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THE CARBON LOOPHOLE IN CLIMATE POLICY

Quantifying the Embodied Carbon in Traded Products

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KGM & Associates Pty Ltd.

KGM & Associates are economic consultants specializing in international trade analysis. Much of their work centers around KGM's Eora MRIO model: a high-resolution global trade database. Eora covers the domestic economies and international trade between 187 countries (capturing >99.5% of global GDP) in high sector detail, for each year 1970-2015. Eora is used by researchers at over 800 universities worldwide. Applications include analyzing value added in trade, inter-industry flows, international supply chains, and calculating carbon, water, and biodiversity footprints. KGM's clients who have used the Eora model include: McKinsey, Deloitte, Ernst & Young, KPMG, Standard & Poors, the World Bank, the IMF, OECD, and the United Nations. Academic papers based on the Eora model have been published in Nature, Nature Climate Change, and PNAS.

Global Efficiency Intelligence, LLC.

Global Efficiency Intelligence, LLC is an energy and environmental consulting and market research firm located in San Francisco, California. We provide global market-based solutions and in-depth technology, systems, industry, business, and policy analyses to tackle the world's energy, environmental, and climate challenges. We conduct analysis to quantify the CO_2 emissions related to different industries and products and how to mitigate them. We use systems thinking, integrative modeling, and data analytics to turn data into actionable information and to provide scientific-engineering solutions. We offer Modeling and Analysis, Policy Design and Evaluation, Technology and Industry Roadmapping, Market Research, and Training and Capacity Building services in the following areas: Energy Efficiency; GHG Emissions Reduction; Water-Energy-Climate Nexus; Manufacturing Resources Efficiency; Demand Response; Smart Manufacturing & Industrial IOT; Emerging Technologies; Supply Chain Carbon and Energy Footprint; and Deep Electrification and Decarbonization.

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Executive Summary

The carbon loophole refers to the embodied greenhouse gas emissions associated with production of goods that are ultimately traded across countries. These emissions are a growing issue for global efforts to decarbonize the world economy. Embodied emissions in trade are not accounted for in current greenhouse gas accounting systems.[1] If they were, many promising climate trends would be negated or reversed. For example, many achievements of reducing emissions by developed countries under the Kyoto Protocol would actually appear as emissions outsourced to developing countries.

This report aims to provide a newly updated analysis of the carbon loophole, also known as imported consumption-based or embodied emissions, at the global level. Using the Eora global supply chain model, along with additional data, our analysis surveys global trends and does a deep dive into the countries and sectors most implicated in the carbon loophole. This report presents the latest available data (sourced from the Eora model with data year 2015, presented for the first time in this report) and paves the way for regular updates in analysis of the carbon loophole in the future.

First, we confirm earlier reports that around one quarter of global CO_2 emissions are embodied in imported goods, thus escaping attribution in the consuming country (the end user) and instead being debited at the producer side. And we clearly see that the proportion of embodied emissions has been growing. Since carbon intensity varies between countries, as new climate policies emerge, the loophole could be widened further. The shifting of air pollution provides a worrying example: despite strong, successful air quality legislation in the U.S. and EU starting in the 1970s, global air pollution in total has continued to grow. The carbon loophole could permit the same to occur with GHG emissions.

Many large countries – like the U.S. and China – have a significant imbalance in import or export of embodied emissions. Many of the top global flows of embodied CO_2 emissions involve China, though flows from other countries including India and Russia are also starting to grow. Emissions transfers from developing and middle-income countries to countries with traditionally high consumption levels like the U.S. and EU appear to have plateaued in recent years. Whether this is a peak or just a pause remains to be seen, and is closely linked to global economic trends. Finally, another emerging mega-trend is the rise of South-South trade, or trade among countries outside of Europe and North America. Embodied emissions transfers among these countries have risen even while transfers to North America and Europe have stabilized.

While virtually all goods carry with them some embodied emissions, two goods in particular stand out as heavily traded and carbon-intensive - also known as emissions-intensive trade-exposed (EITE) goods: steel and cement. The report looks closely at the embodied CO_2 associated with the international trade of these two goods. The steel and cement sectors together represent over 10% of global anthropogenic CO_2 emissions. We find that steel and clinker (a carbon-intensive intermediate product of cement) are mostly traded across very long distances

[1] For example, countries only report their domestic carbon dioxide emissions (also known as production-based or territorial accounting) to the Intergovernmental Panel on Climate Change.

outside of their region of production, while half of the cement trade is also extra-regional. In addition, world clinker trade has an embodied carbon footprint almost equal to that of cement itself. China, while slowing down as 'the world's factory', is still by far the biggest exporter of embodied emissions in steel. Meanwhile, embodied emissions from India have grown rapidly, with the U.S. as the largest recipient of embodied emissions in Indian goods.

Better regular monitoring of trade in embodied carbon is needed. The MRIO models used to track embodied CO_2 are strong, but they lack institutional backing. Building government or institutional support for this consumption-based accounting is the only way to ensure regular updates, improve the accounting standardization, and complete the transition currently underway from academic project to an officially recognized and supported tool.

Unless consumption-based accounting is used, countries may continue to export their emissions to meet their Paris Agreement targets, as occurred with the Kyoto Protocol. Countries have reported reductions that exceeded their Kyoto targets, however, the changes in emissions embodied in imports are comparable to or larger than changes in domestic emissions. Traded emissions have undermined emissions reductions in the Kyoto Protocol, and threaten to continue to do so for the Paris Agreement. In this report, we present a current and state-of-the-art overview tracking these traded emissions. We also propose a way forward for regularly updating these results, which can inform promising new climate policies that close the carbon loophole, such as California's Buy Clean Act, the Netherlands' government procurement policy, as well as efforts in the private sector.

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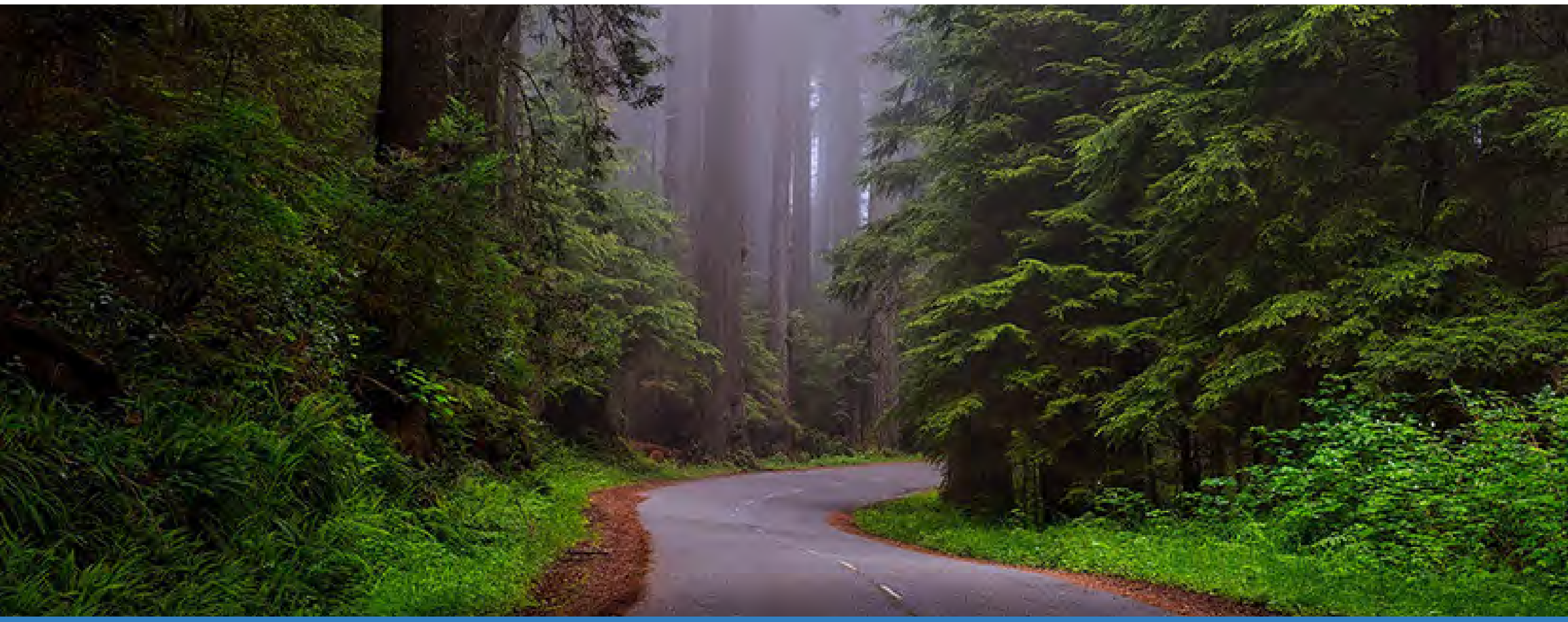


1 Introduction

The globalized trade system entails substantial flows of goods and services from countries of production and provision to different countries of consumption. In many cases, and increasingly so, the majority of production and provision is occurring in developing countries, with developed countries acting as importers and net consumers.

Under the UNFCCC, countries report their greenhouse gas (GHG) emissions on the basis of territorial emissions (also called production-based emissions (PBA)). When goods are traded, the emissions associated with their production (or embodied emissions) are also traded, and these emissions for imported goods are not counted towards the consumer country's emissions reporting. Many argue that these accounts should be corrected to account for emissions embodied in imported goods, or consumption-based accounting (CBA). The term 'embodied emissions' refers to the total amount of emissions from all upstream processes required to deliver a certain product or service. These embodied flows of carbon, which are not accounted for in PBA, are called embodied emissions, emission transfers, displacement, or are said to be falling through the carbon loophole.

More local and national governments are trying to address the issue of carbon embodied in trade. For example, the new Buy Clean Act in California (AB 262) requires that certain carbon-intensive infrastructure materials (including steel and glass) purchased with state funds are produced below a given threshold of carbon intensity. The Buy Clean legislation helps expand the market for companies that have invested in low-carbon technologies for producing materials.

Recent studies have shown that, when using consumption-based accounting, the apparent progress among developed countries in reducing their emissions is actually negated or reversed due to import of embodied emissions into developing countries. Accordingly, much of the increase in emissions in developing countries can be attributed to production for export to developed countries. It is estimated that 20-30% of global CO_2 emissions are part of the carbon loophole; that is, these emissions comprise of goods and services that are internationally traded. Better understanding of embodied emissions and accounting methods is critical to informing future discussion on decarbonizing industry. Consumption-based accounting allows developed countries to take responsibility for upstream emissions that could otherwise be ignored. However, data and research in this area are still emerging, and have only analyzed the carbon loophole at relatively low-resolution in terms of countries and sectors. A detailed, up-to-date global quantification that can inform policy is needed.

