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Embodied Carbon in Trade: Carbon Loophole

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Global Efficiency Intelligence

Foreword by Authors

This report is an update to our previous report titled "The Carbon Loophole in Climate Policy Quantifying the Embodied Carbon in Traded Products". The results in this report may be different from the results presented in our previous report primarily because, in the previous report, we used the Eora database to build an Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model using 2015 data, whereas, in this report, we used EXIOBASE (V 3.8.2) database with 2019 data. The use of different databases can result in different embodied carbon in trade. The major source of difference across MRIO databases is the environmental stressor accounts. This is where GHG emissions are attributed to primary production activities. There are several major reasons for such differences: which gases are included in the study, which line items are included in the study (e.g., some studies include emissions from biomass burning or from land-use change, while others do not), and different data sources for emissions, and the allocation of emissions to sectors. Also, the difference in global trade volume and flows can impact the embodied carbon in trade analysis.

Acknowledgments

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Executive Summary

The carbon loophole refers to the embodied greenhouse gas (GHG) emissions associated with the production of products and services that are traded across countries. These emissions are a key issue for global efforts to decarbonize the world economy. Embodied emissions in trade are not accounted for in most current GHG accounting systems and climate policies, but if they were, many promising climate trends would be negated or reversed in some countries.

This report aims to provide a newly updated analysis of embodied carbon in global trade (carbon loophole, also known as imported consumption-based emissions). Using the latest EXIOBASE (version 3.8.2) database, along with additional data, we estimated global embodied carbon in trade by developing the Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model. Our analysis investigates global trends and does a deep dive into several key countries/regions and industry sectors. This report presents the results for 2019 to avoid the abnormalities that happened in global trade in 2020 and 2021 because of the global COVID19 pandemic.

Around 22% of global CO_2 emissions are embodied in imported goods, thus escaping attribution in the consuming country (the end-user) and instead being debited to the producer country (Figure ES1). We found that the proportion of embodied emissions in trade from total global emissions increased until 2008 and has stabilized since then remaining between 20% and 25% of global emissions.

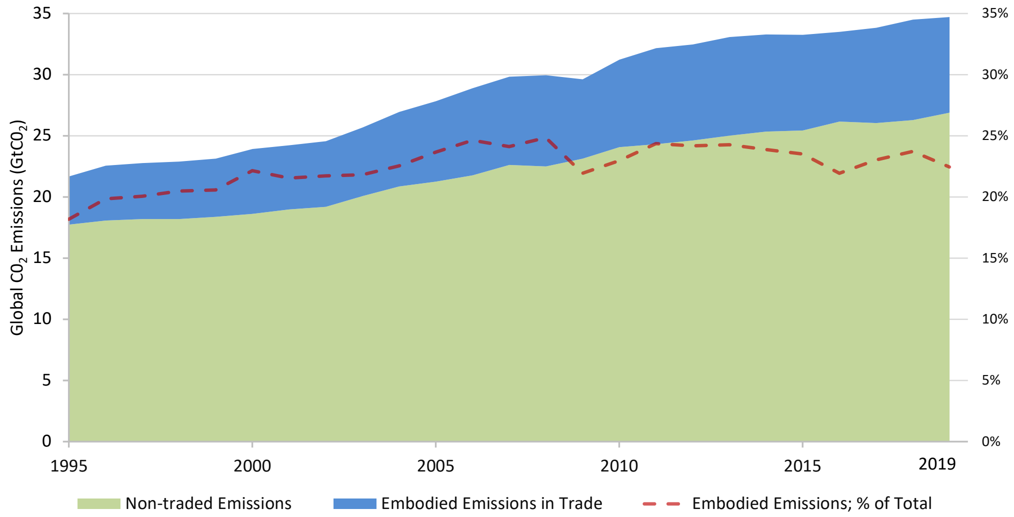

Figure ES1. Global CO_2 emissions and the share of embodied emissions in trade (source: this study).

It is worth highlighting that overall global CO_2 emissions have been increasing, even though the share of embodied emissions in trade from total global emissions has stabilized in recent years, the total volume of embodied emissions in trade has been increasing.

Since the carbon intensity of manufacturing different products vary substantially between countries, the heterogeneous climate policies across countries risk intensifying the carbon loophole as countries import more goods to satisfy their domestic consumption. It may also increase carbon leakage as production continues to shift to countries with lower climate ambition or lesser-regulated countries. Asymmetries in carbon intensity and climate policies thereby can further widen the carbon loophole.

Of the 20 largest global embodied carbon trade flows, eight are originated from China. The top three embodied carbon emissions flows are from China to Other Asia and Pacific region, China to the U.S., and Other Asia and Pacific to China. China is the largest net exporter of carbon emissions, followed by Russia, South Africa, and other developing economies. The U.S., on the other hand, is the largest net importer of emissions, followed by several high-income countries such as the UK, France, Italy, and Germany.

The imbalance in emissions among countries is shifting, with developing and middle-income countries now transferring more emissions to each other than to traditionally high-consumption countries such as the U.S. and EU. This shift is partly due to the rise of South-South trade. Emissions transfers among these countries have risen even while transfers to Global North have stabilized. There are several factors driving this change. Among the most important is the growing demand for goods and services in developing countries. Their growing middle class is increasingly seeking out the same products and services that have long been consumed in developed countries.

Our industry sectoral deep-dive studies showed significant inter-regional and extra-regional flows of carbon embodied in commodity steel, value-added steel, cement, clinker, aluminum, and chemical trade worldwide. The total embodied carbon in the international trade of commodity steel in 2021 was around 700 Mt CO_2. This is equal to 19% of total CO_2 emissions from the global steel industry. In addition, the embodied carbon in the trade of steel-containing goods (e.g. automotive, metal products, machinery, domestic appliances, etc.) is significant. China alone accounted for one-third of the world's embodied carbon in exported steel-containing products. The total embodied carbon in the international trade of cement and clinker in 2019 was around 141 Mt CO_2. This is equal to around 6% of total CO_2 emissions from the global cement industry. The total embodied carbon in the international trade of unwrought aluminum in 2019 was around 147 Mt CO_2. This is equal to around 22% of total CO_2 emissions from the global aluminum industry. The total embodied carbon in the international trade of chemical products in 2019 was around 478 Mt CO_2.

Unless consumption-based GHG accounting is used along with the production-based accounting, countries may meet their Paris Agreement targets while being responsible for increasing emissions abroad. Policies such as border carbon adjustment that are being considered in the EU, U.S., Canada, and UK or Buy Clean/Green Public Procurement (GPP) that have already been implemented in some countries and geographies around the world can help to prevent carbon leakage and close the carbon loophole.

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1 Introduction

International trade enables specialization and geographical separation of production and consumption of goods and services. The production chain has been increasingly globalized, allowing countries to import intermediate as well as final consumption products from other countries as an alternative to producing them domestically. In the past decades, we have witnessed a shift in global production patterns where developing economies have increasingly played an important role as 'the factory of the world' while developed economies have acted as the consumer of goods and services from the former. This raises the issue of emissions attribution: who is going to be responsible for the emissions released in the production of traded goods and services?

The carbon loophole refers to the embodied greenhouse gas (GHG) emissions associated with the production of goods that are ultimately traded across countries. The term 'embodied emissions' refers to the total amount of emissions from all upstream processes required to deliver a certain product or service. These emissions are a growing issue for global efforts to decarbonize the world economy. Embodied emissions in trade are not accounted for in most current GHG accounting systems and climate policies. Under the UNFCCC, countries report their GHG emissions on the basis of territorial emissions (also called production-based emissions (PBA)). When goods and services are traded, the emissions associated with their production (or embodied emissions) are also traded, and these imported emissions are not counted towards the consumer country's emissions reporting. As countries work toward net zero emissions, the relevance of emissions embodied in imported goods becomes more significant, precipitating increased awareness of the need to shift toward consumption-based accounting (CBA).

Emissions shifting manifests in several ways: new and existing emitters can relocate; a company can choose a different supplier to fulfill an order, or a decrease in domestic emissions can be more than compensated for by increased imports. The latter can occur when an economy shifts from an industrial base to an information or service economy, which increases physical imports to compensate for declining domestic production. The microeconomic decisions underlying emissions shifting are complex, and energy and pollution costs are only some of the variables that may influence businesses' decision-making. These decisions will also vary by type of industry. Yet whatever the precise mechanics of emissions shifting (explored by Arto and Dietzenbacher, 2012), the problem is persistent and is growing in certain countries and regions. To prevent further burden-shifting, major economies must recognize that even strong regulation on domestic emissions in major economies may not be effective in reducing total global emissions due to their imported carbon, i.e. carbon loophole.

This could potentially hinder the global effort to reach the target of the Paris Climate Agreement: to limit global warming to "well below" 2 ℃. An alternative emissions attribution, consumption-based accounting, is proposed to correct this issue. This accounting perspective attributes emissions to the consumer of the final product, irrespective of where the production takes place.

While consumption-based emissions accounting seems to echo the equity and justice principle, its implementation has still been limited due to the complexity that occurs due to the involvement of bilateral and multilateral relations between countries. More local and national governments are trying to address the issue of carbon embodied in trade. For example, the

Green Public Procurement (GPP) (also called Buy Clean) policies introduced in several countries and regions require that certain carbon-intensive infrastructure materials (e.g. steel, cement, concrete, etc.) purchased with government funds are produced below a given threshold of carbon intensity (Hasanbeigi 2021a,b). Another example of such policies to address embodied carbon in trade is the carbon border adjustment. For example, the European Council officially accepted a framework for a carbon border adjustment mechanism (CBAM) seeking to reduce carbon leakage on imports, specifically targeting fertilizers, steel, iron, cement, aluminum, and electric energy production (European Council, 2022). These policies help level the playing field and provide a market for companies that have invested in low-carbon technologies for producing materials.

This report provides essential updates to the current state of embodied carbon in international trade and global carbon emissions. The analysis begins from a macro-analysis of global carbon emissions and will narrow down to analyze the embodied carbon in trade in certain countries/regions and for several key carbon-intensive products (steel, cement, aluminum, and chemical).

2 Macro Overview of the Emissions Embodied in Global Trade

2.1. Global Flows of Embodied Emissions in Trade

We developed an Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model to measure the part of the global CO_2 emissions that are transferred through global trade. To be able to do this, we use the latest version of the EXIOBASE 3 database (3.8.2) (EXIOBASE 2022). We further refined the CO_2 intensity of a few key subsectors for which we had good carbon intensity data (e.g. steel, aluminum, and cement). EXIOBASE is a global, detailed Multi-Regional Environmentally Extended Supply-Use Table (MR-SUT) and Input-Output Table (MR-IOT). It was developed by harmonizing and detailing supply-use tables for many countries, estimating emissions and resource extractions by industry. Subsequently, the country supply-use tables were linked via trade creating an MR-SUT and producing MR-IOTs from this. The MR-IOT can be used for the analysis of the environmental impacts associated with the final consumption of product groups. EXIOBASE 3 supplies a time series of EE MRIO tables of 44 countries and 5 rest-of-the-world regions, ranging from 1995 to 2019, with 163 economic sectors. We focus on analyzing CO_2 emissions in this analysis. The EE MRIO model allows us to measure both the direct and indirect emissions embodied in domestic and foreign consumption (EXIOBASE 2022). For this study we only include CO_2 emissions because of data limitation within EXIOBASE.

The total global CO_2 emissions have been increasing and embodied CO_2 emissions in international trade have had a substantial share in the total global emissions. Since 1995, the embodied emissions in international trade have been mostly between 20% and 25% of total global CO_2 emissions (Figure 1). This is the extent of the carbon loophole.

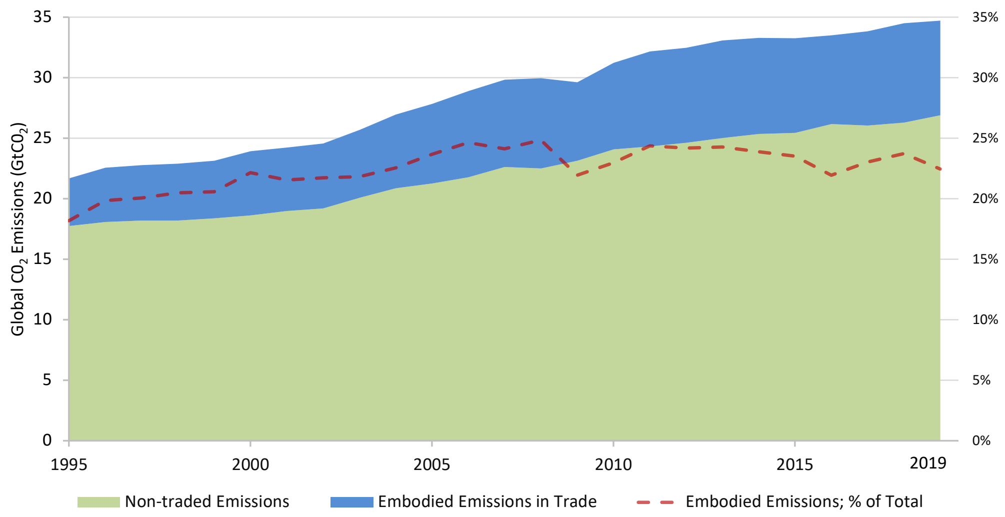


Figure 1. Global CO_2 emissions and the share of embodied emissions in trade (source: this study).

Understanding and addressing the carbon loophole is essential because it has remained internationally unregulated and potentially undermines the effectiveness of national climate reduction targets unless they are set using consumption-based accounting (no countries have set CBA goals to date).

For many countries and for the world economy as a whole, the share of emissions embodied in trade peaked in 2008 and has plateaued or slightly declined since then. There are several elements contributing to the recent plateau, including the general slowdown in trade following the global financial crisis; the improving carbon efficiency of key sectors in China; and, to a limited degree, the higher share of trade in lower-carbon goods in the global mix of traded goods. This latter factor can be attributed to a changing mix of traded products (e.g. less growth in carbon-intensive goods and more growth in non-intensive goods) and to a change in the mix of countries participating in global trade, as the exports of more or less carbon intensive producers wax and wane. However, as China shifts its economy away from heavy industry and begins to decarbonize its economy, Southeast Asia, India and Russia could become carbon-intensive manufacturing powerhouses, which would cause a spike in embodied emissions. Figure 2 shows the top 20 global flows of embodied carbon emissions in trade in 2019. Of the top 20 flows, nine of them originated from China. The three largest embodied carbon emissions flows are from China to Other Asia and Pacific, China to the U.S., from Canada to the U.S.

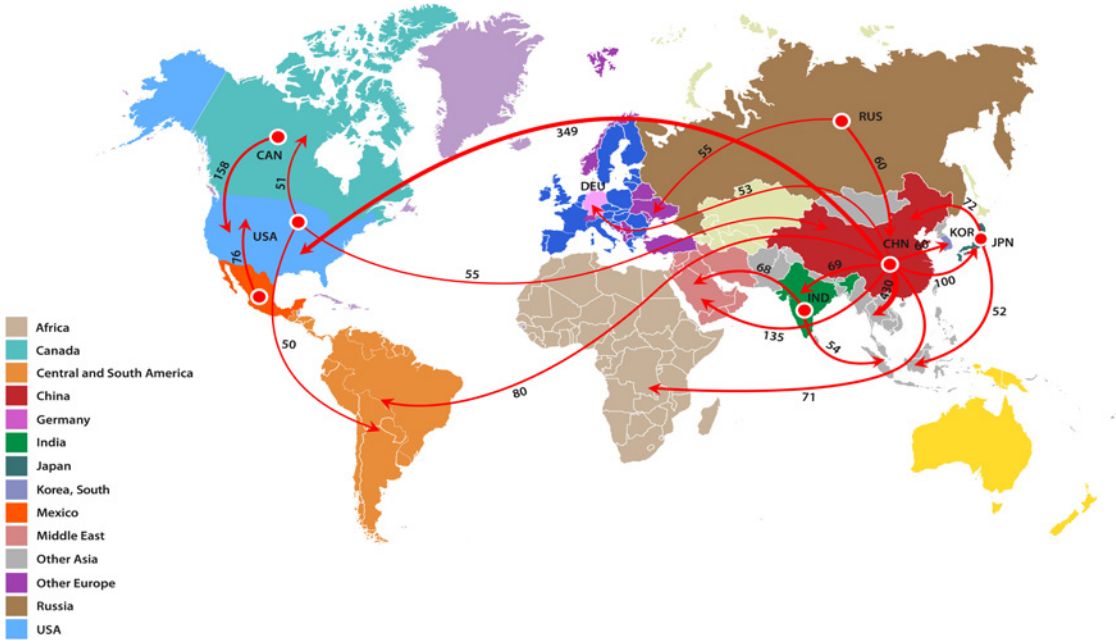


Figure 2. Top global flows of embodied CO_2 emissions in trade (source: this study)

Table 2 shows the top 40 global flows of emissions embodied in trade in 2019. China is a partner in many of the top global emissions flows. In 2019, it exported a staggering 430 Mt CO_2 embodied emissions to Other Asia and Pacific region, 349 Mt CO_2 to the U.S., 135 Mt CO_2 to Middle East, and 624 Mt CO_2 to the G7. China also exports substantial emissions to the global south, exporting 159 Mt CO_2 to emerging markets like India, Russia, Brazil, and Indonesia. Embodied carbon imports to China are relatively smaller and dominated by Japan (72 Mt CO_2), the U.S. (55 Mt CO_2), and South Korea (44 Mt CO_2).

It should be noted that the EU 27 is also a major importer and exporter of embodied carbon (see Figure 3), though not shown as aggregated in Figure 2 and Table 2. A more detailed breakdown of EU carbon flows is explored in section 3.7.

Table 2. Top 40 global flows of embodied CO_2 emissions in 2019 (source: this study).

