 Emission Intensities

As shown in Figure 2, the NIOTs distinguished between domestic products and imported products. Since this analysis targeted domestic CO_2 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]:

$$a_{ij}^{d} = \frac{X_{ij}^{d}}{X_i}, \tag{1}$$

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.

The gross domestic product vector $\mathbf{X}$ is expressed by the following equation [15]:

$$\mathbf{X} = \mathbf{A}^{d}\, \mathbf{X} + (\mathbf{F}^{d} + \mathbf{F}^{E}), \tag{2}$$

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

$$\mathbf{X} = (\mathbf{I} - \mathbf{A}^{d})^{-1} \times (\mathbf{F}^{d} + \mathbf{F}^{E}), \tag{3}$$

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

CO_2 emission intensity ($\mathbf{ICO_2}$), 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):

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

where $\mathbf{ICO_2}$ 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 $\mathbf{CO_2}$ 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_{2i}) per million USD of producer price in Equation (4) are expressed as follows on the basis of emission data:

$$CO_{2i} = \frac{SCO_{2i}}{X_i}, \tag{5}$$

where CO_{2i} 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_{2i} represents the total CO_2 emissions in sector i (kg-CO_2/year).

Therefore, the induced CO_2 emissions (SCO_{2i}) due to the final demand for each sector are expressed by the following equation from Equations (3)–(5):

$$SCO_{2i} = ICO_{2i} \times F_i, \tag{6}$$

where SCO_{2i} represents the induced CO_2 emissions from the final demand of sector i (kg–CO_2/year), ICO_{2i} 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. CO_2 emission intensities (JPN, 2011).

No.	Sectors	CO_2 Emission Intensity (t-CO_2/Million USD)	CO_2 Emission by Sector (t-CO_2)	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

Table 3. *Cont.*

No.	Sectors	CO_2 Emission Intensity (t-CO_2/Million USD)	CO_2 Emission by Sector (t-CO_2)	Ratio (%)
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
38	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	87	1,028,811	0.09
39	Telecommunications	65	6,364,287	0.57
40	Computer programming, consultancy and related activities; information service activities	67	6,104,915	0.55
41	Financial service activities, except insurance and pension funding	42	1,658,484	0.15
42	Insurance, reinsurance and pension funding, except compulsory social security	64	6,951,031	0.62
43	Activities auxiliary to financial services and insurance activities	0	0	0.00
44	Real estate activities	19	15,207,451	1.36
45	Legal and accounting activities; activities of head offices; management consultancy activities	0	0	0.00
46	Architectural and engineering activities; technical testing and analysis	0	0	0.00
47	Scientific research and development	225	4,224,921	0.38
48	Advertising and market research	105	139,685	0.01
49	Other professional, scientific and technical activities; veterinary activities	51	2,537,592	0.23
50	Administrative and support service activities	47	409,931	0.04
51	Public administration and defence; compulsory social security	106	74,165,062	6.65
52	Education	75	17,767,389	1.59
53	Human health and social work activities	93	59,202,423	5.31
54	Other service activities	130	32,583,913	2.92
55	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use	113	144,863	0.01
56	Activities of extraterritorial organizations and bodies	0	0	0.00
	Total		1,115,880,548	100.00

3.2. Impact by Sectors

Figure 3 shows the results of CO_2 emissions of 56 sectors in 43 countries for each sector, as well as the ratio of each sector to total CO_2 emissions (56 sectors and a total of 43 countries). The sector with the highest share of total CO_2 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 CO_2 emissions.

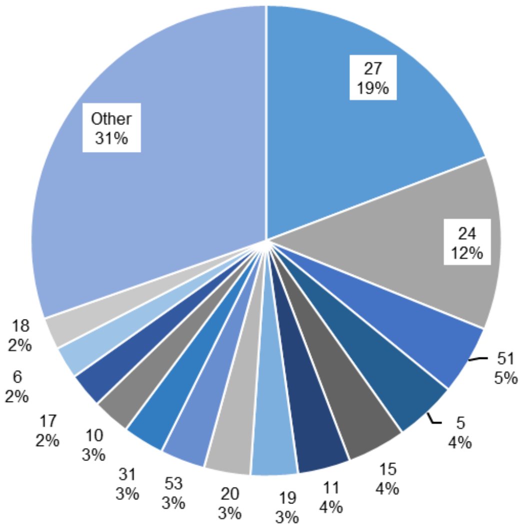


Figure 3. CO_2 emissions of each sector.