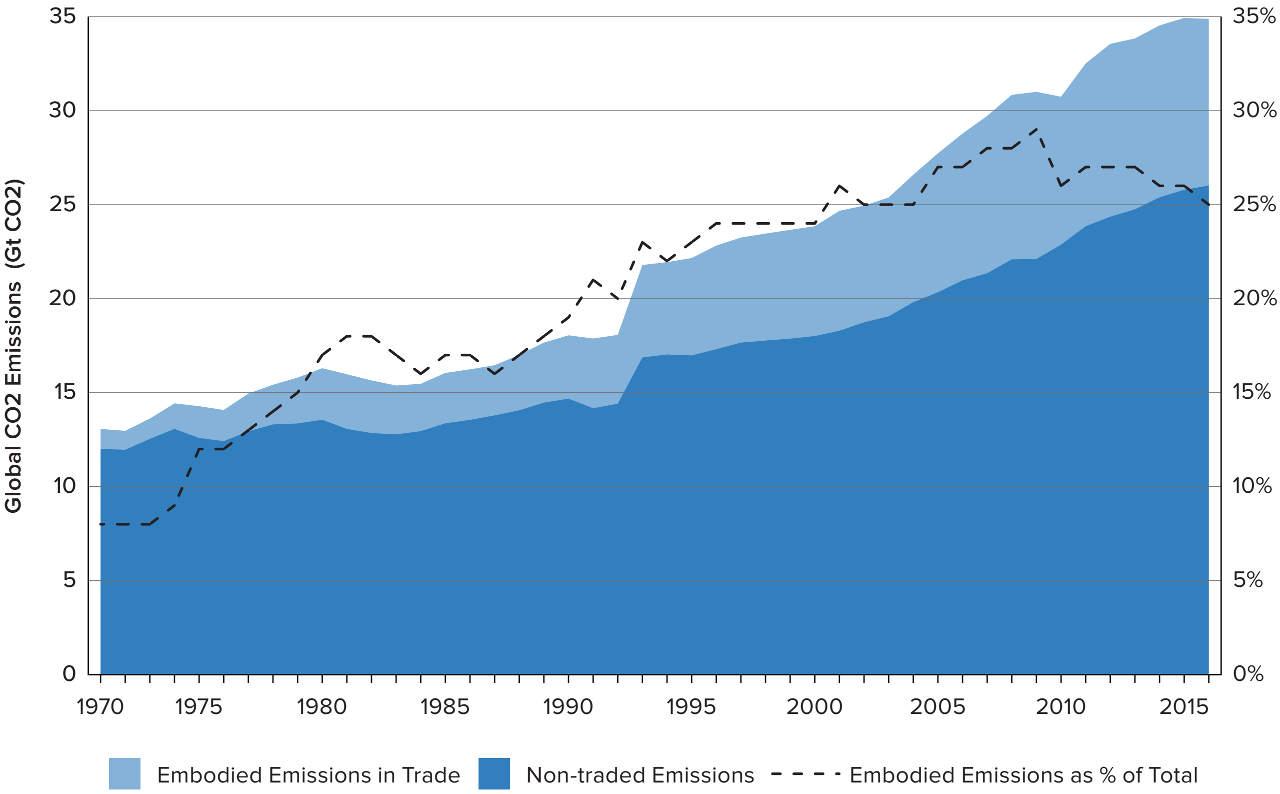
This report aims to fill that shortcoming by providing more up-to-date data, information, and analysis of the embodied carbon trade worldwide. Using the Eora global supply chain model, we summarize the state of embodied emissions and highlight key trends using the latest data. Furthermore, we have conducted several deep-dive studies for key regions of the world (China and India) and emissions-intensive trade exposed (EITE) industrial sectors (steel and cement industry) that are highly entangled in the carbon loophole. In addition, we have presented the state of the knowledge in this field based on a literature review of the methodology for tracking embodied carbon. We also discuss the current state of private and public sector usage of embodied carbon emissions accounting. Finally, the report summarizes our conclusions and implications for future climate policy.

2 High-Level View of Global Traded Carbon

This section answers the high-level questions about embodied carbon footprint flows between countries: Are emissions transfers growing? Where do they come from? Where do they go? Which countries and products are most implicated in this trade in embedded emissions?

For this report, the Eora global trade model was updated to include the year 2015, the most recent year for which complete data were available. The Eora model details the transactions, both domestic and foreign, linking 15,000 sectors across 189 countries using input-output analysis, an economic accounting method that documents the financial flows between sectors. Multiregional input-output (MRIO) models like Eora can be used to estimate consumption-based inventories of CO_2 and other greenhouse gas emissions. The MRIO model links primary emissions within a sector through multiple trade and transformation steps to allocate those emissions to intermediate and final consumers (final consumers effectively refers to households but also includes government purchases and inventory accumulation, so that the total consumption in a country, from all buyers, is accounted for). In total, the model traces more than 5 billion global supply chains in each year. This section presents the key, high-level findings from the model output.

On average, one quarter of the global carbon footprint is embodied in imported goods. These hidden flows evade most types of carbon policy.



"Figure 2.1. Global CO_2 emissions and proportion embodied in trade"

The carbon loophole is an important feature of global GHG emissions patterns. A growing share of global GHG emissions flow through the carbon loophole.

This is problematic because embodied carbon flowing through international trade undermines national GHG targets, unless they are set using consumption-based accounting (no countries have set CBA goals to date).

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, if at all, in businesses' decision-making. These decisions will also vary by type of industry. The embodied CO_2 used to manufacture a television or truck can easily be emitted abroad, but it is more difficult to relocate the GHG emissions needed to light a home or fuel a car. Yet whatever the precise mechanics of emissions shifting (explored by Arto and Dietzenbacher, 2012), the problem is growing.

The displacement of air pollution sets a worrying precedent: despite strong, successful legislation in the U.S. and EU, total global air pollution has increased.

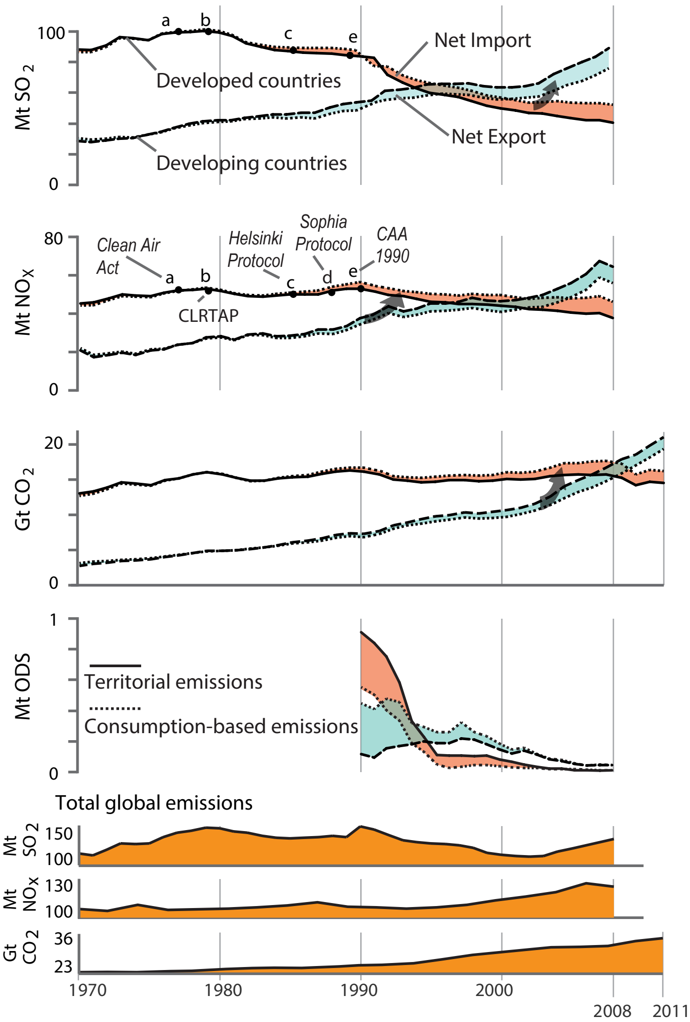


Figure 2.2. Territorial and consumption-based emissions trajectories for developed and developing countries, 1970-2011 (reproduced from Kanemoto et al. 2014)

Historically, air pollution regulation has been undermined by burden shifting. There is a risk that GHG emissions regulation will follow this precedent. An earlier study using Eora (Kanemoto et al. 2014) compared flows of GHGs and air pollutants associated with traded goods since the 1970s. For NOx and SOx emissions, total global emissions have risen despite a series of successful air quality legislations in the U.S. and EU[2], formerly the largest polluters. And the share of these emissions associated with traded goods has also grown.

In contrast, for ozone-depleting substances (ODS), the Montreal Protocol banned both the manufacture and trade of CFCs. As trade in ODS-containing products was also controlled, displacement of production was impossible. As a result, global ODS emissions have fallen to near zero.

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 footprint.

[2] For this analysis, the United Kingdom was included in the EU region

Globally, traded embodied emissions have been growing.

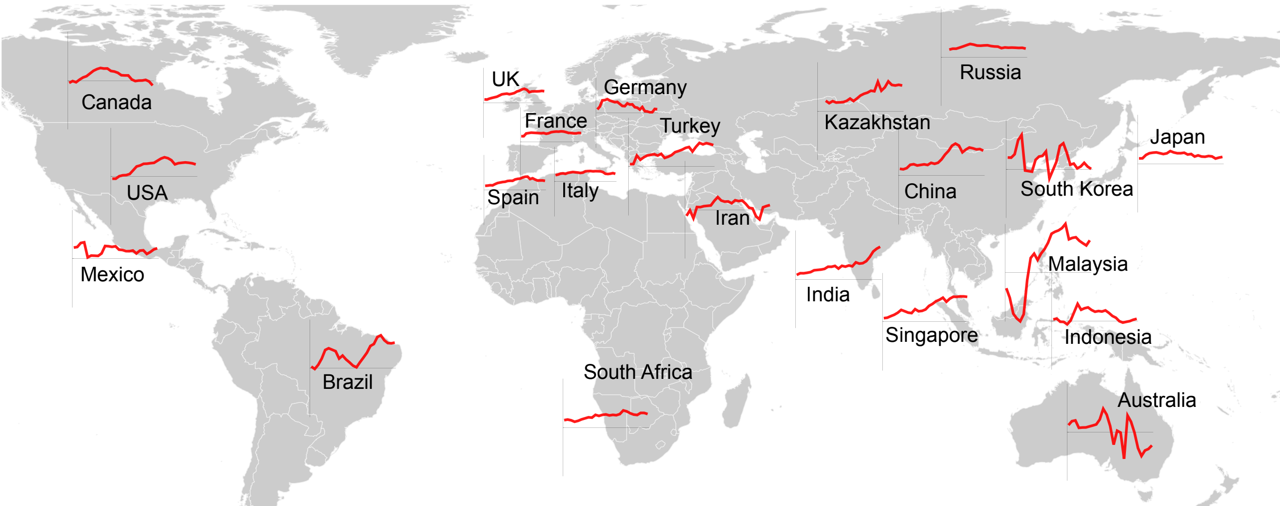


Figure 2.3. National trends in embodied carbon trade: Net imports 1990-2015, indexed to year 2000

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 overall decarbonization of 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.