Rank	Origin	Destination	Embodied Emissions in Trade (Mt CO_2)	Rank	Origin	Destination	Embodied Emissions in Trade (Mt CO_2)
1	China	Other Asia and Pacific	430	21	Middle East	India	56
2	China	United States	349	22	United States	China	55
3	Other Asia and Pacific	China	205	23	Russia	Other Europe	55
4	Canada	United States	158	24	India	Other Asia and Pacific	54
5	China	Middle East	135	25	China	Germany	53
6	Other Asia and Pacific	United States	114	26	Japan	Other Asia and Pacific	52
7	Middle East	China	110	27	Central & South America (Excl. Brazil)	United States	52
8	Middle East	United States	109	28	Middle East	Africa (Excl. South Africa)	51
9	China	Japan	100	29	United States	Canada	51
10	Middle East	Other Asia and Pacific	83	30	United States	Central & South America (Excl. Brazil)	50
11	China	Central & South America (Excl. Brazil)	80	31	India	United States	48
12	Mexico	United States	76	32	Russia	Other Asia and Pacific	46
13	Japan	China	72	33	Other Asia and Pacific	India	46
14	China	Africa (Excl. South Africa)	71	34	Japan	United States	46
15	China	India	69	35	Other Asia and Pacific	Middle East	45
16	India	Middle East	68	36	United States	Mexico	45
17	Other Asia and Pacific	Japan	66	37	South Korea	China	44
18	Russia	China	60	38	Central & South America (Excl. Brazil)	China	41
19	China	South Korea	60	39	South Korea	Other Asia and Pacific	40
20	South Africa	Africa (Excl. South Africa)	59	40	Other Asia and Pacific	Indonesia	39

The U.S. is the largest net importer of emissions with significant flows from China (349 Mt CO_2), Canada (158 Mt CO_2), and Mexico (76 Mt CO_2). In total, net U.S. carbon imports represent 14% and gross U.S. carbon imports represent 22% of total domestic consumption-based emissions.

Ireland has the largest share of imported emissions as a percentage of domestic consumption-based emissions (76%), and imports substantial flows from the UK, the US, and China.

Our findings indicate that the top 10 global emissions flows are still dominated by China, the U.S., and Japan. India, Russia, Canada, and South Korea have a substantial role in the top 20 global emissions flows as well. While individual European countries do not appear in the top trade flows, in aggregate, the EU27 region is the largest importer and second largest exporter of embodied emissions.

Several large economies contribute more to the global carbon loophole. Most of the developed countries have higher emissions embodied in imports than in exports, whereas the developing countries export more than importing emissions. In 2019, China released 1,757 Mt CO_2 emissions to produce goods and services to be consumed by other countries; the U.S. consumption was responsible for the release of 1,258 Mt CO_2 emissions outside its territory (Figure 3).

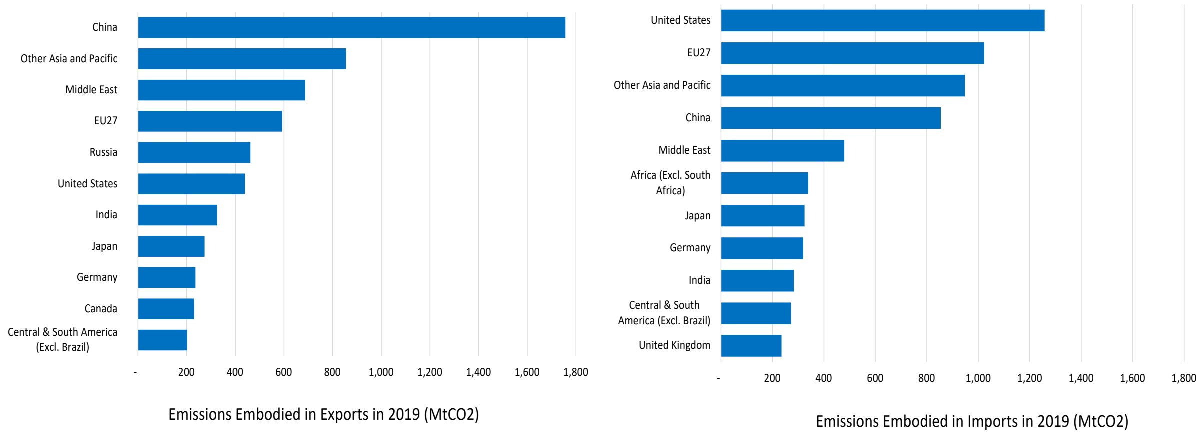


Figure 3. Top countries by CO_2 emissions embodied in exports and imports in 2019 (source: this study)

The CO_2 emissions associated with India-China trade have grown significantly, with India-to-China emissions flows recording 4,305% increases between 1995 and 2019 and China-to-India emissions flows increasing 4,803% during that period (Table 3). The growth is also noticeable in South Korea-to-India, Japan-to-India, and U.S.-to-India trade during 1995-2019. Overall, the top 10 largest-growth embodied emissions flows during 1995-2019 mainly involve trade between four Asian countries: China, India, South Korea, and Japan. The significant economic development in China and India in the past two decades, strong manufacturing base, and geographical proximity likely contribute to this trend.

Table 3. Top largest-growing embodied CO2 emissions flow from 1995-2019, ranked in absolute terms and shown as the percentage growth rate (source: this study).

Rank	Origin	Destination	Growth of CO_2 Emissions Embodied in Trade from 1995 to 2019
1	China	India	4,803%
2	India	China	4,305%
3	Japan	India	2,206%
4	United States	India	1,293%
5	Japan	China	1,062%
6	United States	China	1,021%
7	India	South Korea	880%
8	India	Russia	735%
9	India	United States	673%
10	China	Russia	523%

2.2. Balance of Emissions Embodied in Trade

The balance of emissions embodied in trade is evaluated by the difference between embodied emissions in exports and imports. A country is a net exporter of emissions when it records higher embodied emissions in exports than in imports, while it is a net importer of emissions when it records higher embodied emissions in imports than in exports. Historically, developed economies are net importers of emissions, and developing economies are net exporters of emissions.

China is the largest net exporter of carbon emissions, followed by Russia, South Africa, and other developing economies (Figure 4). The U.S., on the other hand, is the largest net importer of emissions, followed by several high-income countries such as the UK, France, Italy, and Germany.

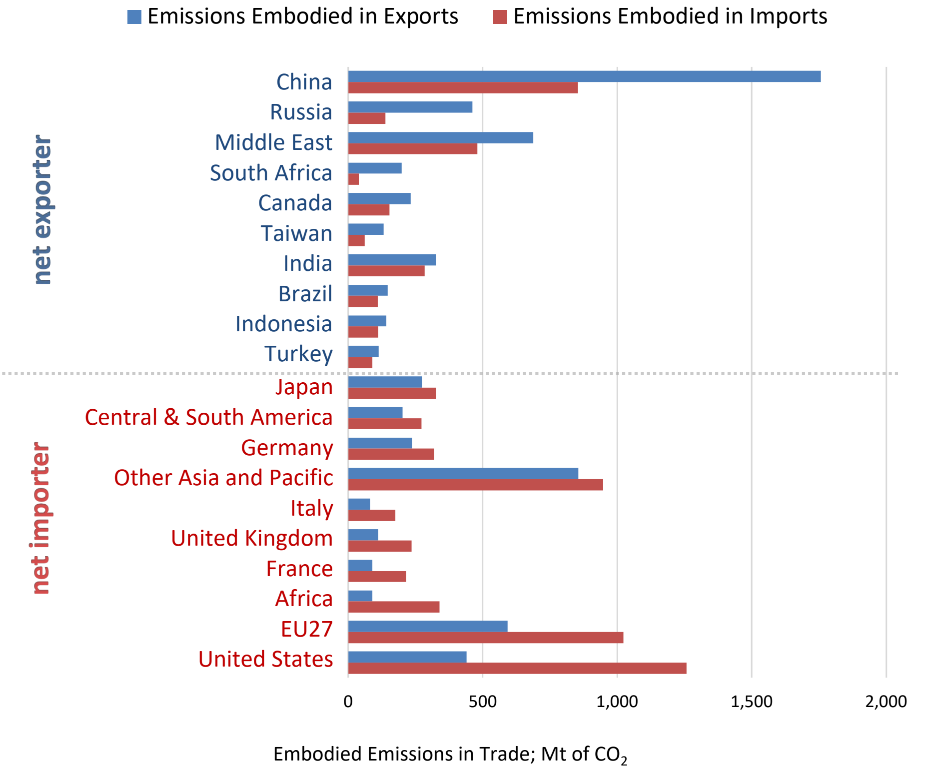


Figure 4. Countries ranked by net CO_2 emissions embodied in trade (year: 2019) (source: this study).

High-income countries are said to have decoupled economic growth and emissions. Nevertheless, the consumption-based emissions in most of these developed countries are higher than their production-based emissions. Figure 5 shows the net-imports of CO_2 emissions for several large economies and regions.

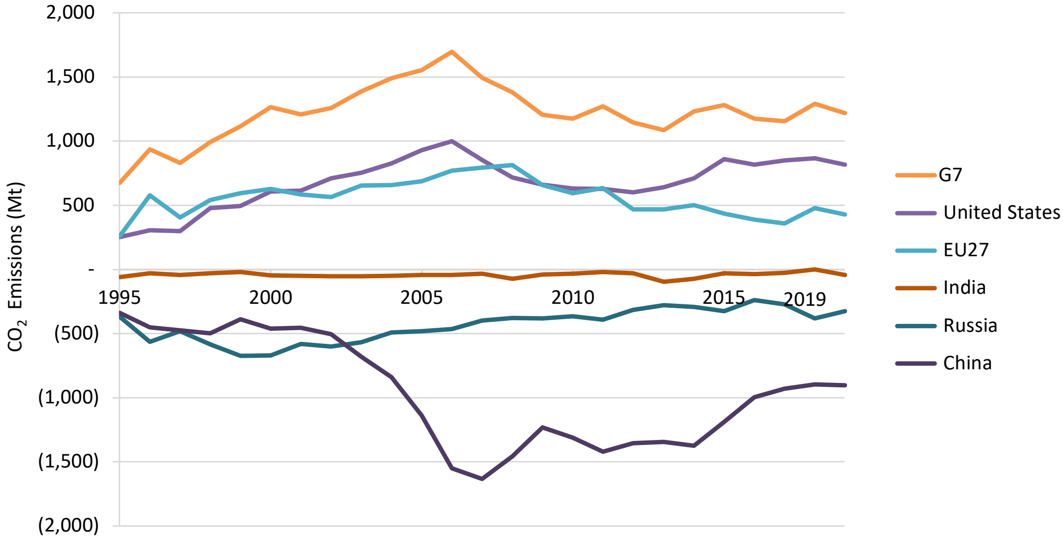


Figure 5. Net imports of CO_2 emissions for several large economies (source: this study).

The net imports of CO_2 emissions have stabilized but are not to be mistaken as a positive sign of decoupling between international trade and emissions embodied in exports. The stabilization is more of a long-run impact of the 2008 Global Financial Crisis. While large developing economies are moving away from emissions-intensive energy (not fully, and at different paces) and adopting lower-carbon manufacturing pathways, they do not have policies to guard against the "rebound effect" of offshoring production to developing economies. Carbon emissions imported via the carbon loophole may potentially overshadow the capacity of developing economies to clean their domestic production.

2.3. Production-based vs Consumption-based Emissions Accounting

The United Nations Framework Convention on Climate Change (UNFCCC) emission inventory attributes emissions to countries based on their geographic origins. This type of emission accounting is known as "production-based" emissions accounting or territorial emissions. The concept behind production-based emissions accounting is straightforward: countries are responsible for the emissions released within their territories. This approach does not adjust for emissions embodied in imported or exported products.

An alternative to production-based emissions accounting is "consumption-based" emissions accounting. Consumption-based emissions accounting assigns emissions appearing along the production chain to the consumer of final products, irrespective of where the production activities take place. The consumption-based emissions account for emissions embodied in imported and exported products. Our results indicate variations in production-based emissions and consumption-based emissions across countries (Figure 6).

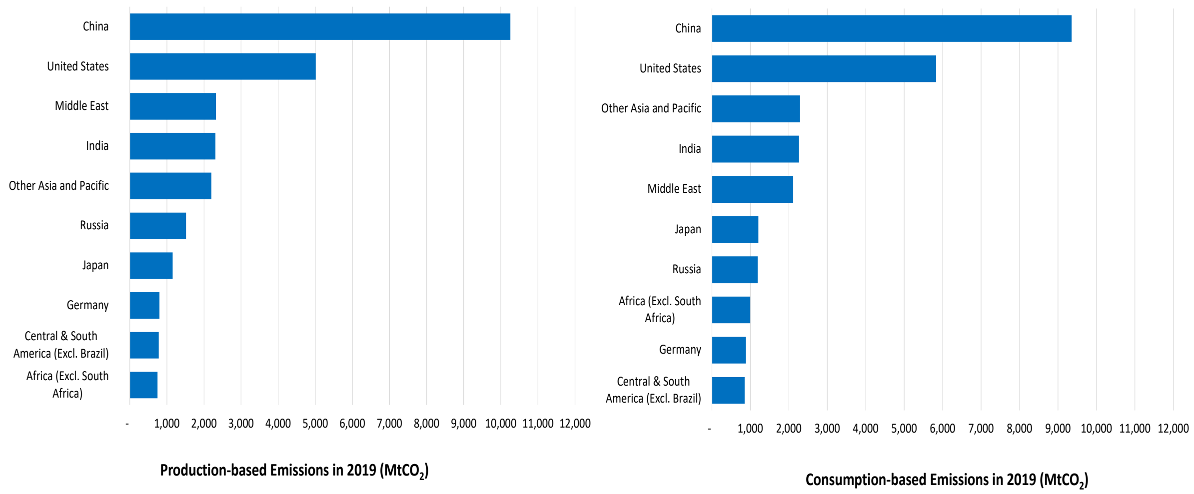


Figure 6. Top countries by territorial (production-based) and consumption-based CO_2 emissions in 2019 (source: this study).

In 2019, the top three countries/region for both production-based and consumption-based emissions were China, the U.S., and EU27. China was the highest CO_2 emitter and its production- and consumption-based emissions were around 10 Gigaton (Gt) CO_2 and 9 Gt CO_2, respectively. The U.S., in contrast, had higher consumption-based than production-based emissions. In the same year, the U.S. emitted around 5 Gt CO_2 and 5.8 Gt CO_2 of production-based and consumption-based emissions, respectively. EU27 was the third largest CO_2 emitter by production- and consumption-based emissions. EU27 emitted 2.7 Gt CO_2 of production-based emissions and 3.2 Gt Mt CO_2 of consumption-based emissions in 2019.

2.4. Products with the Largest Embodied Emissions in Trade

We also investigated the size of the carbon loophole on the product level. In aggregate, embodied CO_2 emissions in the global trade of steel and chemical products were the highest among all products, as shown in Table 4. In 2019, the embodied carbon in the steel and chemical products traded globally were 696 and 478 Mt CO_2, respectively. Other top products and services in terms of embodied carbon in their trade are sea and coastal water transportation services, air transportation services, and aluminum.

Table 4. Top products by embodied CO_2 emissions in trade in 2019.

Rank	Product	Embodied Emissions in Trade ($MtCO_2$)
1	Basic Iron and Steel	696
2	Chemicals	478
3	Aluminum and aluminum products	334
4	Sea and coastal water transportation services	271
5	Air transport services	231
6	Cement, lime and plaster	148
7	Other non-metallic mineral products	109
8	Fabricated metal products, except machinery and equipment	108
9	Textiles	91
10	Furniture; other manufactured goods	79
11	Coke; Oven Coke	67
12	Wearing apparel and furs	58
13	Electrical machinery and apparatus	49
14	Machinery and equipment	49
15	Copper ores and concentrates	47
16	Rubber and plastic products	45
17	Plastics, basic	43
18	Radio, television and communication equipment and apparatus	42
19	Glass and glass products	42
20	Motor vehicles, trailers and semi-trailers	41

3 Regional Case-Studies of Embodied Carbon in Trade

For the country-level case studies, we analyzed China, India, Canada, Russia, U.S., and Japan, which covers the top five GHG-emitting countries in the world, plus Canada (ranks 10th and is the only G7 country that is a net exporter of embodied emissions). These six countries combined account for around 60% of global CO_2 emissions (UCS 2022). The share of embodied carbon in exports from these 6 countries combined account for around 45% of global embedded emissions in trade. The share of embodied carbon in imports of these 6 countries combined account for around 39% of global embedded emissions in trade. For regional-level case studies, we analyzed EU27, G7, Global South, and Global North. The subsections below explain the results of our analysis for each case study in more detail.

3.1. China

China is the world's largest GHG emitter. China is a net exporter of embodied carbon. The embodied CO_2 emissions in imports into China are half of the embodied CO_2 emissions in its exports. In 2019, the country's territorial (production-based) CO_2 emissions were around 10 Gigatons of CO_2 (Gt CO_2). Known as the factory of the world, China's emissions embodied in exports in 2019 were the highest in the world. The country released 1.8 Gt CO_2 in 2019 to produce exported products for the rest of the world. That's equal to 17% of China's total territorial (production-based) CO_2 emissions (Table 5). Two factors contributed significantly to large emissions embodied in Chinese exports: 1) China has been the world's largest manufacturer with a relatively carbon-intensive energy system, and 2) energy-intensive commodities such as steel and chemical have a significant share in China's overall export structure.

Table 5. China's CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	10,258
Consumption-based CO_2 emissions	9,355
CO_2 emissions embodied in exports	1,757
CO_2 emissions embodied in imports	854
CO_2 emissions embodied in net export	903

After joining World Trade Organization (WTO) in 2001, China's export increased suddenly. That in conjunction with economic development and urbanization in China has contributed to the increasing trends of production-based and consumption-based emissions (Figure 7).

After a slowdown in both production-based and consumption-based emissions CO_2 emissions between 2012 and 2015 caused by the economic slowdown in China, the emissions have picked up their increasing trend since 2015. This trend needs to peak and start reversing if China wants to achieve its Paris Agreement climate target to reach peak CO_2 emissions before 2030 and striving to achieve carbon neutrality before 2060.