3.3. Construction EGs

Figure 4 shows the relationship between the fraction of construction EG in each country and the fraction of global CO_2 emissions. The vertical axis is the fraction of construction EG and the horizontal axis is the fraction of global CO_2 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 CO_2 emissions of "27: construction" to domestic emissions, and it is the value shown in the "ratio" column in Table 3.

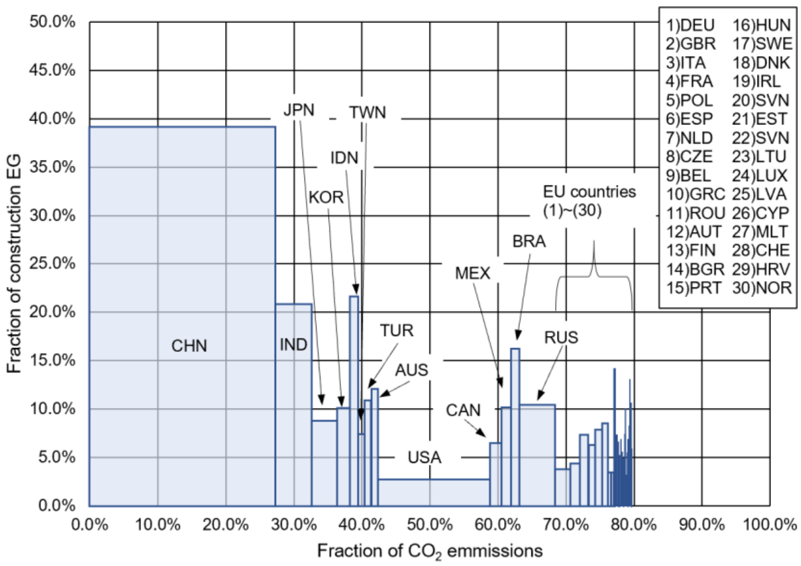


Figure 4. Fraction of construction EG and total CO_2 emissions.

In China, as the fractions of both construction EG and the fraction of CO_2 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 CO_2 emissions related to construction in China and India can contribute to a global reduction in CO_2 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].

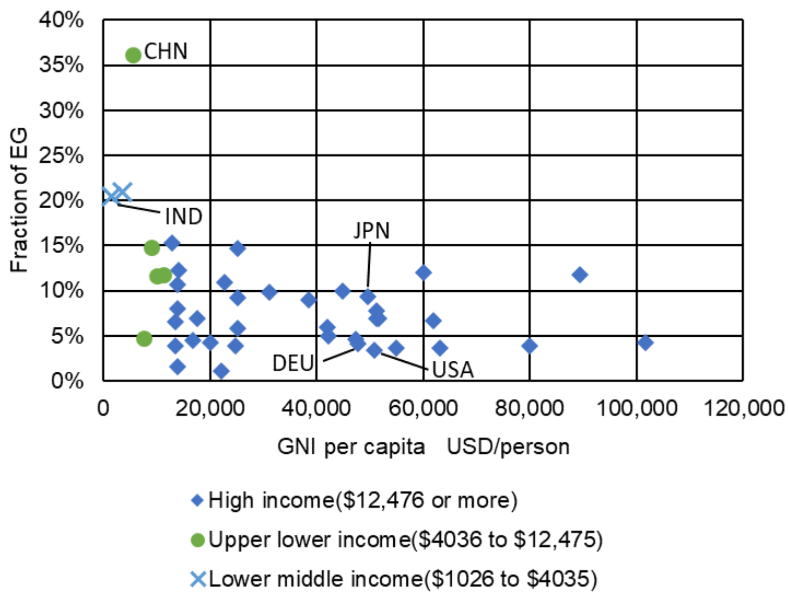


Figure 5. Relationship between GNI per capita and fraction of construction EGs (2011).