Many large countries have a significant imbalance, either exporting considerable embodied emissions or importing them.

While the U.S. is the largest importer of embodied carbon, and China the largest exporter, many other countries are involved in trading embodied CO_2. In Europe, Germany, the UK, France, Italy, and Spain are significant net importers. Asia, India, Russia, and Korea are major net exporters. Japan, Thailand, Australia, Turkey, and Brazil also stand out as notable net importers of embodied CO_2.

Globally, roughly one-quarter of emissions are traded. For individual countries, embodied carbon net imports or net exports typically correspond to ~5-20% of their territorial emissions. As discussed further below, including these hidden flows significantly changes each country's true progress in meeting their emissions reduction targets.

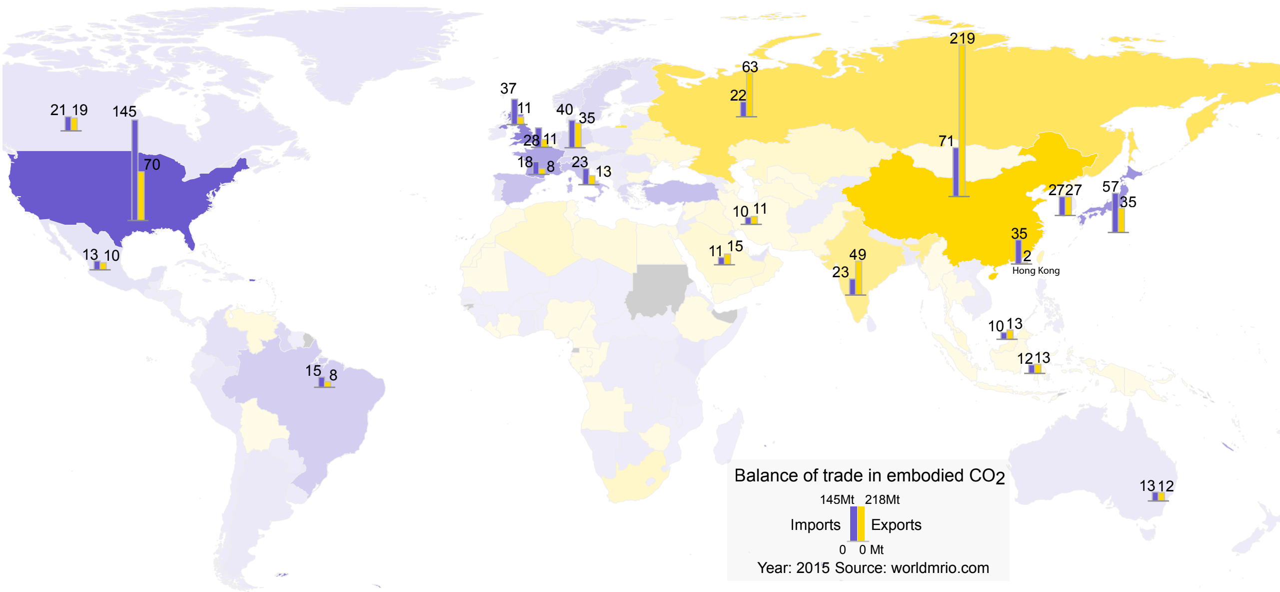


Figure 2.4. Map of composition of trade in embodied CO_2. Blue bars show embodied imports; yellow bars show exports. Dark blue shaded countries are predominantly importers; dark yellow are predominantly exporters.

Table 2.4. Top importers and exporters of embodied CO_2

TOP EMBODIED CO_2 IMPORTERS, 2015			TOP EMBODIED CO_2 EXPORTERS, 2015		
Rank	Country	Embodied CO_2 in Imports (Gt CO_2)	Rank	Country	Embodied CO_2 in Exports (Gt CO_2)
1	U.S.	1.452	1	China	2.186
2	China	0.706	2	USA	0.734
3	Japan	0.567	3	Russia	0.625
4	Germany	0.395	4	India	0.488
5	UK	0.368	5	Germany	0.355
6	Hong Kong	0.349	6	Japan	0.349
7	France	0.281	7	South Korea	0.271
8	South Korea	0.272	8	Canada	0.186
9	India	0.233	9	Taiwan	0.164
10	Italy	0.233	10	Saudi Arabia	0.154
11	All others	4.007	11	All others	3.267

Many of the top global flows involve China, though this is not the whole story.

It is important to distinguish which inter-country flows and supply chains are driving burden-shifting.

China is a major origin and destination for embodied emissions flows. In addition to China's contribution to emissions shifting, several other noteworthy trends can be observed, including:

- Increases in emissions in the Russian ores and minerals sectors have been driven by higher consumption in Europe.
- Despite considerable economic growth in Australia, India, and the Southeast Asian countries in the past two decades, these countries do not break in to the Top 10 of absolute largest-growing flows since 1995.
- However there is growth in south-south trade (this is discussed below).
- While Brazil and South Africa - the other BRICS countries - are significant traders in economics terms, they are not top players, in terms of imports or exports, of embodied carbon trade (table 2.5.1).

The high imports of embodied CO_2 into the U.S., Canada, Mexico, Japan, Korea, and core EU nations can clearly be seen.

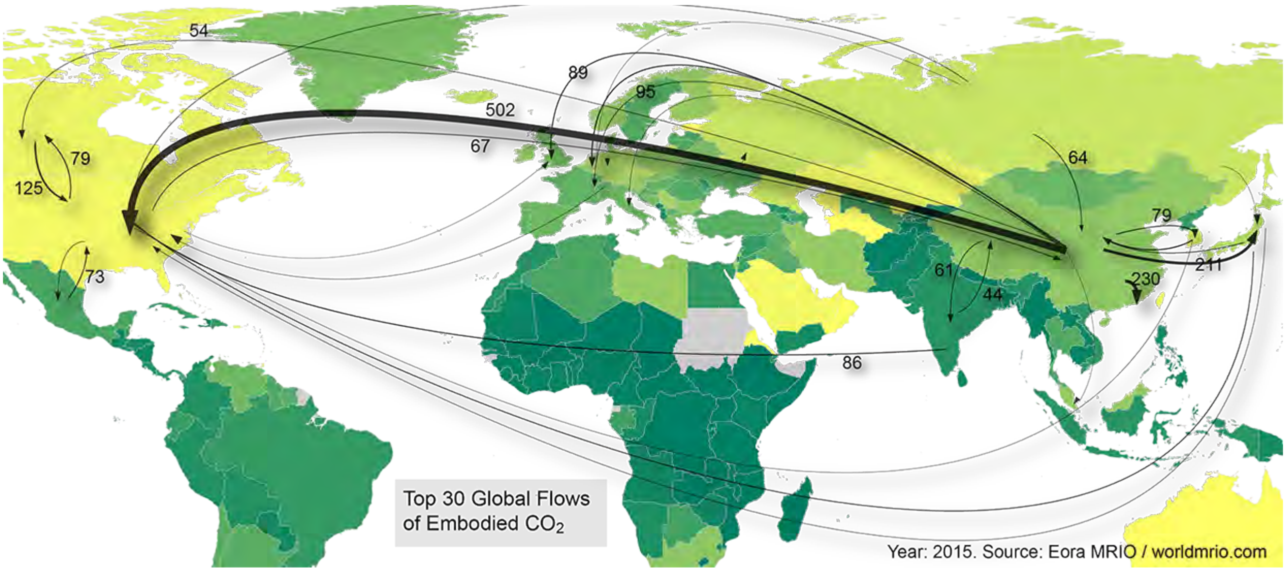


Figure 2.5. Top international flows of embodied carbon. Countries are colored according to CO_2 emissions per capita (yellow = highest; dark green = lowest). Values are in Kt CO_2.

Table 2.5.1. Top 40 global flows of embodied carbon in 2015

Rank	Origin	Destination	Amount ($KtCO_2$)	Rank	Origin	Destination	Amount ($KtCO_2$)
1	China	U.S.	502,228	21	U.S.	Japan	48,967
2	China	Hong Kong	230,928	22	India	China	44,273
3	China	Japan	211,508	23	China	Italy	43,683
4	Canada	U.S.	125,674	24	Germany	U.S.	42,313
5	China	Germany	98,199	25	South Korea	U.S.	40,649
6	South Korea	China	95,451	26	Ukraine	Russia	38,639
7	China	UK	89,358	27	Russia	Germany	38,346
8	India	U.S.	86,846	28	U.S.	UK	38,101
9	U.S.	Canada	79,902	29	Russia	Japan	37,570
10	China	South Korea	79,561	30	China	Singapore	37,295
11	Mexico	U.S.	73,750	31	Belarus	Russia	36,191
12	Japan	U.S.	73,026	32	Russia	Turkey	34,944
13	Japan	China	69,778	33	China	Spain	34,672
14	U.S.	China	67,054	34	China	Australia	34,322
15	Russia	China	64,571	35	China	Thailand	32,150
16	China	India	61,141	36	China	Brazil	31,482
17	China	Canada	54,898	37	Taiwan	U.S.	31,043
18	China	France	54,517	38	China	Indonesia	30,039
19	Russia	U.S.	53,808	39	China	Russia	29,813
20	U.S.	Mexico	52,014	40	U.S.	South Korea	28,757

Since 1995, 6 of the 10 ten fastest growing country-to-country flows (in absolute volume) have originated in China (Table 2.5.2). There has been a modest rise in American exports to developed countries but a large rise in imports from developing countries, particularly China and India. Increases in embodied exports from the U.S. (most substantially to China, Mexico, the UK, Russia, Poland, and Singapore) have been smaller. The result has been a significant net increase in embodied imports into the U.S.

Table 2.5.2. Top largest-growing embodied emissions flows from 1995-2015, ranked in absolute terms and shown as percentage growth rate

Origin	Destination	Growth Rate
China	U.S.	317%
China	Hong Kong	217%
South Korea	China	1431%
China	Japan	145%
China	UK	333%
India	U.S.	350%
Japan	China	594%
China	Germany	240%
China	India	874%
Russia	China	522%

An emerging trend is the rise of South-South trade.

The trend of emissions displacement from developed to developing countries is clear. But there has also been a steep rise in the trade among developing nations (i.e. "South-South" trade), with a nearly doubling of trade between these regions since 2000. This reflects the emergence of a new phase of globalization in which some production is relocating from China to other countries, particularly production of raw materials and intermediate goods such as mining and chemical products.