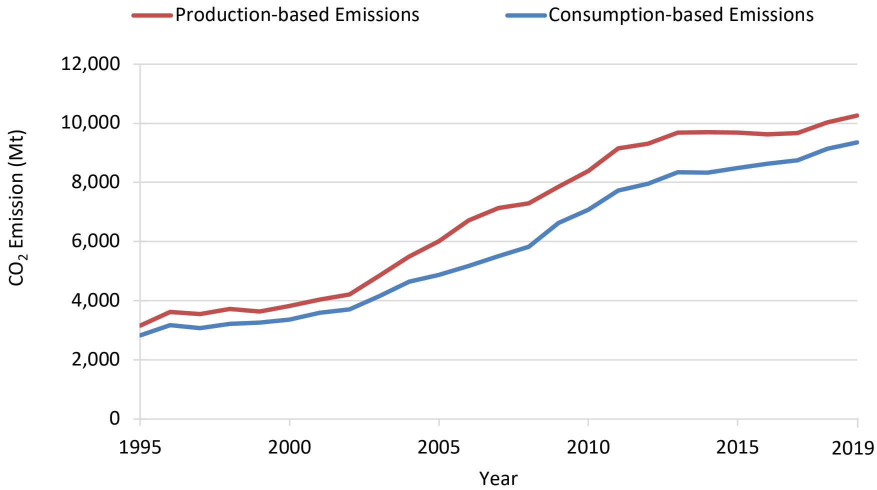


Figure 7. China's territorial (production-based) and consumption-based CO_2 emissions (source: this study).
Note: the gap between production-based and consumption-based emissions is the net export of embodied CO_2.

China's strategic position in international trade is reflected in the interconnection of its production system and global value chain. China has been a crucial trade partner of some large economies like the United States, Japan, India, Russia, and some of the EU countries, producing goods and services to later be exported to those countries (Table 6). The Other Asia and Pacific region, United States, and Middle East are its top destinations of emissions embodied in export in 2019. Emissions embodied in trade to India ranked 24^{th} in 1995 and jumped to 7^{th} in 2019.

China is also a substantial importer of emissions, which represent 9 % of domestic consumption emissions. Emissions embodied in China's imports from Japan accounted for 72 Mt CO_2, higher than any countries in 2019. Emissions embodied in trade from Russia ranked fourth in 2019, accounting for 60 Mt CO_2. In 2019, the U.S. released 55 Mt CO_2 to produce goods and services to be exported to China.

Table 6. China's trade partners, by import and export of embodied CO_2 in 2019 (source: this study).

Exports			Imports		
Consumer	Embodied CO_2 Emissions in Exports (Mt CO_2)	Rank	Origin Country	Embodied CO_2 Emissions in Imports (Mt CO_2)	Rank
Other Asia and Pacific	430	1	Other Asia and Pacific	205	1
United States	349	2	Middle East	110	2
Middle East	135	3	Japan	72	3
Japan	100	4	Russia	60	4
Central & South America (Excl. Brazil)	80	5	United States	55	5
Africa (Excl. South Africa)	71	6	South Korea	44	6
India	69	7	Central & South America (Excl. Brazil)	41	7
South Korea	60	8	Indonesia	31	8
Germany	53	9	Brazil	30	9
United Kingdom	37	10	Australia	29	10

3.2. Russia

The role of Russia in the production and export of energy products, particularly oil and gas, contributes significantly to the global embodied carbon in trade. In 2019, Russia produced 1,516 Mt CO_2 from the production of domestic and exported goods and services. The country's emissions embodied in exports reached 462 Mt CO_2 in 2019 (Table 7). In the same year, Russia's consumption of import products was responsible for 138 Mt CO_2 emissions in other countries.

Table 7. Russia's CO_2 emissions in 2019 (source: this study).

	CO_2 emissions (MtCO_2)
Territorial (production-based) CO_2 emissions	1,516
Consumption-based CO_2 emissions	1,191
CO_2 emissions embodied in exports	462
CO_2 emissions embodied in imports	138
CO_2 emissions embodied in net exports	324

Given the latest conflict in Ukraine, many have called for a rapid transition to renewables. This is not only because the increasing reliance of European countries on Russia's gas has become detrimental to them geopolitically, but also due to the number of emissions released to produce and supply oil and gas. It should be noted that our values do not account for the high amounts of fugitive methane emissions from Russian oil and gas production. The country's production-based emissions are larger than its consumption-based emissions, making Russia a net exporter of embodied carbon emissions (Figure 8).

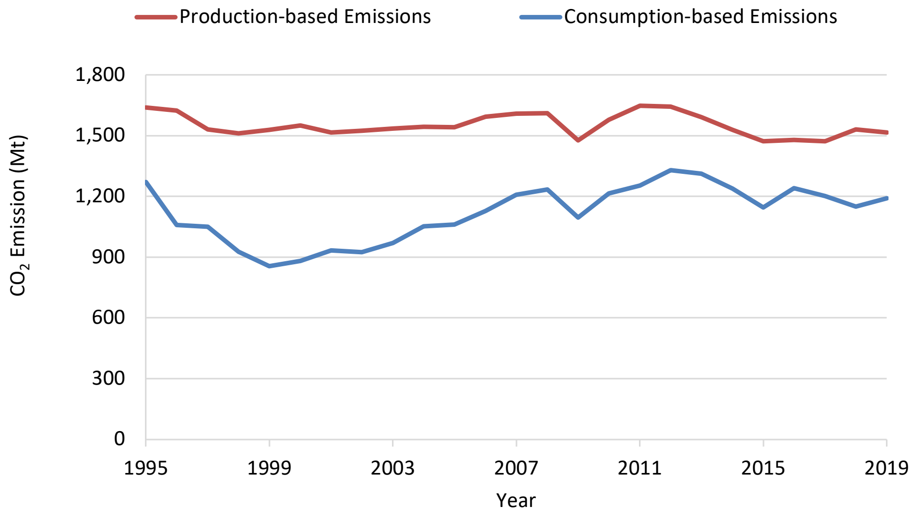


Figure 8. Russia's territorial (production-based) and consumption-based CO_2 emissions (source: this study).

China, Italy, and the U.S. are the top three (individual-country) destinations of embodied emissions from Russia. China ranked 5th in 1995 and 1st in 2019. Emissions embodied in Russia's imports from China ranked 3rd in 1995 and climbed to 1st in 2019. Other top-ranked countries by embodied emissions in Russia's imports include Germany, Turkey, and the U.S.

Table 8. Russia's trade partners, by import and export of embodied CO_2 in 2019 (source: this study)

Exports			Imports		
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports ($MtCO_2$)	Rank
China	60	1	China	32	1
Other Europe	55	2	Other Asia and Pacific	24	2
Other Asia and Pacific	46	3	Other Europe	20	3
Italy	37	4	Middle East	9	4
United States	26	5	Germany	4	5
Germany	21	6	Turkey	4	6
Middle East	20	7	Central & South America (Excl. Brazil)	3	7
South Korea	14	8	United States	3	8
Turkey	13	9	India	3	9
Africa (Excl. South Africa)	13	10	Poland	3	10

3.3. India

As the second most populated country, India's domestic consumption has also increased dramatically since 1995. India's territorial emissions were 832 Mt CO_2 in 1995 and 2,308 Mt CO_2 in 2019, almost a threefold increase. This increase can also be observed in the country's consumption-based emissions. Both accounts have been increasing since 1995.

As a rapidly growing economy, India's emission profile has increasingly been linked with the country's population and economic growth. The economic growth and industrialization in India mainly rely on fossil fuel energy in both the industry and power sectors. India's production- and consumption-based emissions are roughly equal with CO_2 emissions embodied in exports slightly larger than CO_2 emissions embodied in imports (Table 9, Figure 9).

Table 9. India's CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	2,308
Consumption-based CO_2 emissions	2,265
CO_2 emissions embodied in exports	326
CO_2 emissions embodied in imports	283
CO_2 emissions embodied in net exports	43

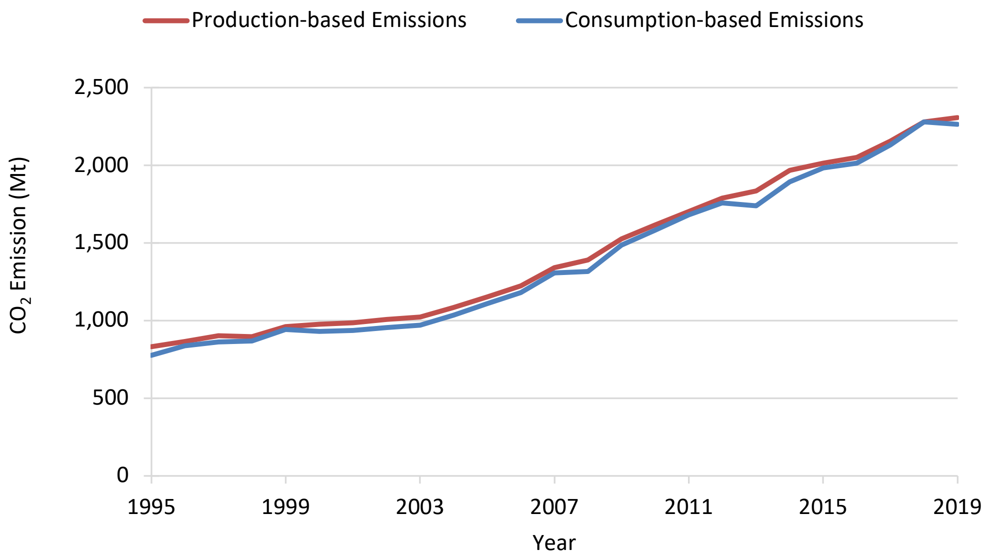


Figure 9. India's territorial (production-based) and consumption-based CO_2 emissions (source: this study).

The U.S. was the largest individual importer of emissions embodied in trade from India in 2019, followed by China, the UK, and Germany. On the other side, China has been the top exporter of emissions to India since 1995. In 2019, 67 Mt CO_2 emissions were emitted by China to produce products exported to India. The other top exporters of embodied emissions to India are Middle East, Other Asia and Pacific, and the U.S. (Table 10).

Table 10. India's trade partners, by imports and exports of embodied CO_2 in 2019 (source: this study).

	Exports			Imports	
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports ($MtCO_2$)	Rank
Middle East	68	1	China	67	1
Other Asia and Pacific	53	2	Middle East	55	2
United States	47	3	Other Asia and Pacific	45	3
China	28	4	United States	12	4
Africa (Excl. South Africa)	24	5	Indonesia	11	5
United Kingdom	9	6	South Africa	10	6
Germany	9	7	Russia	9	7
Central & South America (Excl. Brazil)	8	8	Japan	9	8
France	6	9	Central & South America (Excl. Brazil)	8	9
Japan	6	10	South Korea	7	10

3.4. Canada

Canada has been a net exporter of emissions since 1995, meaning the country produces more emissions for exports than for imports. The case of Canada is an exception within the developed economies. Most of this positive emissions balance is contributed by the embodied emissions in exports to its closest trading partner, the US. In 2019, almost 40% of its production-based emissions were the embodied emissions in exports while only 30% of its consumption-based emissions were the embodied emissions in its imports.

Table 11. Canada's CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	589
Consumption-based CO_2 emissions	511
CO_2 emissions embodied in exports	231
CO_2 emissions embodied in imports	153
CO_2 emissions embodied in net exports	78

Since 1995, both production- and consumption-based emissions of Canada has been slowly increasing. In 1995, the country produced almost 500 Mt CO_2 and increases to 589 Mt CO_2. For consumption-based emissions, Canada consumed around 450 Mt CO_2 in 1995 and around 511 Mt CO_2 in 2019 (Figure 9). From 1995 to 2008, its consumption-based emissions slightly increased and converged to production-based emissions. However, after the Crisis, Canada's consumption-based emissions decreased and plateaued.

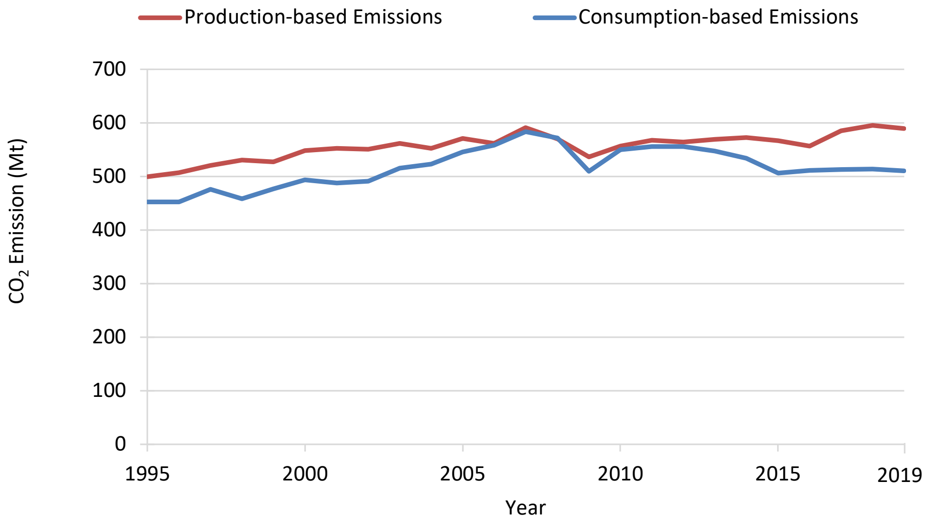


Figure 10. Canada's territorial (production-based) and consumption-based CO_2 emissions (source: this study).

The U.S. is Canada's largest partner in terms of embodied emissions in trade. In 2019, Canada exported 158 Mt CO_2 to the US, almost ten times larger than what it exported to China in the same year (15 Mt CO_2). In the same year, The U.S. and China generated 51 and 35 Mt CO_2 to produce goods and services to be consumed by citizens in Canada, respectively (Table 12). Embodied emissions in exports from Canada to Central and South American countries (excluding Brazil) in 2019 were 9 Mt CO_2. Mexico ranked 4 as the destination of embodied in exports from Canada: 7 Mt CO_2.

Table 12. Canada's trade partners, by import and export of embodied CO_2 in 2019 (source: this study)

Exports			Imports		
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports ($MtCO_2$)	Rank
United States	158	1	United States	51	1
China	15	2	China	35	2
Central & South America (Excl. Brazil)	9	3	Other Asia and Pacific	9	3
Mexico	7	4	Middle East	8	4
Other Asia and Pacific	6	5	Mexico	4	5
Japan	5	6	Japan	4	6
Middle East	4	7	Brazil	4	7
United Kingdom	3	8	Central & South America (Excl. Brazil)	4	8
Germany	3	9	India	4	9
France	2	10	Germany	3	10

3.5. United States

The U.S. has the largest embodied emissions in imports and has been a net importer of emissions since 1995. The embodied emissions in U.S. imports were 1,258 Mt CO_2 in 2019, 28% of which are associated with imports from China and 13% embodied emissions in imports from Canada, U.S.'s two largest trading partners. In the same year, the U.S. released 438 Mt CO_2 emissions to produce products for export (Table 13).

Table 13. The U.S.'s CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	5,014
Consumption-based CO_2 emissions	5,831
CO_2 emissions embodied in exports	440
CO_2 emissions embodied in imports	1,258
CO_2 emissions embodied in net exports	-817*

*The negative value indicates that the U.S. is a net importer of embodied emissions.

The U.S.'s consumption-based emissions have been higher than its production-based emissions each year since 1995. This indicates that higher CO_2 is released both domestically and internationally to produce the goods and services consumed by Americans compared to any other country. The U.S.'s embodied emissions in imports increased significantly from 1995 and peaked just before the 2008 Global Financial Crisis hit the global economy. During and after the Crisis, the trend declined sharply and has since been relatively stable (Figure 11).

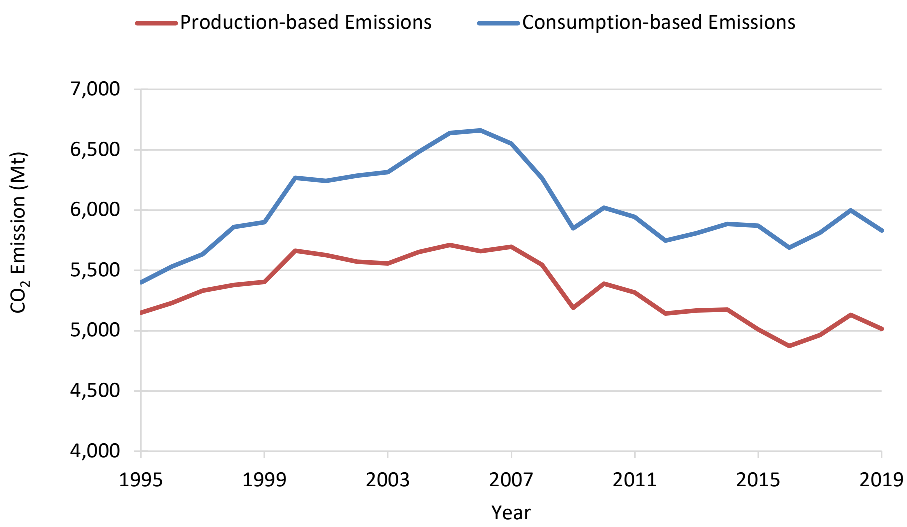


Figure 11. The U.S.'s territorial (production-based) and consumption-based CO_2 emissions (source: this study).

For the U.S., China remains the most significant trade partner, with large volumes of carbon emissions associated with trade since 1995. In 1995, the U.S. imported 114 Mt of CO_2 from China, while in 2019 this figure tripled to 349 Mt of CO_2 (Table 14). Canada ranked third in 1995 and second in 2019 in terms of emissions embodied in exports to the U.S.. Several countries show an increasing role in supplying products and associated embodied emissions to the U.S.. Mexico ranked 13^{th} in embodied emissions in exports to the U.S. in 1995 and climbed to

5th place in 2019. India ranked 7th in 2019 for embodied carbon in exports to the U.S., while the country was nowhere near the top 10 in 1995. Brazil as the exporter of embodied emissions to the U.S. climbed 16 positions from 25th in 1995 to the 9th in 2019. The U.S. exported 50 Mt CO_2 of embodied carbon to Central and South America region.

China, Canada, Central & South America (Excl. Brazil), Mexico, and Other Asia and Pacific region are the top 5 destination of embodied carbon in U.S. exports. U.S. exported 55 Mt of CO_2 to China and 51 Mt of CO_2 to Canada in 2019.