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 CO_2 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.

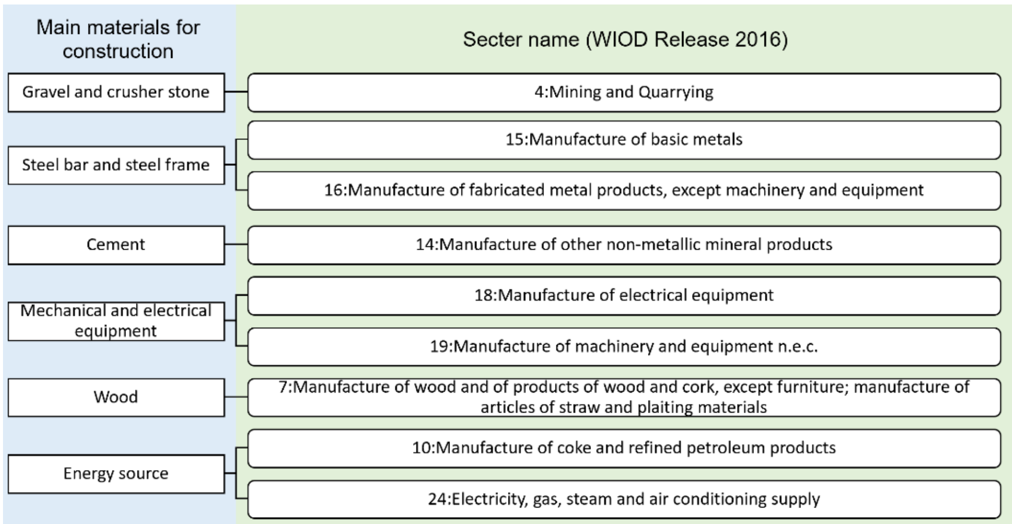


Figure 6. Sector-specific construction materials.

Figure 7 shows the calculation results for CO_2 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.

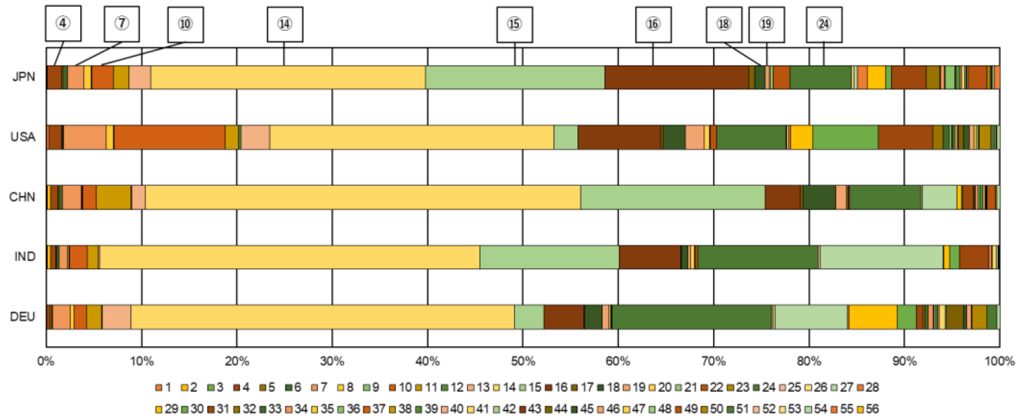


Figure 7. CO_2 emissions by sectors comprising construction EGs.

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 CO_2 emission intensity for each industrial sector was calculated in Section 3.2, the CO_2 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 CO_2 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 CO_2 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, CO_2 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 CO_2 emissions within these sectors.

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 CO_2 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 CO_2 emissions from cement production account for approximately 31% of construction EG in many countries.