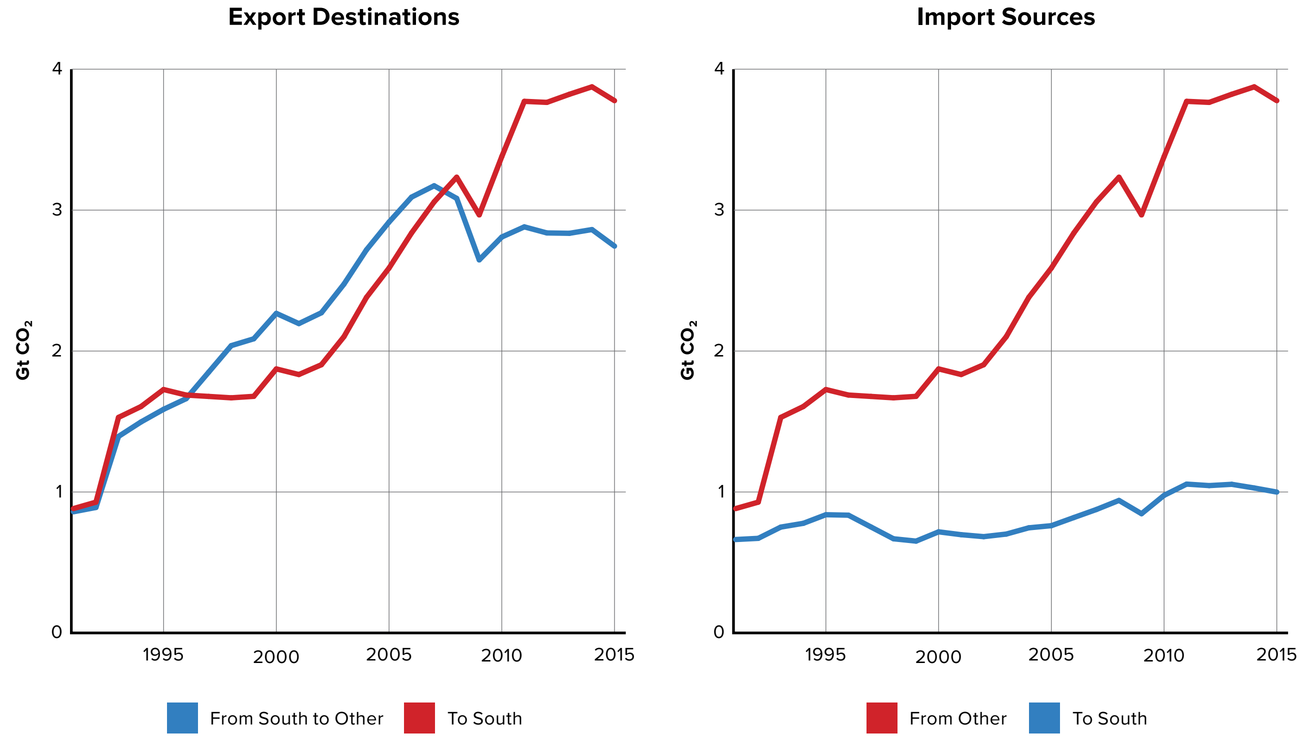


Figure 2.6. Export destinations from the South (ie. non-OECD countries) and import sources (Gt CO_2). The recent rise of trade among Southern countries is clearly visible.

The growth of CO_2 emissions embodied in Chinese exports has slowed in recent years, while the embodied emissions exported from regions including Bangladesh and Vietnam have surged. Ever more complex supply chains are distributing energy-intensive industries across the global South. In order for the Paris Agreement goals to be tenable, these growing hidden emissions flows between developing countries must be accounted for in carbon policy.

The rise in South-South trade has been explored in more depth in recent articles by Mi and colleagues (Mi et al. 2017) and by Meng and colleagues (Meng et al. 2018).

Carbon efficiency varies considerably between countries. This means that as national carbon policies come into effect, it is likely that the loophole will grow more.

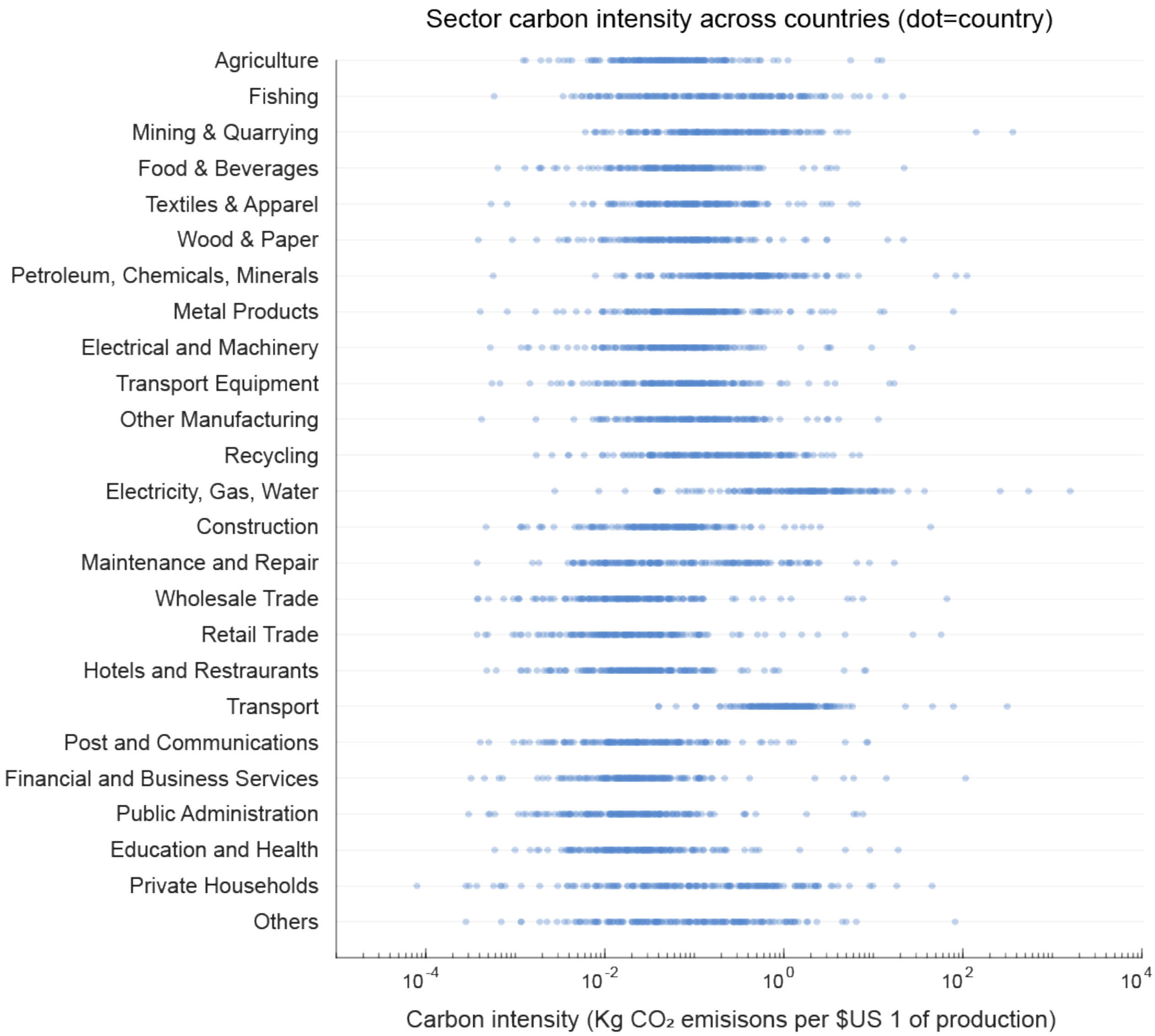


Figure 2.7. Same-sector carbon intensity (kg CO_2 emissions per $US1 of production) (dot = country)

The carbon efficiency of production for specific product and service groups varies widely across sectors and across countries. As seen in this figure, the same sector in different countries can have an over 10-fold difference in carbon efficiency, i.e. the carbon emissions required to produce one unit of economic output. These differences are to an extent due to aggregation in the economic classification used: e.g. the chemicals sector in one country may specialize in more value-added products while the chemicals sector in another country is built around more primary products. Thus, to a degree, intra-sectoral differences make international comparison of sectors difficult.

With that caveat in mind, the wide differences in carbon intensity[3] mean that as more stringent carbon regulation comes into effect, there will be both an opportunity and an economic incentive to avoid regulation. While it is true that carbon costs are a small portion of the total cost structure for most industries, nevertheless as the costs of emitting carbon rise in certain countries and are left unaccounted for in others, it can be expected that businesses make decisions about production and sourcing as those costs rise at the margin.

Green purchasing policies circumvent this potential problem of production fleeing regulation, as they create a level playing field for all who want to sell to the procuring party, which sets a carbon benchmark or maximum carbon threshold. As long as producers meet this specified standard of carbon intensity for their products, buyers need not be discerning about the carbon policy regime in which a producer is operating. Examples of such policies include the California Buy Clean Act and low-carbon procurement requirements in the Netherlands, as well as commitments on the part of individual private companies.

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[3] The main reasons for different carbon intensity are different energy systems and electricity production technologies in use, differences in the technologies in use in the industry, and differences in specialization within the sector.

For top importers (the U.S., UK, and EU), net imports have stabilized in recent years.