Table 14. the U.S.'s trade partners, by import and export of embodied CO_2 in 2019.

Exports			Imports		
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports ($MtCO_2$)	Rank
China	55	1	China	349	1
Canada	51	2	Canada	158	2
Central & South America (Excl. Brazil)	50	3	Other Asia and Pacific	114	3
Mexico	45	4	Middle East	109	4
Other Asia and Pacific	38	5	Mexico	76	5
Middle East	25	6	Central & South America (Excl. Brazil)	52	6
Japan	24	7	India	48	7
Germany	15	8	Japan	46	8
United Kingdom	15	9	Brazil	30	9
Brazil	14	10	Germany	28	10

3.6. Japan

Japan is a net importer of embodied emissions. The embodied emissions in Japanese imports were 325 Mt CO_2 in 2019, around one-third of which are associated with imports from China and 20% embodied emissions in imports from "Other Asia and Pacific" region. In the same year, Japan released 274 Mt CO_2 emissions to produce products for export (Table 15).

Table 15. Japan's CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	1,158
Consumption-based CO_2 emissions	1,209
CO_2 emissions embodied in exports	274
CO_2 emissions embodied in imports	325
CO_2 emissions embodied in net exports	-51*

*The negative value indicates that Japan is a net importer of embodied emissions.

Japan's consumption-based emissions have been higher than its production-based emissions since 1995 although in recent years, the gap has been narrowed. Japan's consumption-based emissions peaked in 2012 and have been declining sharply since then (Figure 12).

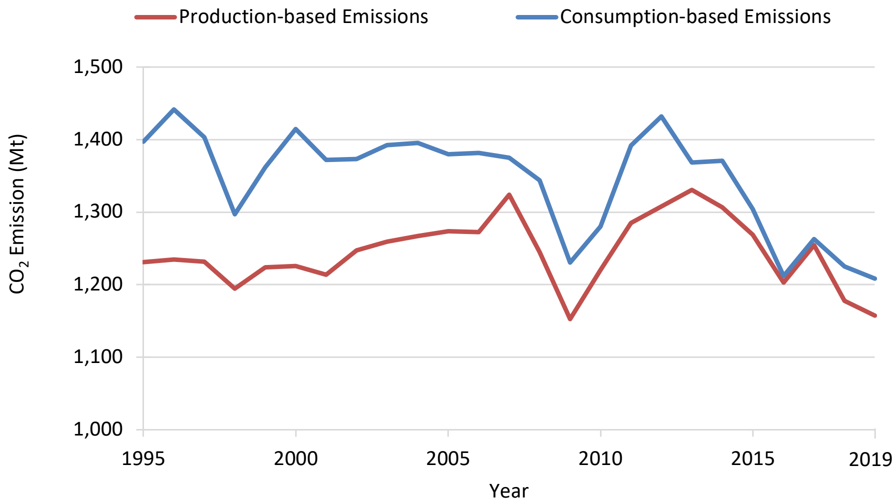


Figure 12. Japan's territorial (production-based) and consumption-based CO_2 emissions (source: this study).

China is the most significant trade partner of Japan, with large volumes of carbon emissions associated with trade since 1995. In 2019, Japan imported 100 Mt of embodied CO_2 from China (Table 14). Other Asia and Pacific region ranked second in 2019 in terms of emissions embodied in import from and exports to Japan. Middle East, United States and South Korea are other key trading partners with substantial embodied carbon in their trade with Japan.

Table 16. Japan's trade partners, by import and export of embodied CO_2 in 2019.

Exports			Imports		
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports ($MtCO_2$)	Rank
China	72	1	China	100	1
Other Asia and Pacific	52	2	Other Asia and Pacific	66	2
United States	46	3	Middle East	32	3
South Korea	17	4	United States	24	4
Middle East	13	5	South Korea	14	5
India	9	6	Russia	11	6
Germany	6	7	Australia	10	7
Central & South America (Excl. Brazil)	6	8	Indonesia	9	8
Indonesia	6	9	Taiwan	7	9
United Kingdom	4	10	India	7	10

3.7. European Union (EU 27)

The EU27 region in general has higher embodied emissions in imports than exports, making them a net importer of emissions. In 2019, EU 27 in total produced 2,732 Mt CO_2 within its territory. In the same year, EU 27's total consumption was responsible for 3,162 Mt CO_2 emissions. The EU 27 imported 1,023 Mt CO_2 and exported 592 Mt CO_2 of embodied emissions. The European Council officially accepted a framework for a carbon border adjustment mechanism (CBAM) seeking to reduce carbon leakage on imports, specifically targeting fertilizers, steel, iron, cement, aluminum, and electric energy production (European Council, 2022).

Table 17. EU 27 CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	2,732
Consumption-based CO_2 emissions	3,162
CO_2 emissions embodied in exports	592
CO_2 emissions embodied in imports	1,023
CO_2 emissions embodied in net exports	-430*

*The negative value indicates that the EU27 is a net importer of embodied emissions.

Similar to the U.S., the EU 27's territorial and consumption-based emissions increased from 1995 to around 2007, and then have been slowly declining (Figure 13).

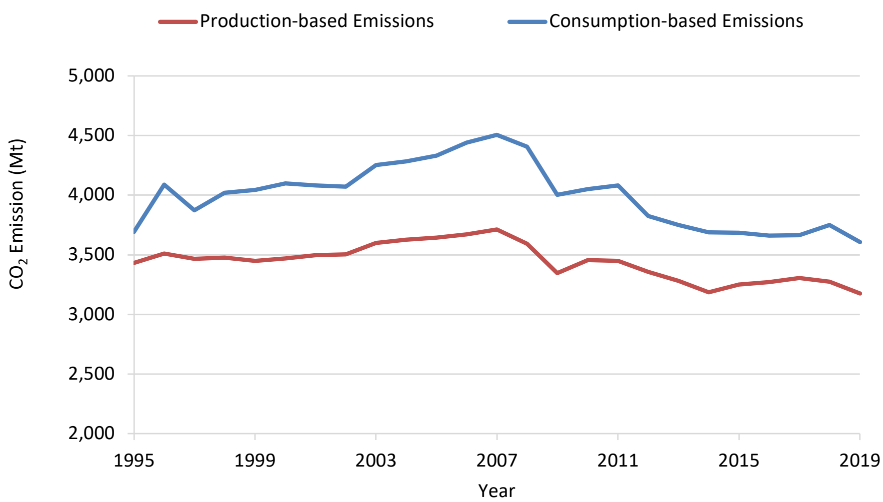


Figure 13. EU27's territorial (production-based) and consumption-based CO_2 emissions (source: this study)

The U.S. was the largest individual consumer of embodied emissions in EU 27 export in 2019, with 102 Mt CO_2 emissions. The embodied emissions in exports from EU 27 to the UK were the second largest, 74 Mt CO_2. In the same year, exports from EU27 to China had 71 Mt CO_2 in embodied emissions. Imports from China had the largest embodied emission in EU27 imports (201 MtCO2) followed by imports from Russia (154 MtCO2) and the U.S. (63 MtCO2) (Table 18).

Table 18. EU 27 trade partners, by import and export of embodied CO_2 in 2019 (Mt CO_2) (source: this study).

Exports			Imports		
Consumer	Embodied Emissions in Exports ($MtCO_2$)	Rank	Origin Country	Embodied Emissions in Imports; ($MtCO_2$)	Rank
United States	102	1	China	201	1
United Kingdom	74	2	Russia	154	2
China	71	3	Other Asia and Pacific	125	3
Middle East	51	4	Middle East	110	4
Other Asia and Pacific	43	5	United States	63	5
Africa (Excl. South Africa)	37	6	United Kingdom	46	6
Other Europe	29	7	Other Europe	45	7
Russia	21	8	India	39	8
Central & South America (Excl. Brazil)	20	9	South Africa	30	9
Switzerland	20	10	Africa (Excl. South Africa)	30	10

3.8. G7 Countries

The Group of Seven (G7) is an inter-governmental political forum consisting of Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States.[1] The G7 accounts for over 50% percent of global net wealth and approximately 10 percent of the world's population.

One of the key outcomes of the latest G7 summit in June 2022 was the establishment of the G7 Climate Club (G7 Germany 2022). In its official statement, the Club builds on the insufficient global climate ambition and implementation and aims to meet the climate goals of the Paris Agreement by accelerating climate actions. The Club notes its attention to address the issues of carbon loophole and carbon leakage. In 2019, the G7's territorial emissions were around 8.1 Gt CO_2 while its consumption-based emissions were around 9.3 Gt CO_2, resulting in a net import of embodied emissions of around 1.2 Gt CO_2 (Table 19).

Table 19. G7 CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	8,081
Consumption-based CO_2 emissions	9,299
CO_2 emissions embodied in exports	918
CO_2 emissions embodied in imports	2,136
CO_2 emissions embodied in net export	-1218*

*The negative value indicates that the G7 is a net importer of embodied emissions.

1 In addition, the European Union is a 'non-enumerated member, but the EU is not included in the G7 embodied emissions analysis.

The consumption-based emissions have been higher than the production-based emissions in G7 since 1995 (Figure 14). When factoring in imports, G7 emissions have risen (not declined) since 1995. Both emissions accounts peaked around 2007 and dropped due to the 2008 Global Financial Crisis. After 2008, both emissions accounts displayed a gradually decreasing trend. U.S. production- and consumption-based emissions have on average contributed to almost 60% of the total G7's production- and consumption-based emissions. Japan, ranked second among G7 members, has contributed around 14% of G7's emissions.

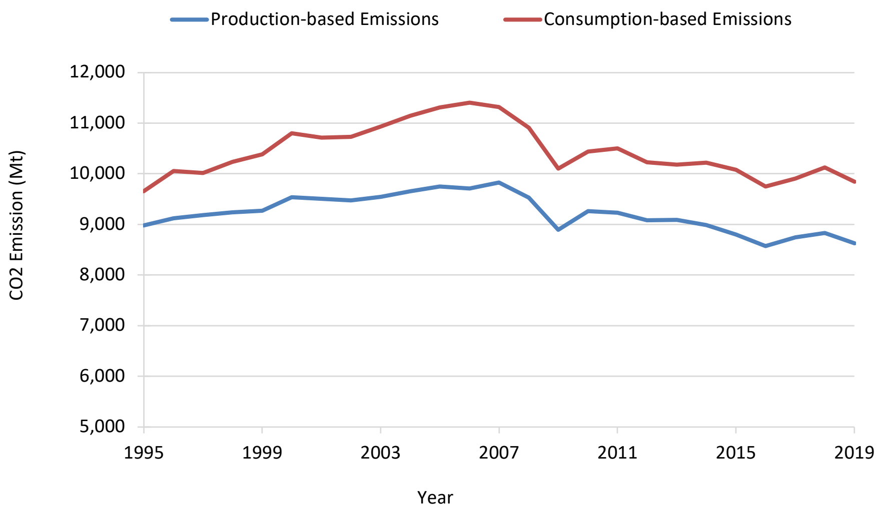


Figure 14 Production-based and consumption-based CO_2 emissions of G7 countries (source: this study).

Since 1995, the emissions embodied in exports from the rest of the world (ROW) to G7 countries have been substantially larger than the emissions embodied in exports from G7 countries to ROW. The margin can be observed from the gap between the red and the blue lines in Figure 15. In 1995, the countries in the ROW exported around 1,200 Mt CO_2 emissions to G7 countries. These figures increased and peaked when other countries exported over 2,300 Mt CO_2 emissions to G7 countries in 2007. Since the 2008 Global Financial Crisis, the emissions embodied in exports to G7 countries have stabilized between 1,800 and 2,200 Mt CO_2. The emissions embodied in the exports from G7 to the rest of the world gradually increased from 1995 to 2007 and have since then plateaued. The emissions embodied in trade within G7 member countries (intra-G7 trade) have also been stable since 1995, implying the significant role of production and embodied emissions outside of G7 members for the consumption of G7 countries.

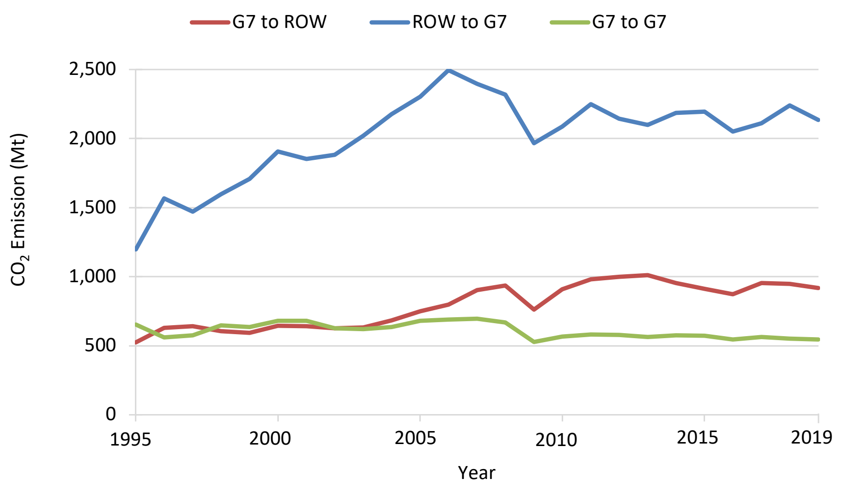


Figure 15. CO_2 emissions are embodied in exports. (Note: ROW denotes the countries in the rest of the world besides G7 countries.) (Source: this study).

China is by far the largest exporter of embodied emissions to the G7 countries. In 2019, China exported 624 Mt CO_2 embodied emissions to the G7, more than five times larger than Russia and seven times larger than Mexico and India. China is also the largest importer of embodied emissions from the G7 followed by Mexico and South Korea. However, the embodied emissions in China's export to G7 is more than three times higher than the embodied emissions in G7's export to China (Table 20).

Table 20. Top 10 CO_2 emissions embodied in Exports from G7 and to G7 in 2019 (source: this study).

Rank	Origin	Destination	Embodied Emissions in Exports (Mt CO_2)	Rank	Origin	Destination	Embodied Emissions in Exports (Mt CO_2)
1	G7	China	187	1	China	G7	624
2	G7	Other Asia and Pacific	121	2	Other Asia and Pacific	G7	277
3	G7	Central & South America (Excl. Brazil)	76	3	Middle East	G7	225
4	G7	Middle East	68	4	Russia	G7	119
5	G7	Mexico	59	5	India	G7	88
6	G7	South Korea	39	6	Mexico	G7	87
7	G7	India	33	7	Central & South America (Excl. Brazil)	G7	75
8	G7	Africa (Excl. South Africa)	32	8	South Korea	G7	48
9	G7	Brazil	27	9	South Africa	G7	47
10	G7	Spain	25	10	Brazil	G7	45

3.9. Global South and Global North

Climate negotiations are centered around the concern of responsibility and equity, particularly between developed countries of the Global North and developing countries of the Global South. There are numerous definitions of Global North and Global South categorizations, which initially were used to divide the world into two groups according to the income per capita. This definition is often expanded to relate the development indicator with other dimensions, for instance, climate-related indicators like CO_2 emissions.

Generally speaking, the countries of the Global North have well-developed, mature economies and are both wealthy and politically stable. They also tend to be the most technologically advanced countries and their population growth is low. Most are located in North America, Europe, and Northern Asia. The Global North has roughly 25% of the world's population, but earns 80% of the wealth and tends to have higher influence globally both politically and economically. Countries in the Global South, by comparison, are those whose economies are still developing (World Population Review 2022).

As for this report, to arrive at a more meaningful insight, the North-South categorization combines two dimensions: income per capita and production- and consumption-based emissions. The complete list of countries included in the analysis is provided in Appendix 3.

Global South CO_2 emissions

In Global South countries both consumption-based and production-based emissions have increased substantially since 1995. Their combined territorial (production-based) CO_2 emissions were 19,592 Mt CO_2 in 2019, while their consumption-based emissions were slightly lower at 18,293 Mt CO_2 in that year (Table 21).

Table 21. Global South CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	19,592
Consumption-based CO_2 emissions	18,293
CO_2 emissions embodied in exports	2,491
CO_2 emissions embodied in imports	1,191
CO_2 emissions embodied in net exports	1300

Both emission accounts increased almost three-fold between 1995 and 2019 (Figure 16). This trend is attributable to the size of the domestic market of some big economies in the South, particularly China, India, Brazil, Indonesia, and South Africa. The carbon emissions embodied in domestic consumption in other Global South countries have also risen significantly as countries develop further, reflecting the increasing role of domestic consumption in driving up the production- and consumption-based emissions in Global South.

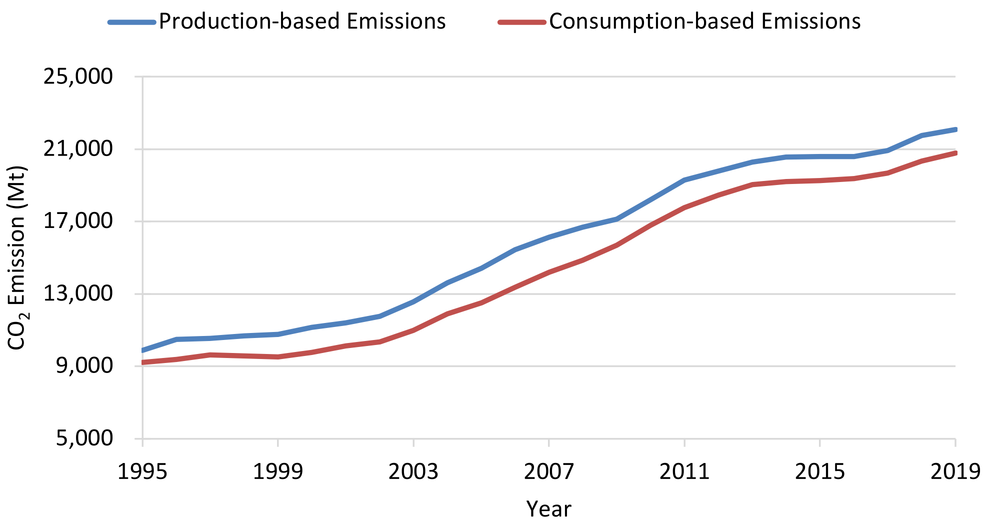


Figure 16. Total Production-based and Consumption-based CO_2 emissions of Global South countries (source: this study).