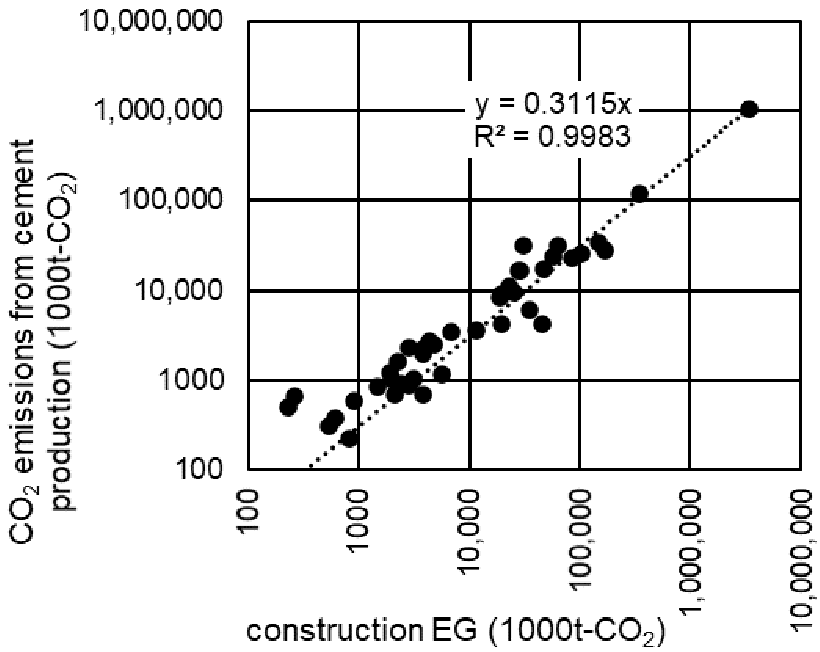


Figure 8. CO_2 emissions from cement production and construction EGs.

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.

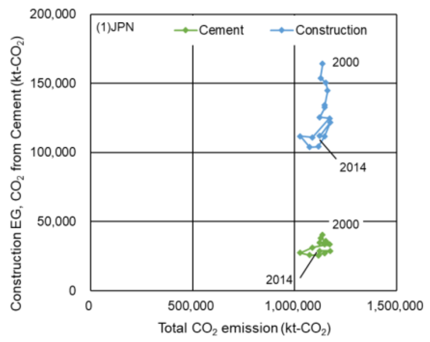
Total CO_2 emissions in China have been on the rise, being 2.9 times higher in 2014 than in 2000. Similarly, construction EGs and CO_2 emissions from cement production have also increased significantly (4.7 times and 4.2 times, respectively).

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).

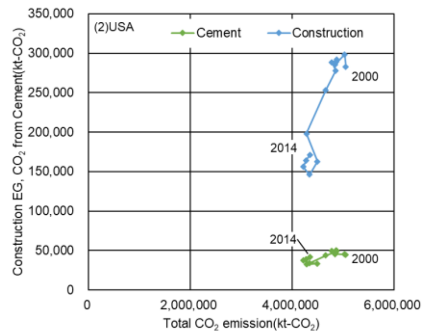
Total CO_2 emissions in Germany have been on a downward trend. Construction EGs were on a downward trend until 2005; however, since 2006, no major fluctuations have been observed, and a similar trend can be seen in CO_2 emissions from cement production.

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.

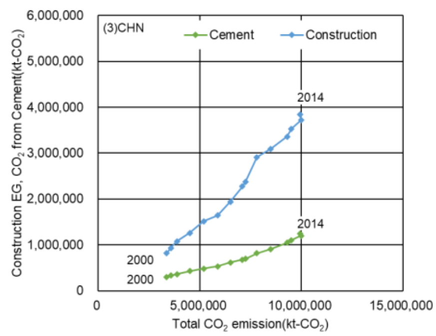
There was a clear trend for developing countries (India and China). By contrast, for developed countries (the United States, Japan, and Germany), the trend was not so clear.