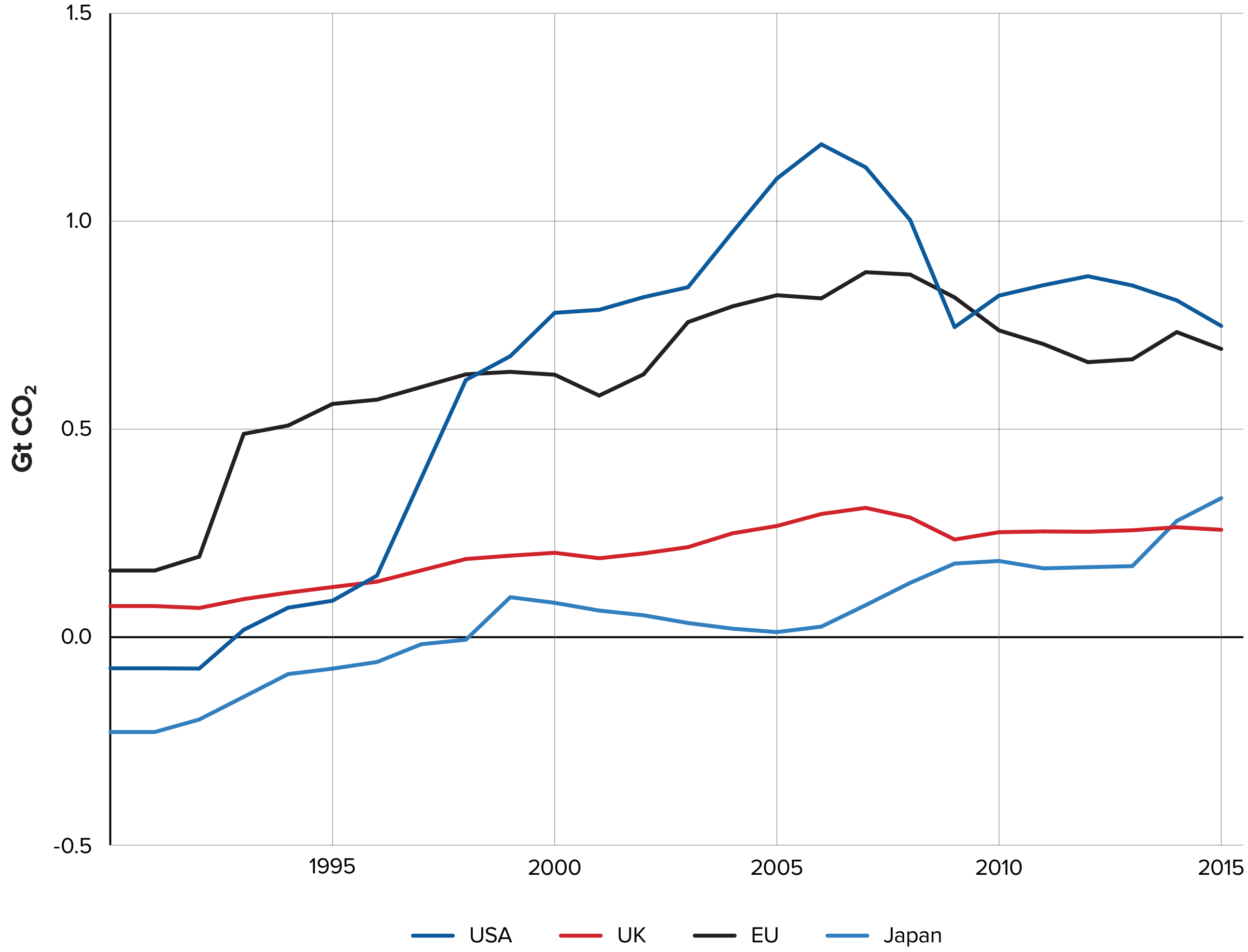

Figure 2.8. Net imports of CO_2 emissions (Gt CO_2) for the U.S., UK, Japan, and EU (other than UK), have plateaued in recent years.

The rapid growth in imports of embodied emissions in the top net importers (U.S., the UK, Japan, and the EU) has slowed and stabilized in recent years. The global economic slowdown around 2008 played a major role in this stabilization. Additionally, the growth in global CO_2 emissions from fossil fuels and industry has also slowed, despite continued economic growth.

According to an analysis by Jackson and colleagues (Jackson et al 2015), decreased coal use in China was largely responsible, coupled with slower global growth in petroleum and faster growth in renewables. However, additional action is still needed, as production shifts out of China and to other countries that will be susceptible to the carbon loophole.

Better regular monitoring of trade in embodied carbon is needed.

Although the total volume of emissions embodied in trade has in recent years plateaued, there is no indication that the carbon loophole is shrinking; if anything, all indications are that heterogeneous climate policies risk intensifying carbon leakage as production continues to shift to lesser-regulated regimes. Therefore, it is important to track the trend of embodied carbon flows over time. Measurement is the first step towards management, and data collection can enable informed policy decisions. Monitoring can allow the establishment of a baseline from which to assess whether introduced policies are benefiting or undermining a country's consumption-based carbon profile.

There are several MRIO databases available for monitoring embodied CO_2 emissions. These databases each have strengths and limitations. These pros and cons are discussed below in the Appendix, and in the Climate Works report "Imported carbon emissions through consumption – the case of Europe". This study was built using the Eora MRIO database. Eora was chosen as it offers the most recent timeseries and most comprehensive coverage of countries, and a high level of detail.

Official endorsement of consumption-based accounting has been slow to develop. The UK is the only country that annually calculates and discloses a consumption-based emissions account, and France does so semi-annually. The statistics bureaus in Sweden (through the PRINCE project) and the Netherlands[4] have also expressed interest. In 2017 the OECD released a series of official input-output tables (the OECD Inter-Country Input-Output Database, or ICIO) for the OECD member nations, and calculated the embodied carbon footprint flows between member nations and key trade partners.

Stronger institutional support from official statistical offices would improve the tracking of embodied carbon flows. In addition to improved IO and trade statistics, a key area where further improvement is needed is the sectoral emissions inventories. Current inventories tend to be broad, and often do not pinpoint in adequate detail which industries are associated with which primary emissions.

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4 Hoekstra and Edens (Hoekstra et al. 2013, Edens et al. 2015) have presented the Simplified National-Account Consistent (SNAC) method for combining an official national IO table with a global MRIO.

03

Deep-Dive Case Studies of Traded Carbon

We chose two countries and two industrial sectors for deep-dive case studies. For the industrial sectors, we analyze two of the most energy- and carbon-intensive sectors: steel and cement. Each of these sectors accounts for over 5% of current anthropogenic CO_2 emissions worldwide. In addition, these energy-intensive commodities are traded at a significant level internationally, making them EITE (emissions intensive trade exposed) sectors.

For country-level case studies, we analyze China and India, which together account for about 30% of the world's embodied emissions in exports, are growing rapidly, and import and export a significant amount of goods.

3.1. Embodied Carbon in the Steel Trade

Steel is a highly CO_2-intensive product that is also traded globally in significant amounts. Steel production is very CO_2-intensive due to the emissions from combustion of fuels for heat, and indirect emissions from high consumption of electricity (primarily in electric arc furnaces and finishing operations). Commodity steel refers to steel that is produced and traded directly, not steel-containing products. According to the Steel Statistical Yearbook by Worldsteel (2017), China exported 112 million tons of commodity steel in 2015, which is 1.4 times the total steel production in the U.S. in that year - although the U.S. itself is the 4th largest steel producer in the world. The significant global trade of such a carbon-intensive commodity has substantial implications for the carbon loophole.

There are significant extra-regional flows of carbon embodied in the commodity steel trade worldwide.

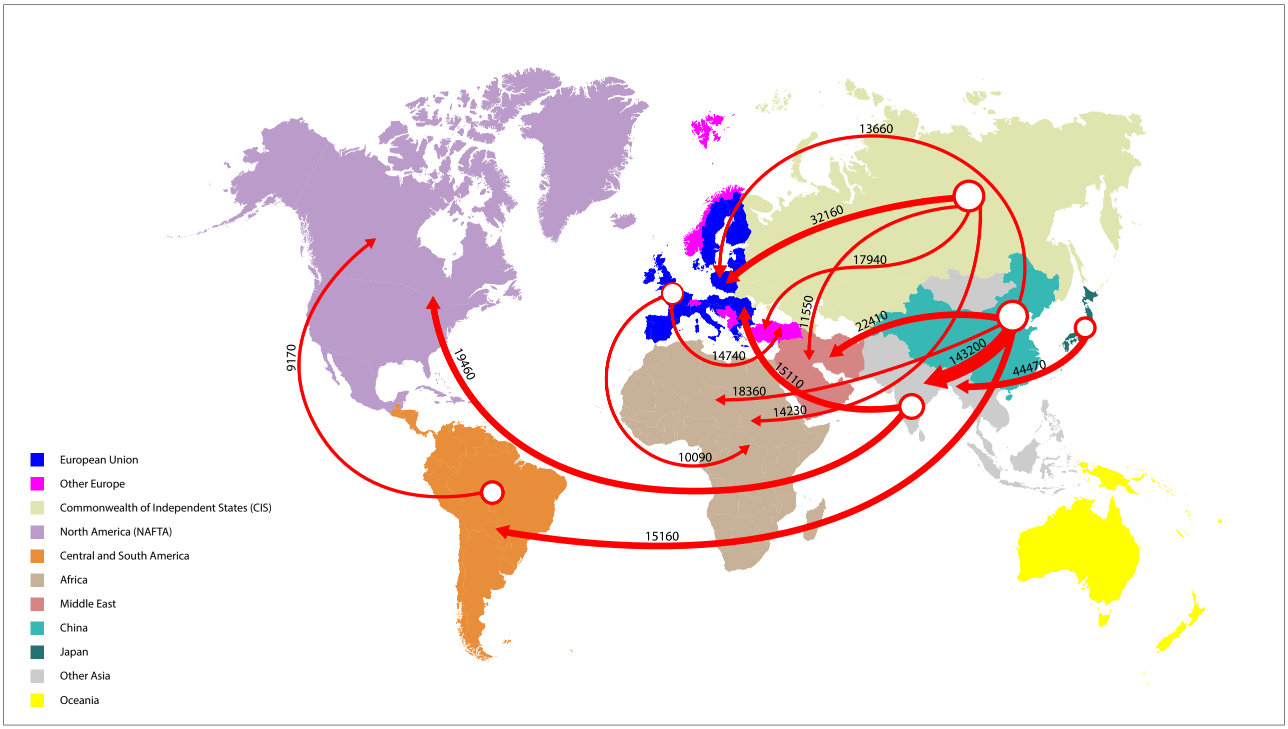


Figure 3.1.1. Top 15 extra-regional flows of CO_2 emissions related to the international trade of commodity steel in 2016 (kt CO_2)

Figure 3.1.1. shows the embodied carbon in commodity steel trade worldwide. Around 67% of the embodied carbon in 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 the region ‘Other Asia ’ is the largest net importer of the embodied carbon in 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 The Commonwealth of Independent States (CIS) to the EU 28 region.

Except for China, Japan, and the Commonwealth of Independent States (CIS), all regions of the world are net importers of carbon emissions embodied in commodity steel.

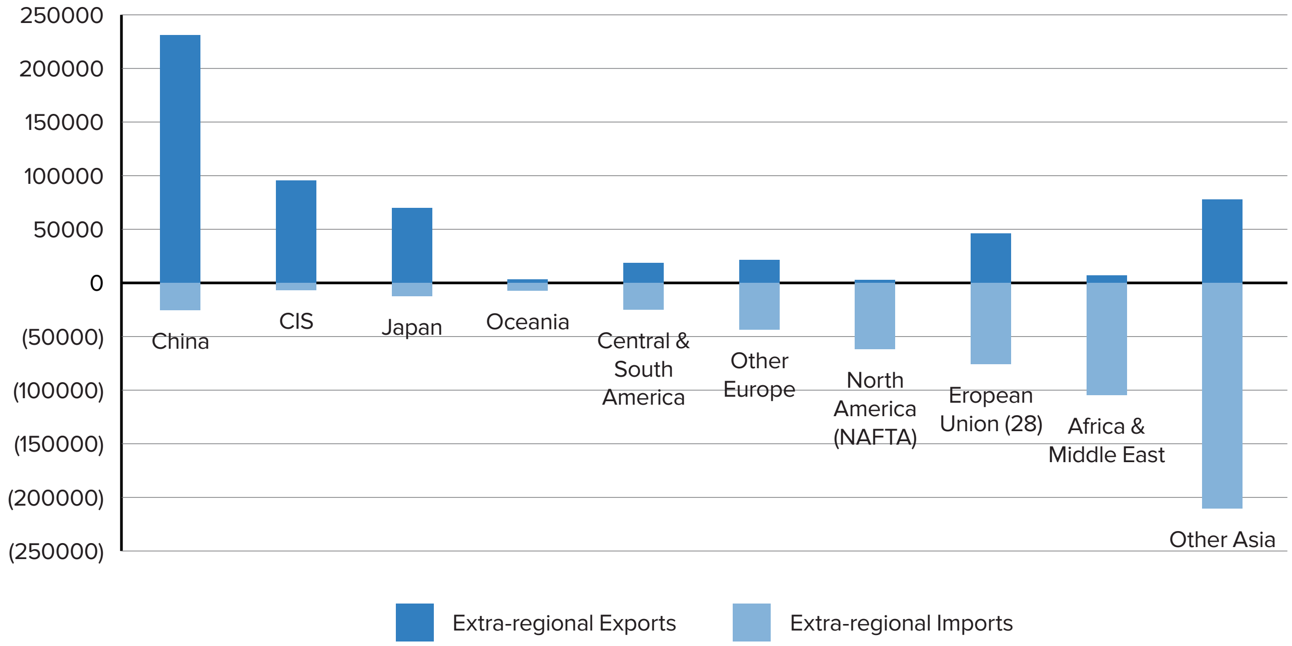


Figure 3.1.2. World trade of carbon embodied in commodity steel by region (kton CO_2) in 2016

Figure 3.1.2. shows the carbon embodied in commodity steel extra-regional export and import for each region separately. Only China, Japan, and CIS are net exporters of embodied carbon in steel trade, while the other regions are net importers of carbon embodied in commodity steel trade. 'Other Asia', Africa, and the Middle East are the largest net importers of carbon embodied in the commodity steel trade. Since countries in these regions are still developing, they have high growth potential and it is likely that they will continue to be large net importers of embodied carbon from the steel industry.