In general, the results confirm the mainstream understanding that Global South produces more emissions than it consumes to produce goods and services exported to Global North countries. As shown in Figure 17, the emissions embodied in exports from South to North increased considerably between 1995 to the year before the Global Financial Crisis in 2008. Since then, the trend has plateaued. The emergence of (emissions) trade between Global South countries can also be observed, as the trend has increased nearly four-fold since 1995 and has stabilized in the last decade.

This significant increase in trade between Global South countries has mostly been associated with the rise of China as a global production hub in the past two decades. China produces a large variety of goods not only for Global North countries but also for other countries within Global South. It should be noted that fossil fuels account for 83% of total primary energy used in China (coal 55%, petroleum 19%, natural gas 9%) (EIA 2022). This makes China's manufacturing sector and exported goods more carbon-intensive.

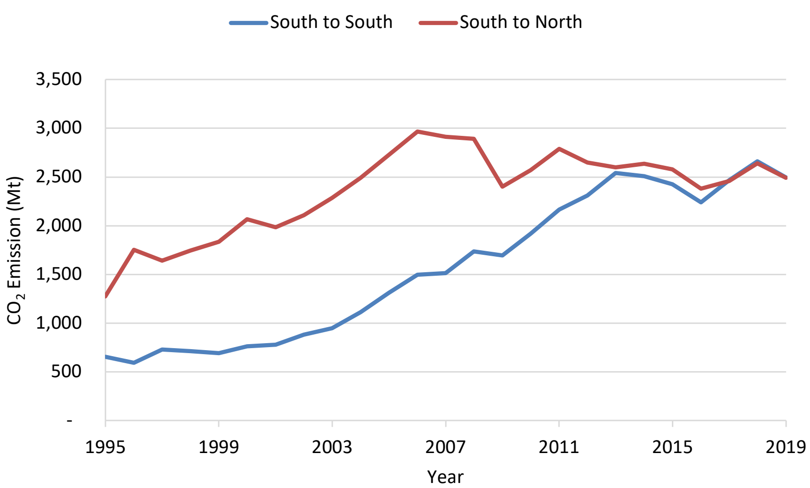


Figure 17. Embodied CO_2 emissions in trade of Global South countries (source: this study).

While the amount and share of embodied carbon exported from Global South to Global North are large, it has been relatively flat in the past 15 years. In the meantime, the embodied carbon from Global South to Global South has been increasing rapidly. For example, larger exporter country like China does not just export embodied carbon to the U.S., EU, and other developed countries, but they also export a massive amount of embodied carbon to countries in the Global South as they develop and expand purchasing power.

Global North CO_2 emissions

The Global North has higher embodied emissions in its imports than in exports. The Global North imported around 1,300 Mt CO_2 of embodied carbon in 2019 (Table 22).

Table 22. Global North CO_2 emissions in 2019 (source: this study).

	CO_2 emissions ($MtCO_2$)
Territorial (production-based) CO_2 emissions	11,008
Consumption-based CO_2 emissions	12,308
CO_2 emissions embodied in exports	1,191
CO_2 emissions embodied in imports	2,491
CO_2 emissions embodied in net exports	-1300*

*The negative value indicates that the Global North is a net importer of embodied emissions.

For Global North, both territorial and consumption-based CO_2 emissions increased considerably between 1995 and 2007 (particularly for consumption-based emissions), dropped significantly between 2007 and 2009, and stabilized afterward (Figure 18).

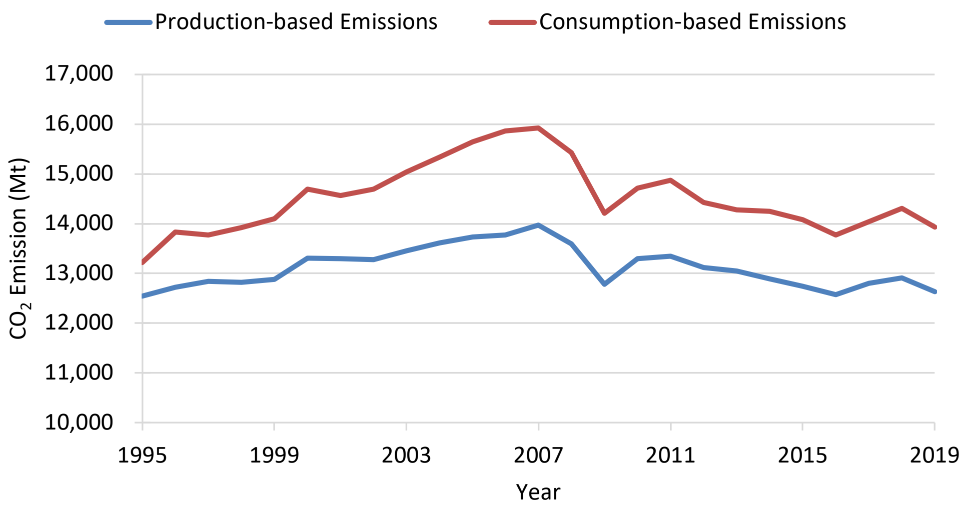


Figure 18. Total Production-based and Consumption-based CO_2 emissions of Global North countries (source: this study).

The embodied emissions in trade within Global North countries have not varied significantly and have remained around 1,600 Mt CO_2 since 1995. However, from 1995 to 2014 the embodied emissions in export from Global North to Global South increased substantially and have plateaued since 2014 (Figure 19).

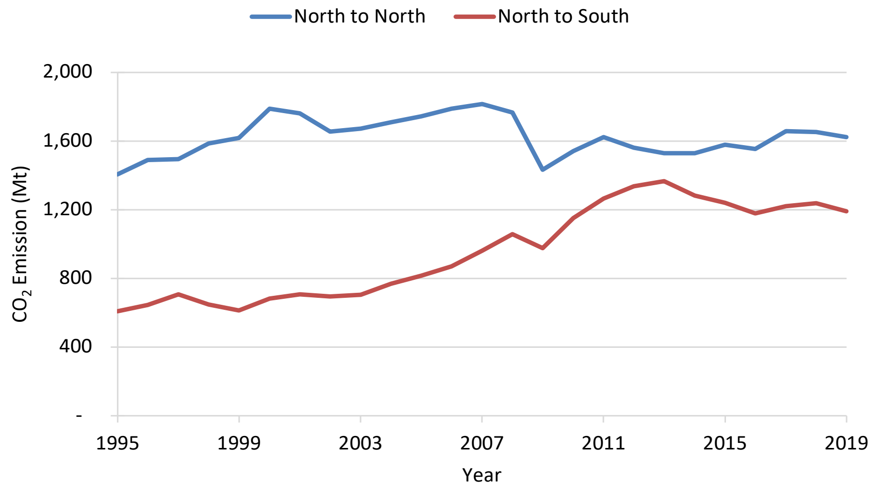


Figure 19. Embodied CO_2 emissions in Trade of Global North countries (source: this study).

Global North countries have structurally shifted their economies towards high-valued services sectors, while the emerging economies in Global South have relatively recently begun industrializing and developing their economies. This is reflected by the patterns of CO_2 emissions in both regions, as the emissions for Global South have in the past two decades risen dramatically and the emissions of Global North have stabilized.

Historically, Global North countries are responsible for a great share of CO_2 emissions, as shown in Figure 20. Their economies largely developed in the presence of available and affordable fossil fuels, driving up global emissions. Global North countries continue to score higher per capita emissions than Global South countries despite annual emissions stabilizing.

Without the technological and institutional capacity for climate change mitigation and adaptation and access to reliable and sufficient capital, Global South will be excessively burdened by the negative impacts of climate change. For these reasons, among others, Global South countries have put forward equity concerns when dealing with the climate crisis.

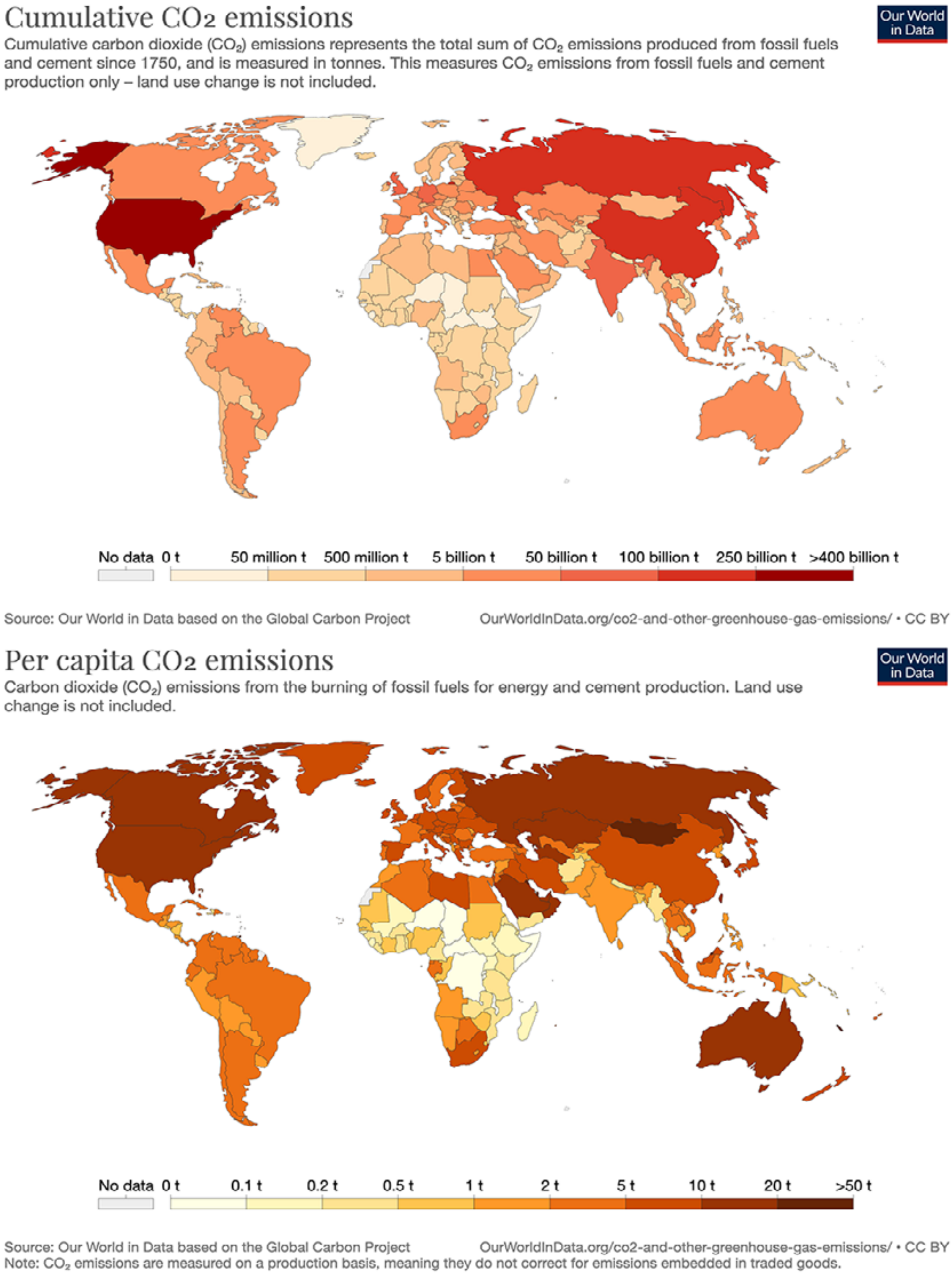
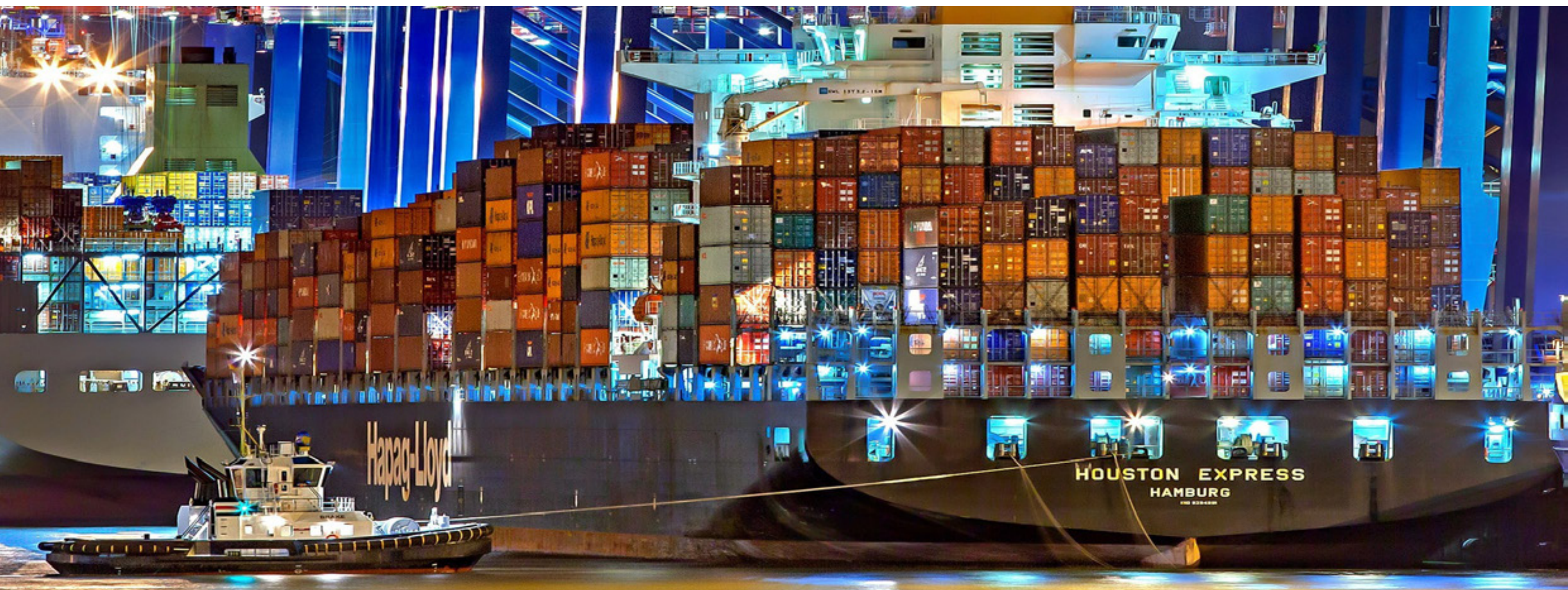


Figure 20. Cumulative CO_2 emissions and per capita CO_2 emissions by country (source: Our World in Data).



4 Sectoral Case-Studies of Embodied Carbon in Trade

We chose four carbon-intensive industrial sectors for deep-dive case studies: steel, cement, aluminum, and chemical industry. The steel, cement, aluminum, and chemical industry account for around 11%, 7%, 2%, and 7% of total global anthropogenic CO_2 emissions, respectively (Hasanbeigi 2022, Hasanbeigi et al. 2022, Hasanbeigi 2021, Rissman et al. 2020). In addition, these emissions-intensive commodities, especially steel, chemicals, and aluminum, are traded at a significant level internationally, making them emissions-intensive trade-exposed sectors (EITEs). The subsections below explain the results of our analysis for each case study in more detail.

It should be highlighted that for the steel, cement, and aluminum deep-dive case studies, our analysis relies on physical values of trade (in tonne) and physical-basis intensities (CO_2/tone), rather than the monetary basis in the country-level analysis above. Overall, such physical-basis analysis gives a more accurate results compared to monetary basis analysis where monetary values of trade (in $) and monetary-basis intensities (CO_2/$). However, for the chemical industry, which is an especially heterogenous sector with many different subsectors and products that are completely different in production and characteristics, it is not possible to do such physical-basis analysis. Therefore, in this report, for the chemical industry deep-dive, we used monetary-basis using data from the EXIOBASE database.

4.1. Global Embodied Carbon in Steel Trade

Steel is a highly CO_2-intensive product that is also traded globally in significant amounts. The steel industry accounts for around 11% of global CO_2 emissions (Hasanbeigi 2022).

Embodied Carbon in Commodity Steel Trade

Commodity steel refers to steel that is produced and traded directly, not steel-containing products. According to the worldsteel (2022), China exported 66 Mt of commodity steel in 2021, which is equal to 77% of the entire steel production in the U.S. in that year. The significant global trade of such a carbon-intensive commodity has substantial implications for the carbon loophole (Figure 21).

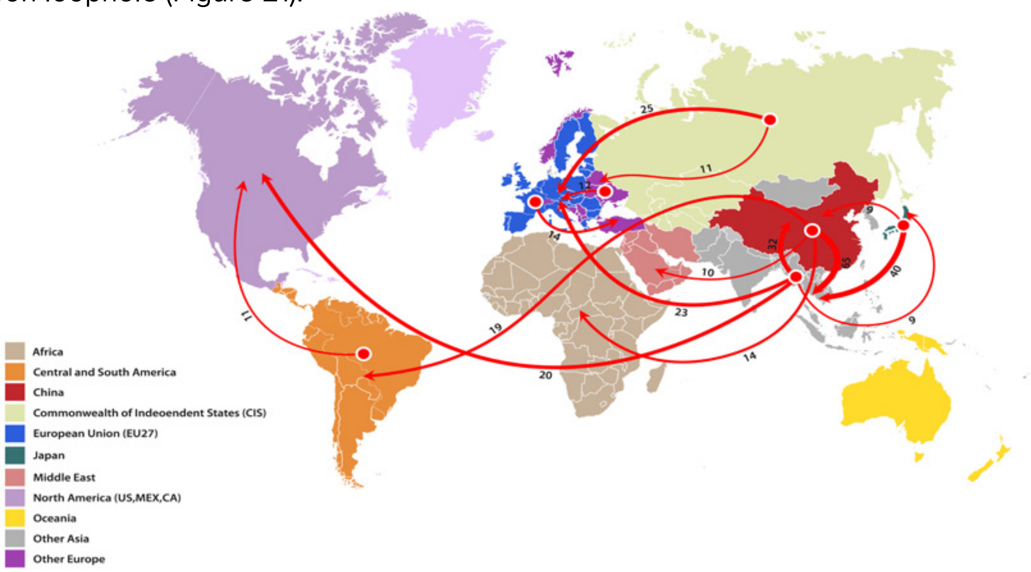


Figure 21. Top 15 extra-regional flows of CO_2 emissions related to the international trade of commodity steel in 2021 (values in Mt CO_2) (source: this study).