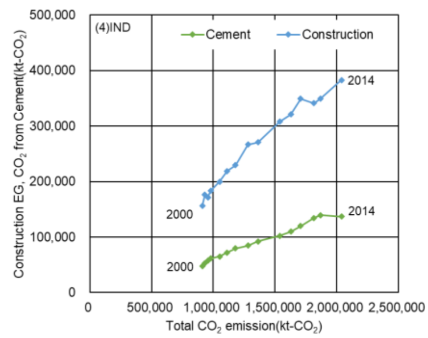
(**a**) JPN



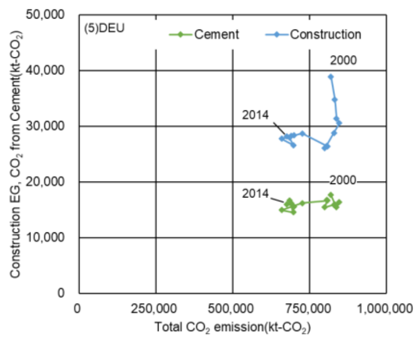
(**b**) USA



(**c**) CHN



(**d**) IND



(**e**) DEU

Figure 9. Annual variations in total CO_2 emissions, construction EGs, and CO_2 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).

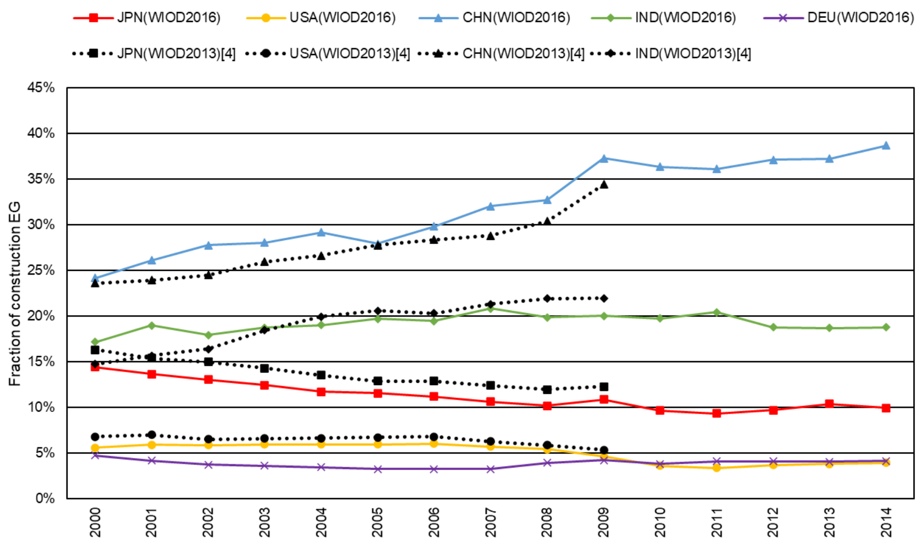


Figure 10. Annual variations in fraction of construction EGs. The fraction of construction EG of WIOD (2013) is cited from Reference [4].

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.

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 CO_2 emission data of the 2016 World Input/Output Database, published by the EU were used in this analysis. The CO_2 emissions intensities in 56 sectors in 43 countries were obtained.

The total CO_2 emissions of the 43 countries included in this analysis account for about 80% of the world's total energy-derived CO_2 emissions. In addition, the sector with the highest share of total CO_2 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.

CO_2 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 CO_2 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 CO_2 emissions, construction EGs, CO_2 emissions from cement production in five countries as above were compared. In China and India, total CO_2 emissions, construction EGs, and CO_2 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 CO_2 emissions, construction EGs, and CO_2 emissions from cement production have been on a downward trend; 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. 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.

CO_2 emissions from cement production, steel production, and energy supply heavily affect construction EG. Therefore, measures to reduce these CO_2 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 CO_2 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 CO_2 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_2	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

CO_2	the direct CO_2 emission row vector per manufacturer price of 1 million USD in each industry, kg-CO_2/million USD
CO_{2i}	the direct CO_2 emissions per manufacturer price of 1 million USD in sector i, kg–CO_2/million USD
SCO_{2i}	the induced CO_2 emissions from the final demand of sector i, kg–CO_2/year
ICO_{2i}	the CO_2 emission intensity of sector i, kg-CO_2/million USD
F_i	the final demand of sector i, million USD/year
Subscripts	
d	domestic
E	export
i	sector numbers of row
j	sector numbers of column

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