China produces over one quarter of traded carbon embodied in commodity steel.

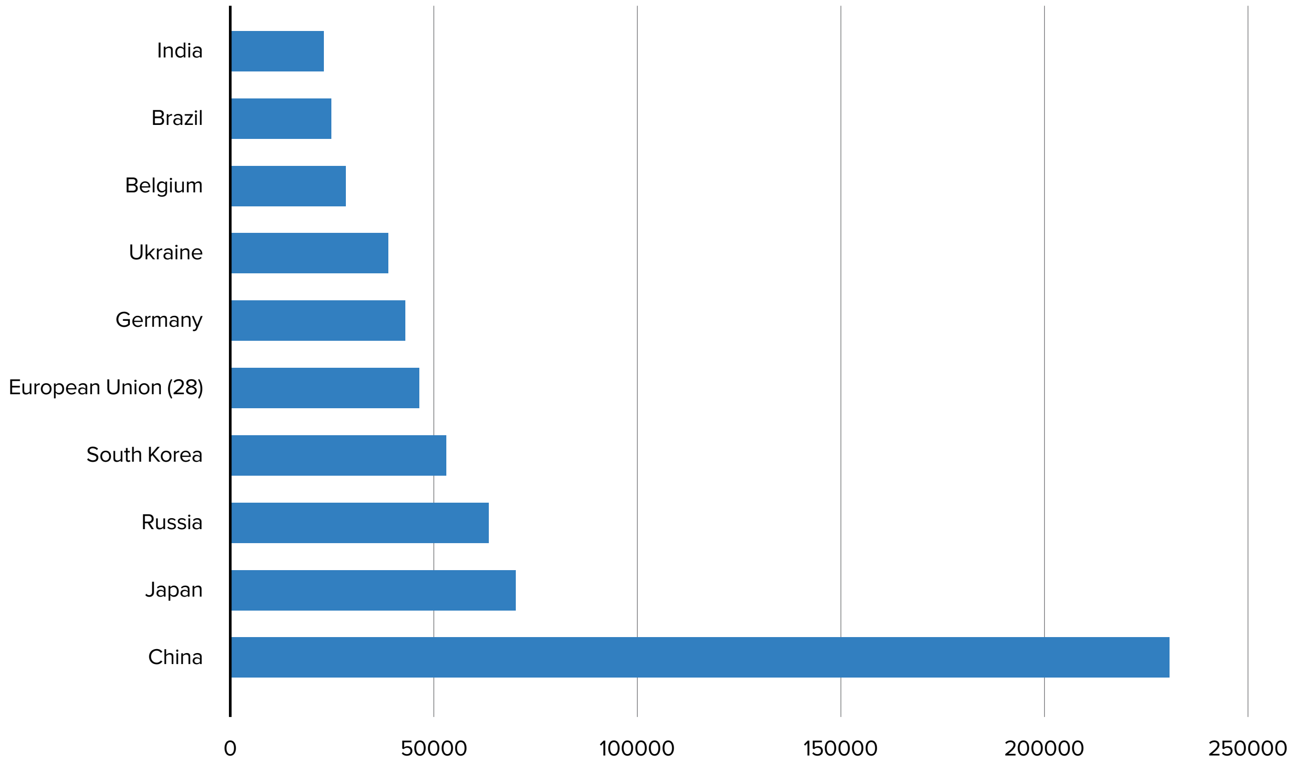
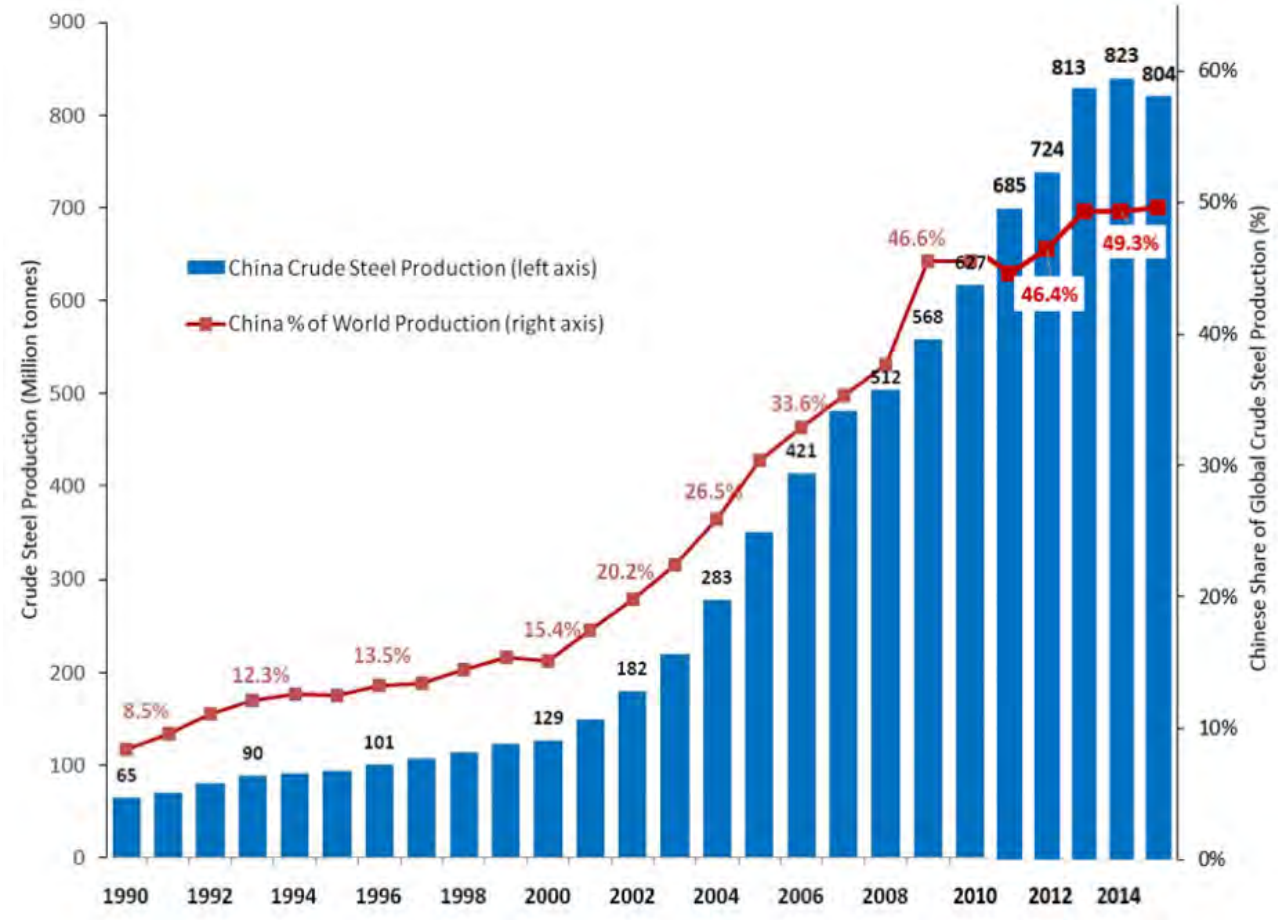


Figure 3.1.3. Embodied carbon of top 10 major exporter countries of commodity steel in 2016 (kton CO_2)

Figure 3.1.3. shows the top 10 exporter countries for embodied carbon in the steel trade. China alone accounts for 27% of total export of embodied carbon in commodity steel trade. Other top embodied carbon-exporting countries for commodity steel are Japan, Russia and South Korea. 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 export of more value-added steel products instead of commodity steel and facilitating increased demand for steel products in countries connected to its One Belt One Road initiative.

It should be noted that China has implemented aggressive policies to reduce the energy intensity and CO_2 emissions in its steel industry since 2006 by implementation of energy efficiency programs and shutting down old inefficient steel plants. Despite these efforts, the CO_2 intensity of steel production in China is still significantly higher than many other countries mainly because of the fact that more than 90% of the steel in China is produced using the energy-intensive Blast Furnace-Basic Oxygen Furnace process as opposed to the Electric Arc Furnace process that uses significantly less energy and primarily uses steel scrap. In addition, coal is the primary fuel used in the Chinese steel industry. Figure 3.1.4 shows Chinese steel production and its share in total world production in 1990-2015.



Sources: EBCISIY, various years; NBS 2015a; Worldsteel Association 2016

Figure 3.1.4. China's crude steel production and share of global production (1990–2015)

The trade in steel-containing goods made up 21% of steel use and 77% of commodity steel exports in 2013, accounting for a significant share of embodied carbon flow.