The top 3 largest flows of embodied carbon in commodity steel trade are from China to "Other Asia", Japan to "Other Asia", and "Other Asia" to China. The total embodied carbon in the international trade of commodity steel in 2021 was around 700 Mt CO_2. This is equal to 19% of total CO_2 emissions from the global steel industry.

Around 65% of the embodied carbon in the commodity steel trade is extra-regional (between different global regions, highlighted in the figure), while the remainder is traded within each region. China is the largest net exporter and North America is the largest net importer of embodied carbon in the commodity steel trade. The 'Other Asia[2]' region has a large amount of both extra-regional import and export of the embodied carbon in the commodity steel trade.

The top three largest flows of embodied carbon in the commodity steel trade are from China to Other Asia, Japan to Other Asia, and Other Asia to China. Except for China, Japan, and the Commonwealth of Independent States (CIS)[3], all regions of the world are net importers of carbon emissions embodied in commodity steel. North America, Africa and the Middle East, and EU27 are the largest net importers of carbon embodied in the commodity steel trade (Figure 22).

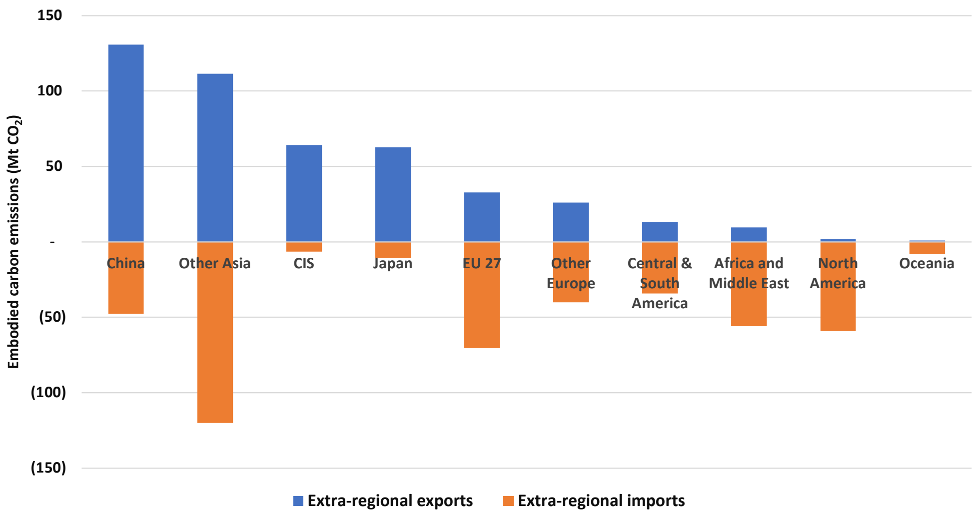


Figure 22. World trade of carbon embodied in commodity steel by region in 2021 (source: this study).

Figure 23 shows the top 10 exporter countries for embodied carbon in the commodity steel trade. China alone accounts for around 20% of the total export of embodied carbon in the commodity steel trade globally. Other top embodied carbon-exporting countries for commodity steel are Japan, Russia, and South Korea. The steel production in these four countries is highly carbon-intensive because a high share of steel is produced using the energy-and carbon-intensive Blast Furnace-Basic Oxygen Furnace process as opposed to the Electric Arc Furnace process which uses significantly less energy and primarily uses steel scrap (Hasanbeigi 2022).

2 Other Asia region includes countries in Asia continent except China, Japan, and countries in Middle East and Commonwealth of Independent States (CIS) region which are separately identified in the map and in this analysis.

3 Commonwealth of Independent States (CIS) countries are Azerbaijan, Armenia, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan, and Ukraine.

China's domestic steel demand has peaked, yet 80% of its steel production capacity is less than 15 years old. Therefore, it is likely that China will look to increase its steel export in the coming years, potentially shifting to the export of more value-added steel products instead of commodity steel and facilitating increased demand for steel products in countries connected to its Belt and Road initiative.

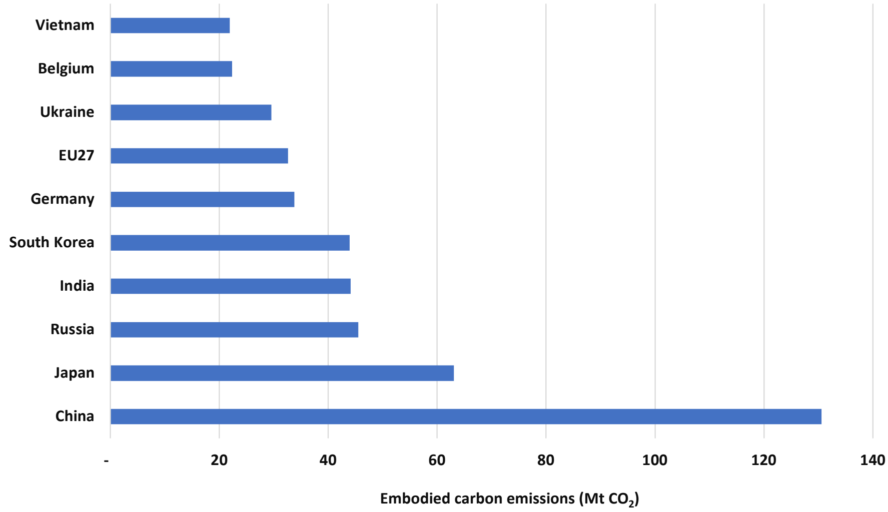


Figure 23. Embodied carbon of top 10 major exporter countries of commodity steel in 2021 (source: this study).

Embodied Carbon in Indirect Steel Trade

There is also substantial trade in steel-containing products such as automotive, metal products, machinery, domestic appliances, etc. The indirect trade in steel made up around 20% of the steel used in 2019. The indirect export of steel through steel-containing products was 359 Mt in 2019 (worldsteel 2022). This is equivalent to 78% of commodity steel exports, accounting for a significant share of embodied carbon flow. The top 10 countries listed in Figure 24 account for about 70% of the total indirect export of steel through steel-containing products.

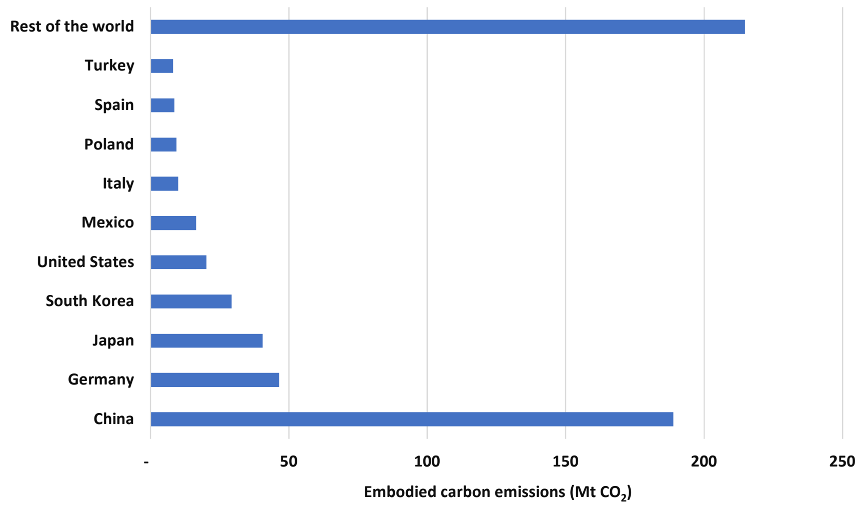


Figure 24. Embodied carbon in exported steel-containing products for the top 10 countries in 2019 (source: this study).

Figure 24 shows the embodied carbon in exported steel-containing products for each country and the rest of the world. China accounted for one-third of the world's embodied carbon in exported steel-containing products. As the Chinese economy matures and demand for infrastructure and building construction decreases, China will increasingly shift from commodity export to value-added steel-containing products export. Thus, China's export of embodied carbon in value-added steel products is likely to increase in the coming years.

Also, many of the countries ranked high for embodied carbon in exported value-added steel products in Figure 24 are substantial importers of commodity steel (Worldsteel 2022). In other words, they import significant amounts of commodity steel that may have high embodied carbon, produce high value-added steel-containing products, and export a substantial portion of those products. These countries gain more economic benefits from trade in value-added steel-containing products without being held accountable for the high CO_2 emissions (Scope 3 emissions) that occur during commodity steel production in their supply chains.

4.2. Global Embodied Carbon in Cement and Clinker Trade

Cement is one of the most energy- and carbon-intensive products that are also traded globally in significant quantities. The cement industry accounts for around 7% of global CO_2 emissions (Hasanbeigi 2021). The production of one ton of cement releases about 0.6 – 1.0 tons of CO_2 depending on the clinker-to-cement ratio, fuel mix, and other factors. More than half of the CO_2 emissions in cement manufacturing are from the chemical reaction in the calcination process in which limestone ($CaCO_3$) is transformed into lime (CaO) and byproduct CO_2. The rest of the CO_2 emitted is the result of burning fuel to provide the heat for calcination, electricity use, and quarry mining and transport. Clinker is an intermediary product in the cement production process that is also traded globally. In this report, we analyzed the embodied carbon in cement trade and clinker trade separately as shown in the subsections below.

Embodied Carbon in Cement Trade

Figure 25 illustrates the embodied carbon in the cement trade worldwide. Around 46% of the embodied carbon in the cement trade is extra-regional (between different global regions, highlighted in the figure), while the remainder is traded within each region.

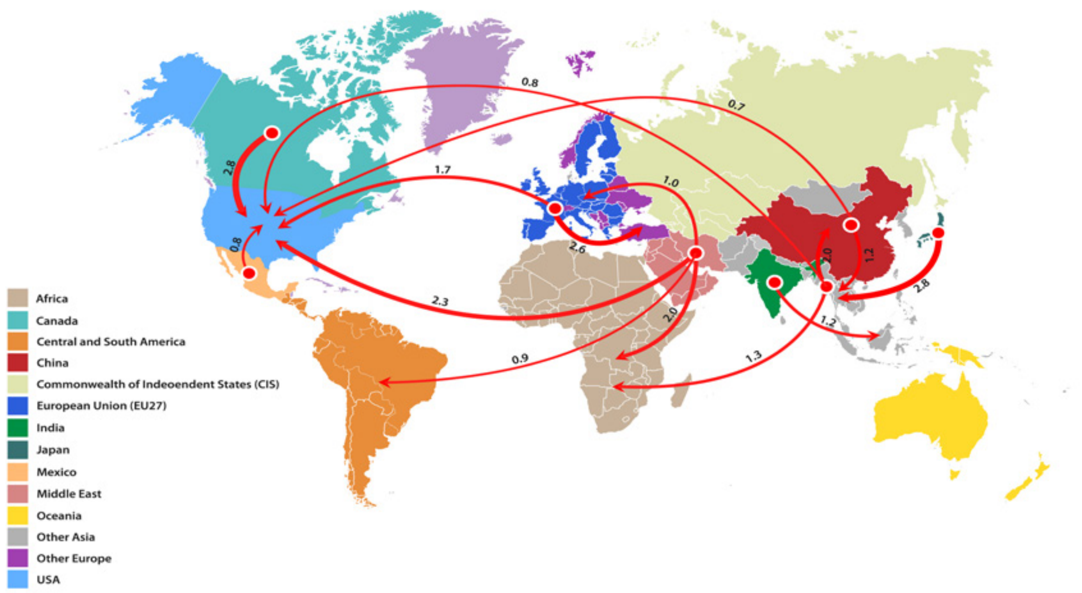


Figure 25. Top 15 extra-regional flows of CO_2 emissions relating to the international cement trade in 2019 (values in Mt CO_2) (source: this study).

The top 3 largest flows of embodied carbon in cement trade are from Japan to Other Asia[4], Canada to the U.S., and EU27 to Other Europe[5].

The total embodied carbon in the international trade of cement and clinker in 2019 was around 141 Mt CO_2. This is equal to around 6% of total CO_2 emissions from the global cement industry.

United States is the largest net importer of carbon embodied in cement, followed by Africa, "Other Europe" and "central and South America" regions, while the Middle East, Japan, and EU27 regions are the three largest net exporters of embodied carbon in cement (Figure 26). Since many countries in Africa and Central and South America are rapidly developing, these regions will likely continue to be large net importers of embodied carbon in cement unless their domestic cement production capacity increases.

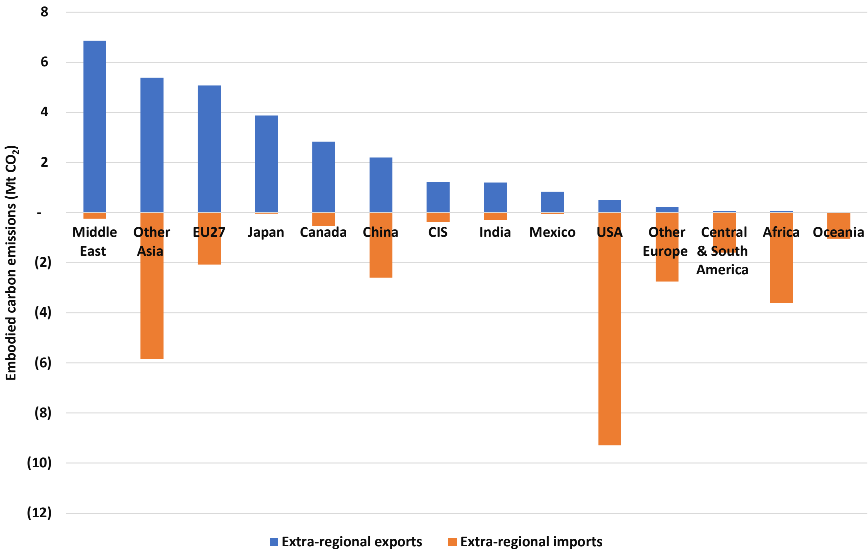


Figure 26. World trade of carbon embodied in cement by region in 2019 (source: this study).

Embodied Carbon in Clinker Trade

The embodied carbon in the extra-regional clinker trade worldwide is even larger than the embodied carbon in the cement trade. Clinker is an intermediary product in the cement production process. Due to process emissions and combustion of fuel for heat, around 95% of the CO_2 emitted in the cement industry is for clinker production. To reduce shipment costs, clinker is often traded instead of cement. In the destination country, the clinker is ground with some additives (e.g. gypsum, fly ash, etc.) to produce cement. Figure 27 shows the embodied carbon in the clinker trade worldwide. The top 3 largest flows of embodied carbon in clinker trade are from Other Asia to China, the Middle East to Africa, and the Middle East to Other Asia.

4 Other Asia region includes countries in Asia continent except India, China, Japan, and countries in Middle East and Commonwealth of Independent States (CIS) region which are separately identified in the map and in this analysis. It should be noted that unlike in steel trade analysis, India is not included in Other Asia region because different sources of data were used for the cement and steel trade.

5 Other Europe region include all European countries that are not a member of EU27.

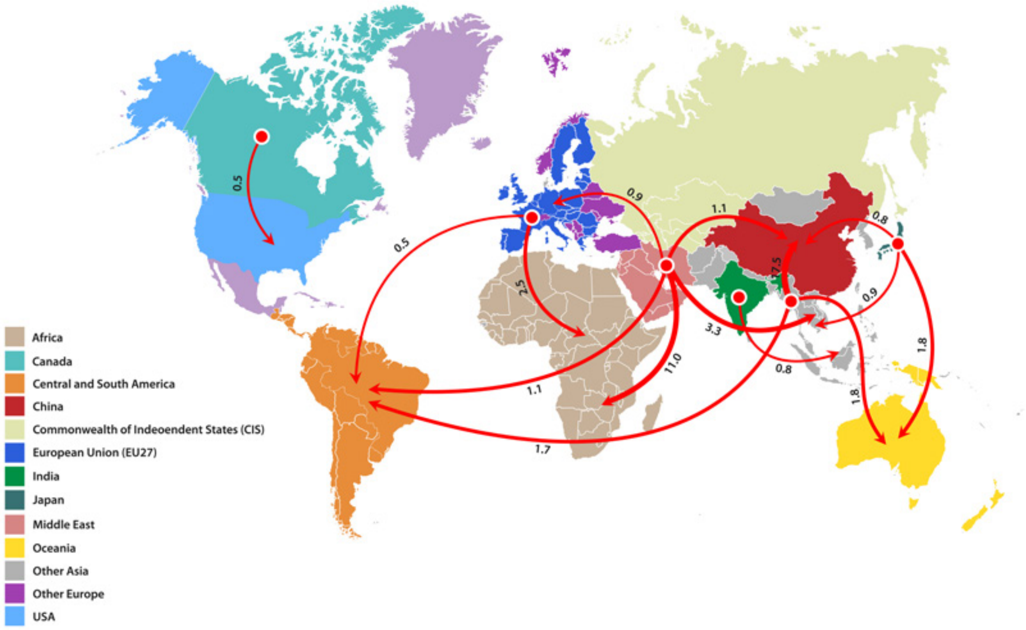


Figure 27. Top 15 extra-regional flows of CO_2 emissions associated with international clinker trade in 2019 (values in Mt CO_2) (source: this study).

Around 66% of the embodied carbon in the clinker trade is extra-regional (between different global regions, highlighted in the figure) while the remainder is traded within each region. The Middle East, Other Asia, and Japan are the three largest net exporters of embodied carbon in the clinker trade. China, Africa, and Oceania are the largest net importers of embodied carbon in the clinker trade (Figure 28). An interesting finding is that even though China accounts for over half of the world's total cement production and based on various reports has an overcapacity of cement production, it imports a substantial amount of clinker from Other Asian countries (majority from Vietnam but also substantial clinker import from South Korea, Thailand, and Indonesia).