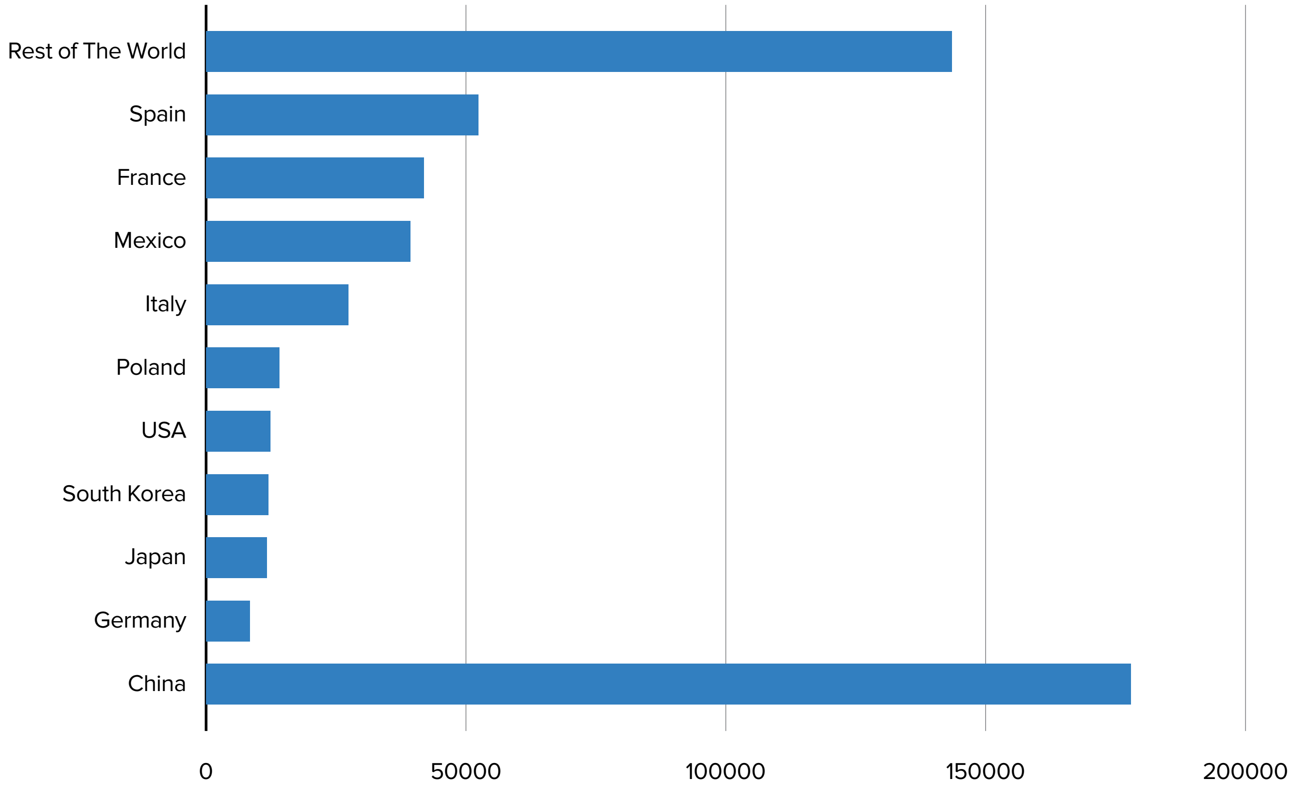


Figure 3.1.5. Embodied carbon in exported value-added steel products for top 10 countries in 2013 (kton CO_2)

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 (value-added steel products). The top 10 countries listed in Figure 3.1.5. account for about 70% of the total export of value-added steel. Figure 3.1.5. shows the embodied carbon in value-added steel export for each country and the rest of the world. China alone accounted for over a quarter of the world's embodied carbon in exported value-added steel products. As the Chinese economy matures and demand for infrastructure and building construction decreases, China will increasingly shift from commodity export to value-added products export. Thus, China's export of embodied carbon in value-added steel products is likely to increase in the coming years.

Also, as can be seen from this graph and Table A.4.3 in the Appendix section, many of the countries ranked high for embodied carbon in exported value-added steel products in Figure 3.1.6 are among the top importers of commodity steel as shown in Table A.4.3. In other words, they import significant amounts of commodity steel that has high embodied carbon and produce high value added steel and export a substantial portion of it. These countries gain more economic benefits from value-added steel trade without being held accountable for the high CO_2 emissions that occur during commodity steel production.

3.2. Embodied Carbon in the Cement and Clinker Trade

Cement is a highly CO_2-intensive product that is also traded globally in significant quantities. The production of one ton of cement releases about 0.6 – 1.0 ton of CO_2 depending on the clinker-to-cement ratio, fuel mix, and other factors. The dominant driver of CO_2 emissions in cement manufacture is from calcination to produce clinker, in which limestone ($CaCO_3$) is transformed into lime (CaO) and byproduct CO_2. The rest of the CO_2 emitted during cement manufacture 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. According to the U.S. Geological Survey (2016), China alone exported about 15 million tons of cement in 2015, or 18% of the total cement production in the U.S. in that year. The trade of cement and clinker worldwide has significant implications for the embodied carbon in global trade.

There are large extra-regional flows of carbon embodied in the cement trade worldwide.

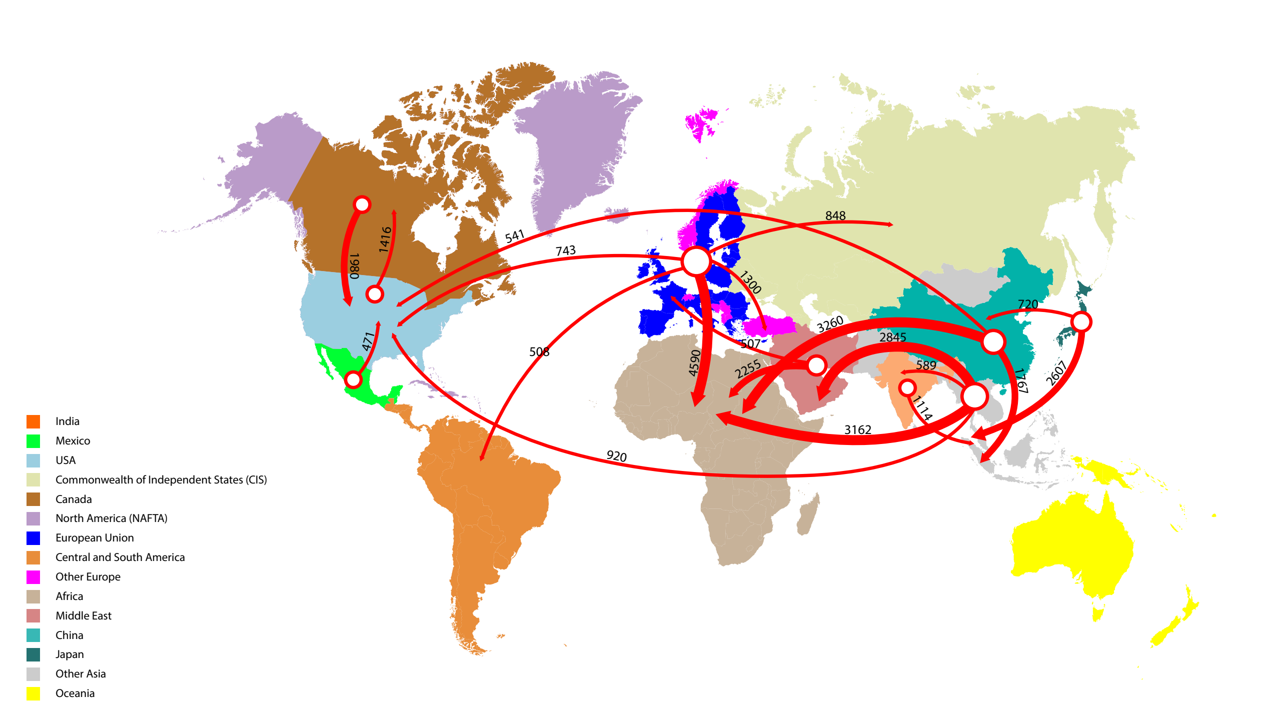
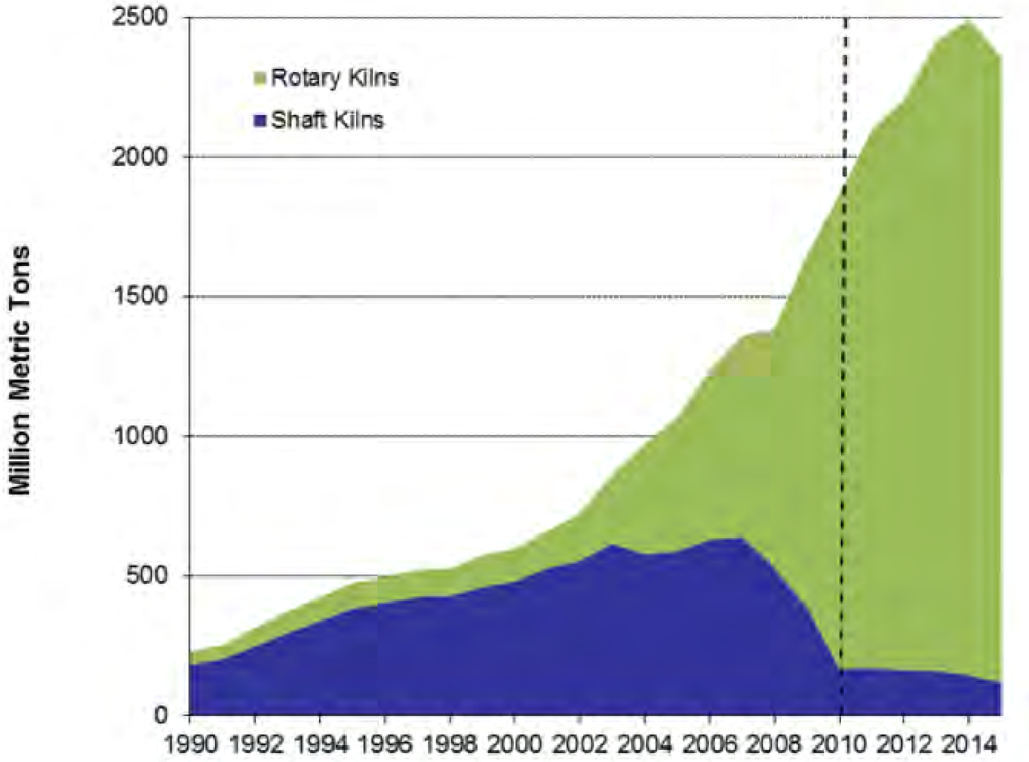


Figure 3.2.1. The main extra-regional flows of CO_2 emissions relating to the international cement trade in 2014

Figure 3.2.1. illustrates the embodied carbon in the cement trade worldwide. Around 50% 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. The 'Other Asia ' region is the largest net exporter and Africa is the largest net importer of the embodied carbon in the cement trade. The top three largest flows of embodied carbon in the cement trade are from the EU, China, and Other Asia regions to Africa.

China accounts for about half of the cement production in the world. Similar to what has been discussed for the steel industry in the previous section, China has implemented aggressive policies to reduce the energy intensity and CO_2 emissions in its cement industry since 2006 by implementation of energy efficiency programs and shutting down old inefficient cement plants. China used to have large cement production capacity from inefficient vertical shaft kilns. Over the past decade, Chinese government aggressively pushed for closing down of these outdated plants and replacing them with efficient rotary kilns. By 2015, less than 6% of the cement production capacity in China was using vertical shaft kilns. As a result of this action, the energy intensity and CO_2 emissions intensity of cement production in China dropped significantly over the past decade. Figure 3.2.2 shows cement production in China by kiln type during 1990-2015.

[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.



Sources: ITIBMIC 2004; MIIT 2011; NBS 2015.

Figure 3.2.2. Cement production in China by kiln type, 1990–2015

The embodied carbon in extra-regional clinker trade worldwide is almost equal to the embodied carbon in cement trade.

Clinker is an intermediary product in the cement production process. Due to process emissions and combustion of fuel for heat, over 95% of the CO_2 emitted in producing cement is emitted from calcination 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 to produce cement.