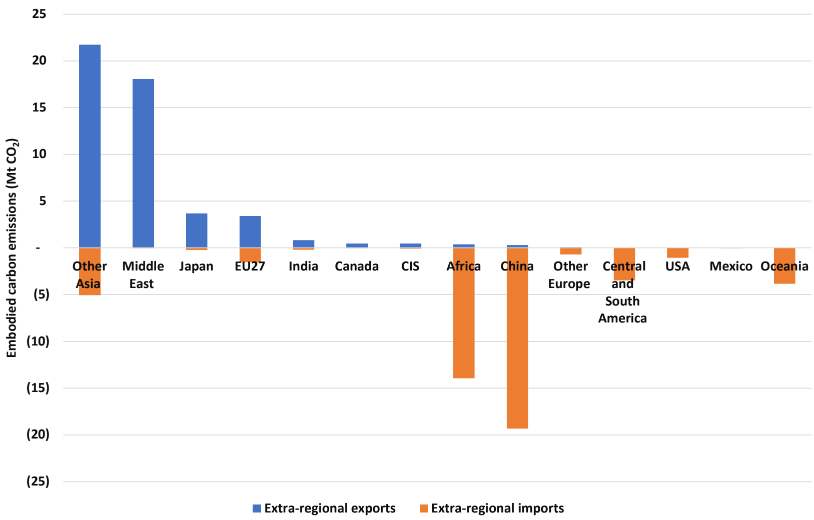


Figure 28. World trade of carbon embodied in clinker by region in 2019 (source: this study).

4.3. Global Embodied Carbon in Aluminum Trade

Aluminum is another carbon-intensive product that is traded globally in significant amounts. The aluminum industry accounts for around 2% of global CO_2 emissions (Hasanbeigi et al. 2022). Unwrought aluminum refers to Aluminum products in the form of ingots, blocks, billets, slabs, and similar manufactured forms, but not rolled, forged, drawn, or extruded products, tubular products, or cast or sintered forms that have been machined or processed otherwise than by simple trimming, scalping or descaling. These products are typically created from molten aluminum at a primary smelter (where the raw material is alumina) or a secondary smelter (where the raw material is scrap).

According to the UN Comtrade (2022), Russia, Canada, and United Arab Emirates were the top three exporters, and the U.S., Japan, and Germany were the top three importers of unwrought aluminum in 2019. The significant global trade of such carbon-intensive commodities results in substantial trade in embodied carbon. There are significant extra-regional flows of carbon embodied in the commodity unwrought aluminum trade worldwide. The top 15 extra-regional flows are shown in Figure 29.

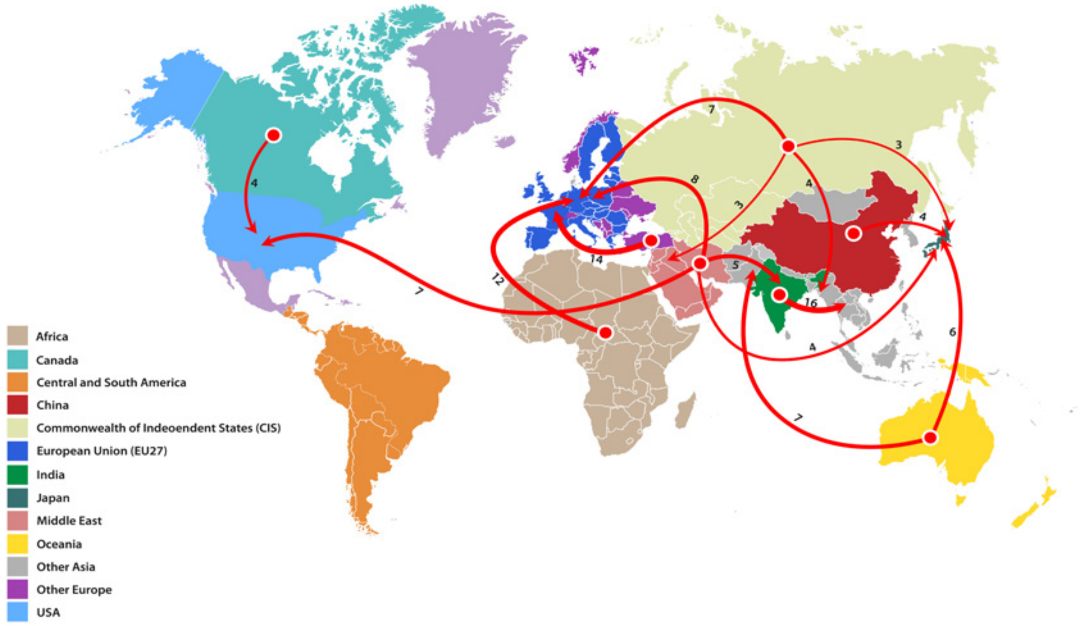


Figure 29. Top 15 extra-regional flows of CO_2 emissions relating to the international unwrought aluminum trade in 2019 (values in Mt CO_2) (source: this study).

The top 3 largest flows of embodied carbon in unwrought aluminum trade are from India to Other Asia[6], Other Europe to EU27, and Africa to EU27. The total embodied carbon in the international trade of unwrought aluminum in 2019 was around 147 Mt CO_2. This is equal to around 22% of total CO_2 emissions from the global aluminum industry.

Around 90% of the embodied carbon in unwrought aluminum trade is extra-regional (between different global regions, highlighted in the figure), while the remainder is traded within each region. India, the Middle East, and CIS are the three largest net exporters, and EU27, Other Asia, and Japan are the three largest net importers of the embodied carbon in the unwrought aluminum trade (Figure 30).

6 Other Asia region includes countries in Asia continent except India, China, Japan, and countries in Middle East and Commonwealth of Independent States (CIS) region which are separately identified in the map and in this analysis. It should be noted that unlike in steel trade analysis, India is not included in Other Asia region because different sources of data were used for the cement and steel trade.

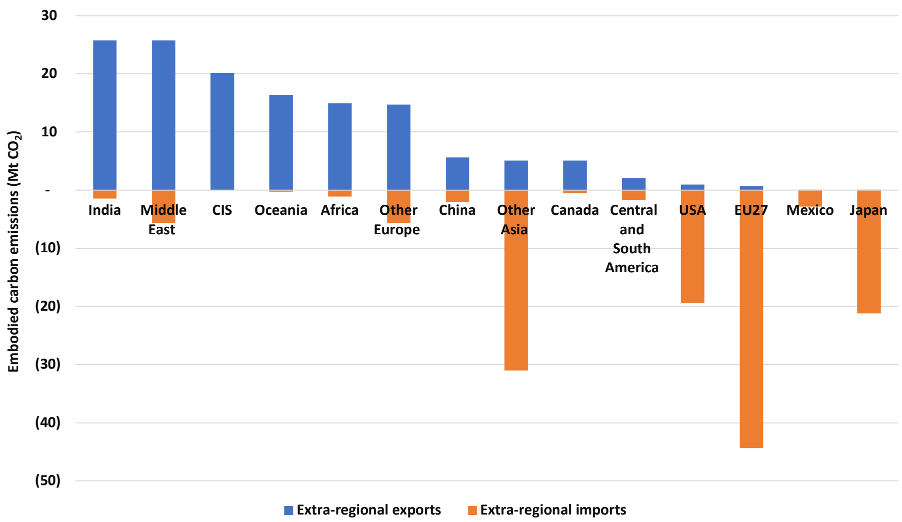


Figure 30. World trade of carbon embodied in unwrought aluminum by region in 2019 (source: this study).

Figure 31 shows the major exporter countries of unwrought aluminum and the embodied carbon in their export in 2019. These top 10 exporter countries account for around 57% of the total export of embodied carbon in the unwrought aluminum trade globally. India, Russia, and UAE are the top three carbon-exporting countries for unwrought aluminum.

Figure 31 also shows that the ranking of the top 10 major exporter countries of unwrought aluminum is not the same as the top 10 countries in terms of embodied carbon in unwrought aluminum export. For example, while India is the 4th largest exporter of unwrought aluminum, it has the largest embodied carbon in unwrought aluminum export. On the other hand, while Canada is the 2nd largest exporter of unwrought aluminum, it has lower embodied carbon in unwrought aluminum export than Russia, UAE, and India. This is primarily because of the substantial difference in carbon intensity (kg CO_2/ton aluminum) produced across these countries. Hasanbeigi et al. (2022) show a detailed benchmarking of the carbon intensity of aluminum production across major aluminum-producing countries.

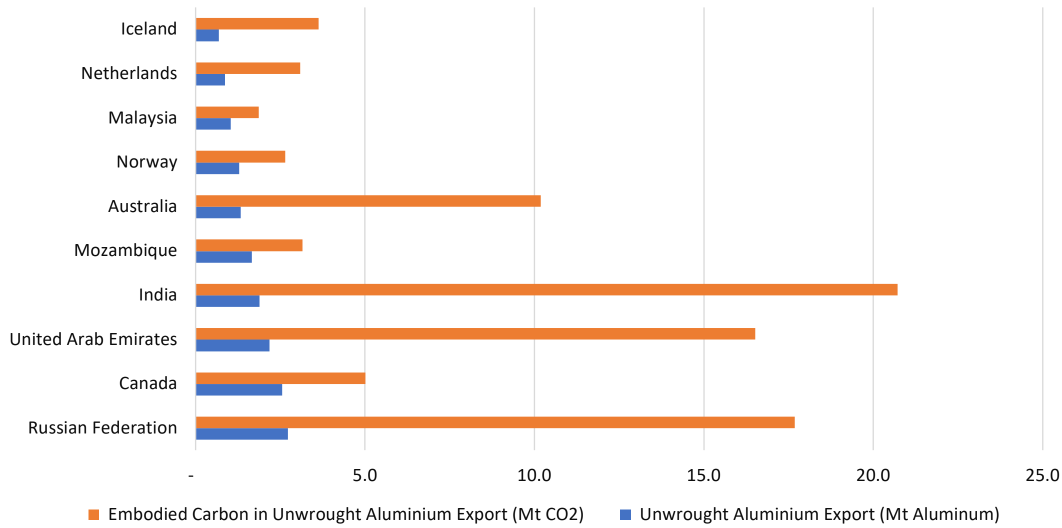


Figure 31. Top 10 major exporter countries of unwrought aluminum and the embodied carbon in their export in 2019 (source: this study).

4.4. Global Embodied Carbon in Chemical Trade

Chemicals are carbon-intensive products that are traded extensively globally. The CO_2 emissions from the chemical industry accounts for around 7% of global CO_2 emissions (Rissman et al. 2020). With more than 70 thousand products, thousands of manufacturing facilities, and deep supply chain interconnections, the chemical industry is very complex and heterogenous. Numerous chemicals are precursors of other chemical products. Across these basic product families, several chemicals dominate GHG emissions, including the large-volume chemicals (e.g., ammonia, ethylene, propylene, methanol, benzene, toluene, and xylenes (BTX), and polyethylene) that account for 80% of the subsector's energy demand and 75% of the industry's global GHG emissions (IEA 2013).

Because of this complexity and heterogeneity of the chemical industry, unlike other sectors deep-dive case studies, for the chemical industry it was not possible to do such physical-basis (per ton product) analysis. Therefore, in this report, for the chemical industry deep-dive, we used monetary-basis analysis using trade data (in \$) and carbon intensity data (kgCO_2/\$) from the EXIOBASE database.

The significant global trade of such carbon-intensive commodities results in substantial trade in embodied carbon. There are significant extra-regional flows of carbon embodied in the commodity chemicals trade worldwide. The top 15 extra-regional flows are shown in Figure 32.

The top 3 largest flows of embodied carbon in chemicals trade are from India to Other Asia and Pacific region[7], China to U.S., and Other Asia and Pacific region to China. The total embodied carbon in the international trade of chemicals in 2019 was around 478 Mt CO_2.

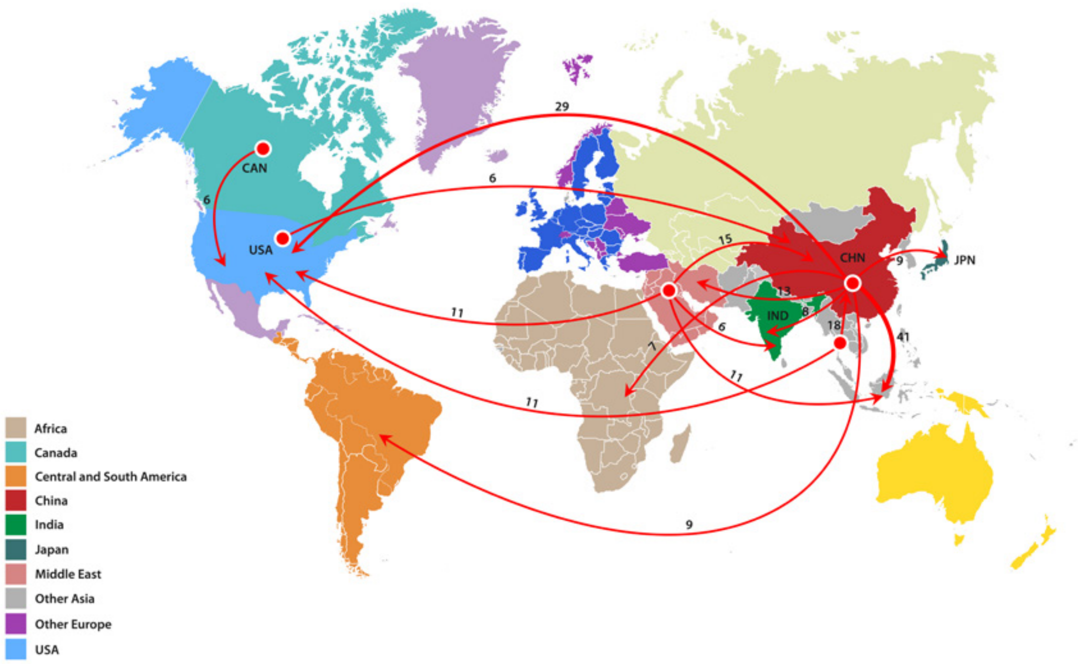


Figure 32. Top 15 extra-regional flows of CO_2 emissions relating to the international chemicals trade in 2019 (values in Mt CO_2) (source: this study).

7 Other Asia and Pacific region includes countries in Asia and Oceania except India, China, Japan, and countries in Middle East region which are separately identified in the map and in this analysis. It should be noted this regional classification is slightly different from other industry subsector deep dives in this report because different sources of data were used.

China, Other Asia and Pacific region and Middle East were the top three exporters, and Other Asia and Pacific region, EU27, and the U.S. were the top three importers of chemicals in 2019 (Figure 33).

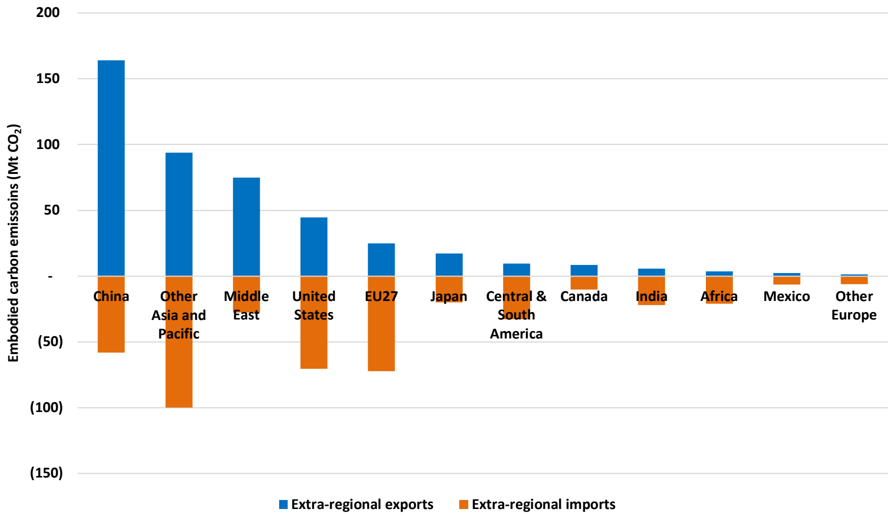


Figure 33. World trade of carbon embodied in chemicals by region in 2019 (source: this study).

5 Policy Implications

As discussed throughout this paper, we document substantial flows of carbon embodied in traded goods and services. This is the carbon loophole, which tends to shift emissions between the Global North and the Global South.

To date, the international climate system has yet to explore the implications of the carbon loophole and has left unanswered the question of who should be responsible for trade-related emissions. Indeed, accounting protocols relevant to the global climate dialog under the United Nations Framework Convention on Climate Change (UNFCCC) focus solely on production emissions; this allows climate-ambitious countries to demonstrate progress on domestic abatement targets without incorporating figures for (higher) consumption emissions. The existing reporting structure paints a misleading picture of emissions reductions and may raise issues related to equity and fairness by forcing developing countries to account for emissions related to consumption in richer trading partners, making the emissions profiles of developing countries look worse.

The UNFCCC process is committed to “common but differentiated responsibilities,” implying that all countries are responsible for addressing climate change but are not equally responsible. Current accounting approaches appear to shift responsibility for emissions abatement to poorer developing countries that serve as the “factories of the world” and are becoming the primary emitters. Indeed, over the last two decades, emissions in the Global South have risen dramatically as emissions in the Global North have stabilized and started to shrink.

Asymmetric climate policy is one force enabling the carbon loophole. Indeed, even when countries meet or exceed their nationally determined contributions (NDCs) to global emissions reductions, their domestic efforts may be offset by carbon-intensive imports.

More ambitious advanced economies like the U.S., EU, and Japan enforce more stringent environmental regulations and standards than the Global South. As net importers of carbon, these countries’ past and future success in decreasing domestic emissions are at least partially offset by imports of carbon-intensive goods from abroad. In other words, advanced economies are reducing domestic emissions even as their consumption behaviors support increases in global carbon emissions.

To successfully and meaningfully address emissions, climate-ambitious countries must also address the carbon emissions embodied in the imported goods, i.e., the carbon loophole. Several approaches are available. At a minimum, integrating a consumption-based emissions accounting framework will allow governments to begin to measure and report their emissions footprint in more relevant terms. Countries can also access a more expansive policy toolkit to address consumption emissions. Production-oriented policies may establish domestic emissions targets or regulatory approaches. Along the supply chain, policies like border carbon adjustments can allow markets to favor lower-carbon imports over higher-carbon alternatives. Policies targeting consumption can establish procurement standards for government operations, create novel product labeling approaches, certify retailers, or otherwise tilt the marketplace toward products made with lower carbon emissions.

Consider, for example, the case of the international aluminum trade. Asymmetries in decarbonization policies between countries can change relative prices and reward carbon-inefficient producers, particularly for goods in EITE sectors. For example, Russia, the United Arab Emirates, and India are responsible for 37% of global unwrought aluminum exports and have domestic average carbon intensities of production more than 3 to 6 times higher than major competitor Canada, the second largest exporter of unwrought aluminum worldwide. Canada's low carbon intensity for aluminum production is mainly due to carbon-free electricity available in Quebec and the British Columbia region, where all its primary aluminum plants are located and an underlying regulatory and carbon pricing regime that favors manufacturing in more carbon-efficient regions. Domestic climate policies in Russia, the UAE, and India are, in contrast, far less ambitious, and fail to tilt the domestic playing field toward lower-carbon manufacturing outcomes. Major importers like the EU, Japan, and the U.S. have no existing tools and policies to be selective for unwrought aluminum manufactured with lower carbon emissions. As a result, the loophole may not just be relocating emissions between countries but increasing emissions due to varying carbon intensity of production.

Policymakers in many Global North markets, including the EU, Canada, the U.K., the U.S., and the G7, are expressing an interest in adopting policies that address consumption emissions. By shifting from policies targeted at domestic production emissions toward policies that account for the emissions associated with imports through instruments like border carbon adjustments, commodity agreements, and inclusive climate clubs, these countries can extend domestic standards and intensity targets to imports. Novel procurement policies such as Buy Clean and labeling strategies can directly influence purchasing behaviors. Both strategies will allow countries to begin tackling consumption emissions. Especially in the pursuit of deep mid-century emissions cuts, addressing consumption emissions will be essential; achieving net-zero domestic emissions targets will be irrelevant if imported emissions offset – or overtake – domestic emissions cuts.

Countries can go even further by working multilaterally to reduce their contributions to the carbon loophole. This is especially essential for emerging markets. Over the last 15 years, there has been a fourfold increase in emissions traded between countries in the Global South. In order to support global decarbonization, Global North countries cannot act on their own; rather, they must reorient production and trade toward lower-carbon markets while extending support to key emerging economies ready and willing to decarbonize.

6 Conclusions

This study provides up-to-date data, information, and analysis of embodied carbon in trade worldwide. Using the latest version of the EXIOBASE database, we have summarized the state of embodied emissions in global trade and highlighted key trends from the most recent year for which we have data, 2019. Furthermore, we have conducted several deep-dive studies for key countries/regions of the world (China, United States, India, Russia, Japan, Canada, EU27, G7, Global South, and Global North) and industrial sectors (steel, cement, and aluminum industry) that are highly entangled in the carbon loophole.

Around 22% of global CO_2 emissions are embodied in imported goods, thus escaping attribution in the consuming country (the end-user) and instead being debited to the producer country Since carbon intensity varies between countries and sectors, as climate-ambitious countries adopt increasingly stringent policies, the loophole could be widened further.

Of the top 20 flows, eight of them originated from China. The top three embodied carbon emissions flows are from China to Other Asia and Pacific region, China to the U.S., and Other Asia and Pacific to China. China is the largest net exporter of carbon emissions, followed by Russia, and Middle East. The U.S., on the other hand, is the largest net importer of emissions, followed by EU27, Africa (excluding South Africa), France, and UK.

Many large countries have a significant imbalance in the import or export of embodied emissions. Emissions transfers from developing countries to the U.S., EU, G7, and Global North appear to have plateaued in the last decade. Instead, growth in the trade of embodied carbon is mostly occurring through South-South trade or trade among countries outside of Europe and North America. Embodied emissions transfers among these countries have risen four-fold since 1995.

In aggregate, embodied CO_2 emissions in the global trade of steel and chemical products were the highest among all products traded globally. Our industry sectoral deep-dive studies showed that there are significant inter-regional and extra-regional flows of carbon embodied in all the industries studied: commodity steel, value-added steel, cement, clinker, aluminum, and chemical trade worldwide.

The total embodied carbon in the international trade of commodity steel in 2021 was around 700 Mt CO_2. This is equal to 19% of total CO_2 emissions from the global steel industry. China is the largest net exporter and North America is the largest net importer of embodied carbon in the commodity steel trade. The embodied carbon in commodity steel covers only about half the picture of carbon flow in the steel trade. The other half consists of embodied carbon in the trade of steel-containing goods (e.g. automotive, metal products, machinery, domestic appliances, etc.). China alone accounted for one-third of the world's embodied carbon in exported steel-containing products.

The total embodied carbon in the international trade of cement and clinker in 2019 was around 141 Mt CO_2. This is equal to around 6% of total CO_2 emissions from the global cement industry. United States is the largest net importer of carbon embodied in cement, followed by Africa, "Other Europe" and "central and South America" regions, while the Middle East, Japan, and EU27 regions are the top three largest net exporters of embodied carbon in cement. The embodied carbon in the extra-regional clinker trade worldwide is even larger than the embodied carbon in the cement trade. The Middle East, Other Asia, and Japan are the three largest net exporters of embodied carbon in the clinker trade. China, Africa, and Oceania are the largest net importer of embodied carbon in the clinker trade.

The total embodied carbon in the international trade of unwrought aluminum in 2019 was around 147 Mt CO_2. This is equal to around 22% of total CO_2 emissions from the global aluminum industry. India, the Middle East, and CIS are the three largest net exporters and EU27, Other Asia, and Japan are the three largest net importers of the embodied carbon in unwrought aluminum trade.

Unless consumption-based accounting is used, countries may meet their Paris Agreement targets while being responsible for increasing emissions abroad. Policies such as border carbon adjustment that are being considered in the EU, U.S., Canada, and the UK, green public procurement policy that has already been implemented in many countries and geographies around the world, and multilateral inclusive climate clubs that pair trade policies with investments and technology assistance, can shrink the size of the carbon loophole while strengthening international trade and accelerating global decarbonization.

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Appendices

Appendix 1. List of Acronyms

CBA	Consumption-based accounting
CO_2	Carbon dioxide
EE MRIO	Environmentally-Extended Multi-Regional Input-Output
ETS	European Trading System
GHG	Greenhouse Gas
Gt	Gigaton
GTAP	Global Trade Analysis Project
ICIO	Inter-Country Input-Output
IMF	International Monetary Fund
IPCC	United Nations Intergovernmental Panel on Climate Change
IO	Input-Output
Kt	Kiloton
MRIO	Multiregional Input-Output
Mt	Megaton
OECD	Organization for Economic Cooperation and Development
PBA	Production-based accounting
UNFCCC	United Nations Framework Convention on Climate Change
WIOD	World Input-Output Database

Appendix 2. Data and Methodology

A.2.1. Data and methods used for MRIO analysis

Methodology

In calculating total CO_2 emissions embodied in domestic and international trade, we follow the basic Environmentally-Extended Multi-Regional Input-Output (EE MRIO) model from Miller and Blair (2009), which stems from the original Input-Output model of Leontief (1986). For ease of exposition, we simplify by assuming a world in which only two countries in existence: Country 1 and Country 2. We also assume there exist two sectors: Sector A and B. The trade flows between both countries are depicted in the table below.

		Country 1 A	Country 1 B	Country 2 A	Country 2 B	y^1	y^2	X
Country 1	A	z_{aa}^{11}	z_{ab}^{11}	z_{aa}^{12}	z_{ab}^{12}	y_a^{11}	y_a^{12}	x_a^1
	B	z_{ba}^{11}	z_{bb}^{11}	z_{ba}^{12}	z_{bb}^{12}	y_b^{11}	y_b^{12}	x_b^1
Country 2	A	z_{aa}^{21}	z_{ab}^{21}	z_{aa}^{22}	z_{ab}^{22}	y_a^{21}	y_a^{22}	x_a^2
	B	z_{ba}^{21}	z_{bb}^{21}	z_{ba}^{22}	z_{bb}^{22}	y_b^{21}	y_b^{22}	x_b^2
Value Added		v_a^1	v_b^1	v_a^2	v_b^2	y^1	y^2	
Total Output		x_a^1	x_b^1	x_a^2	x_b^2			

The table above summarizes the yearly monetary transactions between countries-industries. *z* , *y* , *x*, and *v* symbolize the intermediate input, final demand, gross output, and value added, respectively. From the output side, z_{ab}^{11} and z_{ab}^{12} is the output of Sector A of Country 1, which then become the intermediate input to Sector B of Country 1 and Country 2, respectively. x_a^1 is the output of Sector A produced in Country 1, x_b^1 while is the output of Sector B produced in Country 2. y_a^{11} is the final demand of Sector A's product, demanded by Country 1 (domestic final demand), while y_b^{11} captures the final demand of Sector B's product, demanded by Country 2 (foreign final demand). v_a^1 is the value added of Sector A of Country 1.

The economywide technical coefficient, *A* , of this economy is depicted in the following matrix.

$$A = \begin{bmatrix} z_{aa}^{11}/x_a^1 & z_{ab}^{11}/x_b^1 & z_{aa}^{12}/x_a^2 & z_{ab}^{12}/x_b^2 \\ z_{ba}^{11}/x_a^1 & z_{bb}^{11}/x_b^1 & z_{ba}^{12}/x_a^2 & z_{bb}^{12}/x_b^2 \\ z_{aa}^{21}/x_a^1 & z_{ab}^{21}/x_b^1 & z_{aa}^{22}/x_a^2 & z_{ab}^{22}/x_b^2 \\ z_{ba}^{21}/x_a^1 & z_{bb}^{21}/x_b^1 & z_{ba}^{22}/x_a^2 & z_{bb}^{22}/x_b^2 \end{bmatrix}$$

If I is the identity matrix, The Leontief Inverse matrix, *L*, of this economy can be determined in the following way,

$$L = (I - A)^{-1} = \begin{bmatrix} L_{aa}^{11} & L_{ab}^{11} & L_{aa}^{12} & L_{ab}^{12} \\ L_{ba}^{11} & L_{bb}^{11} & L_{ba}^{12} & L_{bb}^{12} \\ L_{aa}^{21} & L_{ab}^{21} & L_{aa}^{22} & L_{ab}^{22} \\ L_{ba}^{21} & L_{bb}^{21} & L_{ba}^{22} & L_{bb}^{22} \end{bmatrix}$$

Suppose that to produce their respective outputs, those sectors emit a certain amount of emissions, which are presented in the vector below.

$$c = [c_a^1 \quad c_b^1 \quad c_a^2 \quad c_b^2]$$

c_a^1 is the total emissions of Industry A in Country 1 associated with the production of x_a^1 amount of output. Direct emissions intensity for all countries-sectors, q , can be determined by dividing the total emission of each country-industry with its respective production output.

$$q = [c_a^1/x_a^1 \quad c_b^1/x_b^1 \quad c_a^2/x_a^2 \quad c_b^2/x_b^2]$$

The final demand matrix of this economy is structured by the following matrix.

$$y = \begin{bmatrix} y_a^{11} & y_a^{12} \\ y_b^{11} & y_b^{12} \\ y_a^{21} & y_a^{22} \\ y_b^{21} & y_b^{22} \end{bmatrix}$$

The EE MRIO model is given by the following form.

$$E = \hat{q}Ly$$

And in its compact matrix form.

$$\begin{bmatrix} e^{11} & e^{12} \\ e^{21} & e^{22} \end{bmatrix} = \begin{bmatrix} \hat{q}^1 & 0 \\ 0 & \hat{q}^2 \end{bmatrix} \begin{bmatrix} L^{11} & L^{12} \\ L^{21} & L^{22} \end{bmatrix} \begin{bmatrix} y^{11} & y^{12} \\ y^{21} & y^{22} \end{bmatrix}$$

On the left-hand side of the equation is the global emission matrix *E*. The first matrix on the right-hand side of the equation represents the global direct emissions intensity vector *q* (the hat denotes a diagonal matrix formed by the vector). The second matrix on the right-hand side is the global Leontief inverse matrix *L*. The last matrix is the global final demand matrix *y*. Country 1 can be considered as the focus country and Country 2 as the rest of the world (ROW).e^{11} and e^{22} each represents the domestic emissions embodied in domestic consumption. We often simplify the term by using "domestic emissions", or DE, to call it. From the perspective of Country 1, $e^{12} = \hat{q}^1 L^{11} y^{12} + \hat{q}^1 L^{12} y^{22}$ represents the emissions embodied in exports, or EEE^1. $e^{21} = \hat{q}^2 L^{21} y^{11} + \hat{q}^2 L^{22} y^{21}$ represents the emissions embodied in imports, or EEE^1 , meaning the foreign emissions embodied in domestic final demand. Country 1's production-based emissions (PBE^1) are the sum of DE^1 and EEE^1 . Country 1's consumption-based emissions (CBE^1) are the sum of DE^1 and EEI^1. Country 1's balance of emissions embodied in trade ($BEET^1$), or the net emissions transfer, is given by $BEET^1 = EEE^1 - EEI^1 = PBE^1 - CBE^1$.

Data

Our source for the annual MRIO tables is the monetary industry-by-industry tables from EXIOBASE (Stadler et al., 2018), in that we use the EXIOBASE 3.8.2, the latest version available. Originally, the EXIOBASE 3.8.2 contains 44 countries and five ROW aggregate regions between 1995-2021. We, however, exclude the last two years, 2020 and 2021, due to the global anomaly induced by Covid-19.

Like any other EE MRIO databases, the EXIOBASE 3.8.2is aimed to analyze the environmental impacts of production and consumption activities between nations, though it is composed to include more EU Countries as well as the major global economies. To this extent, EXIOBASE 3.8.2incorporates the total CO_2 emissions (kg) released by each sector to produce its respective output. Combining sectoral CO_2 emissions with MRIO enables us to trace the total (direct and indirect) CO_2 emissions generated from the production of goods and services across nations.

The EXIOBASE 3.8.2 has several distinguishing features compared to other EE MRIO databases:

- EXIOBASE is a free-to-use open database.

- Compared to other databases, EXIOBASE 3.8.2 covers a relatively large number of sectors (163 sectors). This comparatively fine-grained data enables more precise analysis. The Global Trade Analysis Project (GTAP), a paid Input-Output (IO) database, only consists of 57 economic sectors while having a relatively good country coverage (Aguiar et al., 2016). The EORA MRIO, while covering 190 countries, provides only 26 sectors, even coarse compared to the GTAP (Lenzen et al., 2013). World Input-Output Database (WIOD) only provides 56 sectors and 43 countries, while OECD Input-Output Table (IOT) is available with 64 countries and 34 sectors in its third version (Timmer et al., 2015).

A.2.2. Data and methods used for industry case studies

To calculate the carbon embodied in the trade of cement and steel, we collected the trade data for these commodities as well as CO2 emissions factors for the countries/regions analyzed.

For the cement industry, we looked into carbon embodied in the trade of both cement and clinker. Clinker is an intermediary product in the cement production process. We obtained the clinker and cement trade data from the UN Comtrade database (UN 2022). The latest year for which the good quality trade data were available was 2019. The CO_2 intensities for the cement and clinker production for different regions/countries of the world studied were obtained from the Cement Sustainability Initiative (CSI)'s Getting the Numbers Right (GNR) database, which is a voluntary, independently-managed database of CO_2 and energy performance information on the global cement industry (GCCA 2022). The latest year for which the CO_2 intensity for cement and clinker production was available in the GNR database was 2019.

For the steel industry, we analyzed the carbon embodied in the trade of both commodity steel and steel-containing goods (value-added steel). The international trade data of both commodity steel and value added steel were obtained from three reports by the Worldsteel Association (worldsteel 2022). For the commodity steel, the latest year for which the trade data were available was 2021, whereas for value added steel, the latest data were for 2019. The CO_2 intensity of steel production in different regions/countries were obtained or estimated based on recent steel benchmarking report (Hasanbeigi 2022).

For the aluminum industry, we analyzed the carbon embodied in the trade of both primary and secondary aluminum. We obtained the aluminum trade data from the UN Comtrade database (UN 2022). The latest year for which the good quality trade data were available was 2019. The CO_2 intensity of steel production in different regions/countries were obtained or estimated based on Hasanbeigi et al. (2022) and IAI (2021).

For the chemical industry, we took a different approach and analyzed the carbon embodied in the trade using EXIOBASE data as opposed to physical-basis trade and intensity data that were used for steel, cement, and aluminum analysis. This is because there are many different chemical products, and it is not possible to do physical-basis analysis for the entire chemical industry. Both chemical trade data and carbon intensities are from the EXIOBASE database.

Appendix 3. Additional Tables and Graphs

Appendix 3.1. Countries and regions represented in EXIOBASE (V 3.8.2)

Countries	Group	Countries	Group
China	Global South	**Cyprus**	Global North
Brazil	Global South	**Latvia**	Global North
India	Global South	**Lithuania**	Global North
Mexico	Global South	**Luxembourg**	Global North
Russia	Global South	**Hungary**	Global North
Indonesia	Global South	**Malta**	Global North
South Africa	Global South	**Netherlands**	Global North
ROW Asia	Global South	**Poland**	Global North
ROW Latin America	Global South	**Portugal**	Global North
ROW Africa	Global South	**Romania**	Global North
ROW Middle East	Global South	**Slovenia**	Global North
Austria	Global North	**Slovakia**	Global North
Belgium	Global North	**Finland**	Global North
Bulgaria	Global North	**Sweden**	Global North
Czech Republic	Global North	**United Kingdom**	Global North
Denmark	Global North	**United States**	Global North
Germany	Global North	**Japan**	Global North
Estonia	Global North	**Canada**	Global North
Ireland	Global North	**South Korea**	Global North
Greece	Global North	**Australia**	Global North
Spain	Global North	**Switzerland**	Global North
France	Global North	**Turkey**	Global North
Croatia	Global North	**Taiwan**	Global North
Italy	Global North	**Norway**	Global North
		ROW Europe	Global North