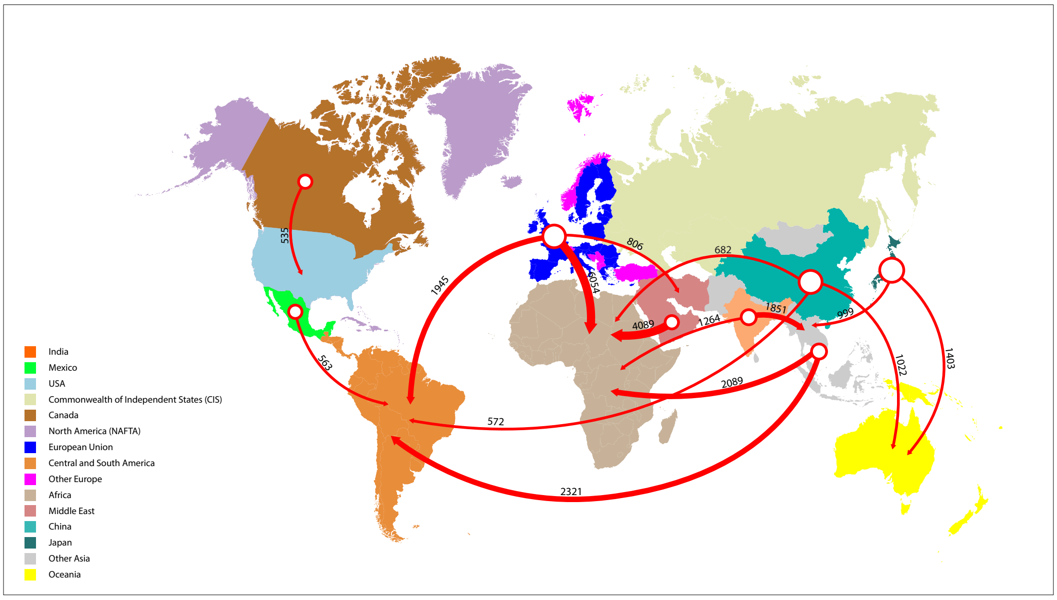


Figure 3.2.3. The main extra-regional flows of CO_2 emissions associated with international clinker trade in 2014

Figure 3.2.3. illustrates the embodied carbon in the clinker trade worldwide. Around 60% 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 EU28 region is the largest net exporter and Africa is the largest net importer of the embodied carbon in the clinker trade. The top three largest flows of embodied carbon in the clinker trade are from the EU and the Middle East to Africa, and from Other Asia to Central and South America.

Africa is by far the largest regional net importer of carbon embodied in cement, followed by Asia and the U.S.

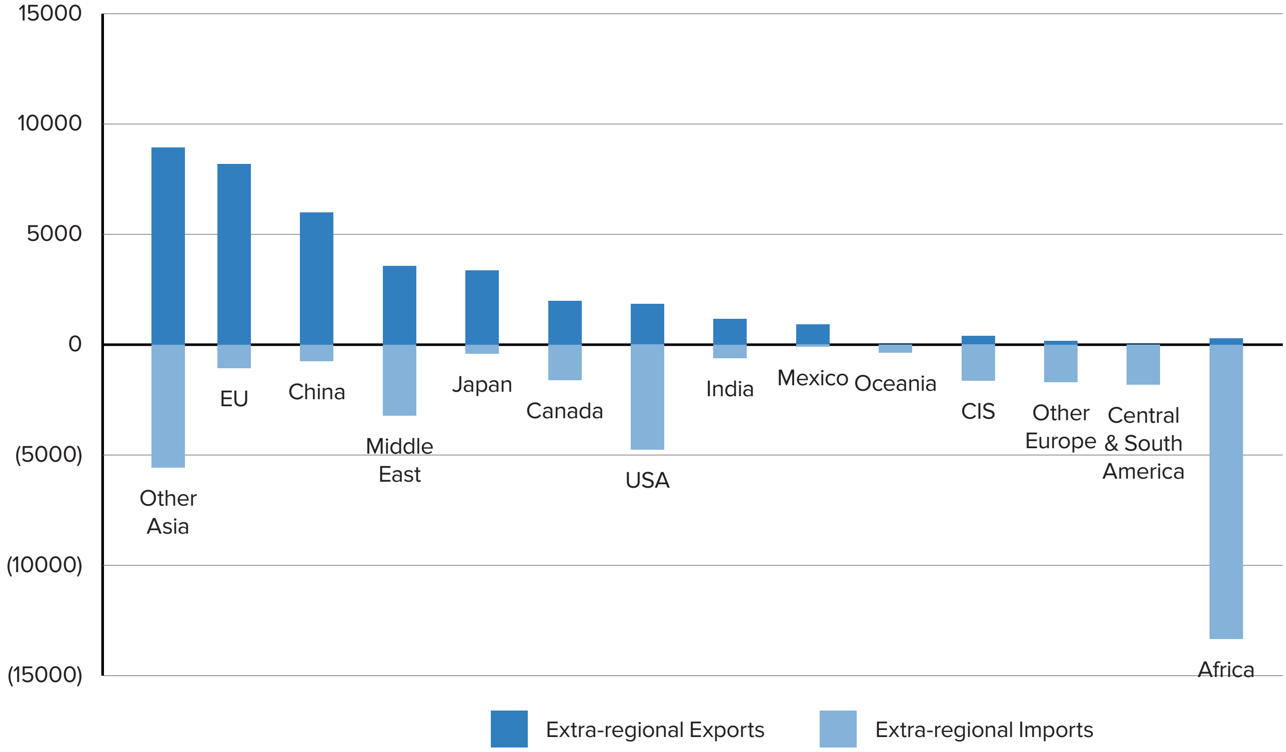


Figure 3.2.4. World trade of carbon embodied in cement by region in 2014 (kton CO_2)

China, the EU 28 and Other Asia are the top three net exporters of embodied carbon in the cement trade, while Africa, the U.S., and the Central and South America regions are the top three largest net importers. Since many countries in Africa and Central and South America are rapidly developing, demand for cement for infrastructure and building construction will likely surge. These regions will likely continue to be large net importers of embodied carbon in cement unless they increase their own domestic cement production capacity. This would require new plants, which could use best available technologies and have lower emissions.

Africa is also by far the largest regional net importer of carbon embodied in clinker, followed by Central and South America and Oceania.

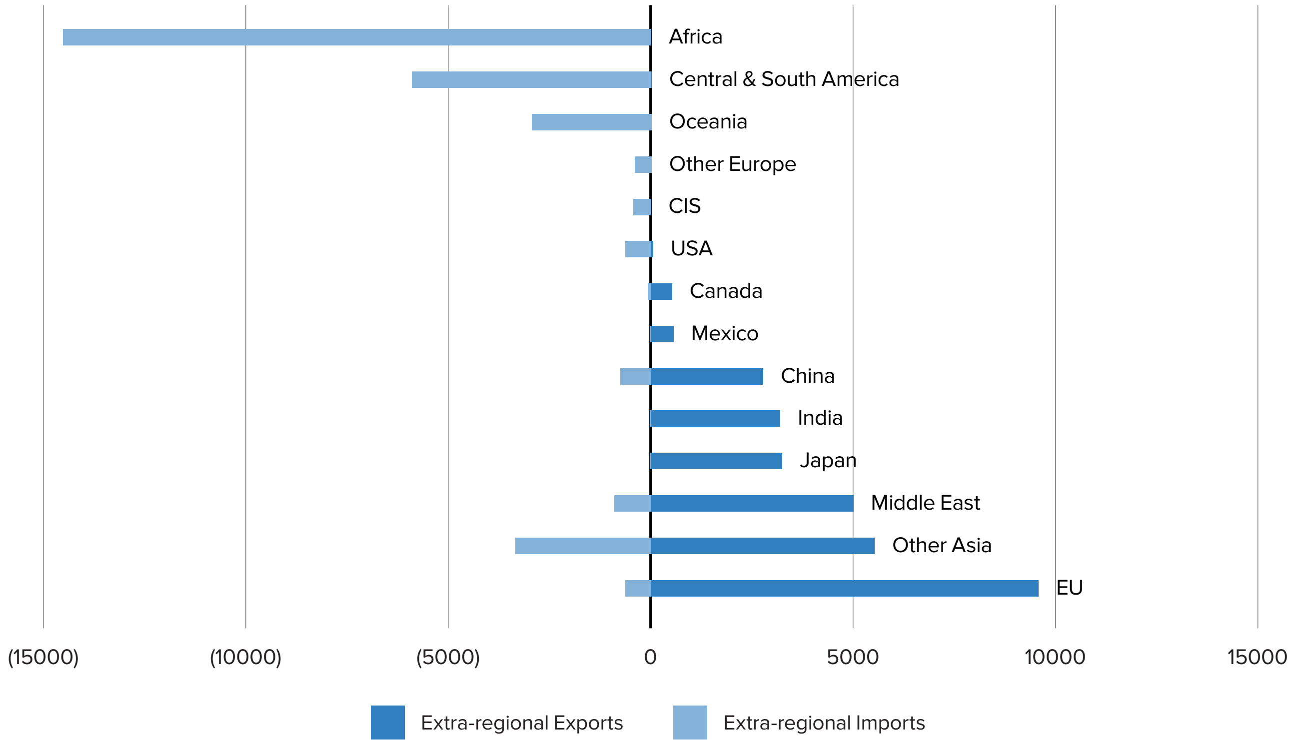


Figure 3.2.5. World trade of carbon embodied in clinker by region in 2014 (kton CO_2)

The patterns for embodied carbon in the clinker trade are somewhat different from the carbon in the cement trade shown on the previous page. The EU 28, Middle East, and Japan are the top three net exporters of embodied carbon in the clinker trade, while Africa, Central and South America, and Oceania are the top three largest net importers.

3.3. Country Deep-Dive: China

China grew enormously as the "world's factory" from the 1990s onward. In the early 1990s, most of China's trade was regional, but over the following two decades, especially after joining the World Trade Organization in 2001 China became a key node in the global economy. China remains a major trader of embodied CO_2, with imports equal to 20% of its territorial emissions and net exports equal to 13% of territorial emissions (Table 3.3.1).

The eclipsing of Western manufacturing by Chinese manufacturing, combined with the relative carbon intensity of the Chinese energy system, means that China has been a prime actor in the rise of carbon leakage and emissions displacement. Much of the apparent emissions reductions occurring in North America and Europe has actually been a shifting of emissions from these countries into China. While this emissions displacement dynamic emerged strongly between 1990 and 2010 (Figure 3.3.1.), since 2010, the phase of fast growth has ended, and the growth rate in carbon embodied in exports has slowed.

Table 3.3.1. China's embodied carbon balance of trade (Unit: $KtCO_2$; Year: 2015)

Territorial emissions from fuel combustion	10,641,789
Embodied in imports	706,053
Embodied in exports	2,186,624
Embodied in net imports:	-1,480,571
Consumption-based account:	9,161,218

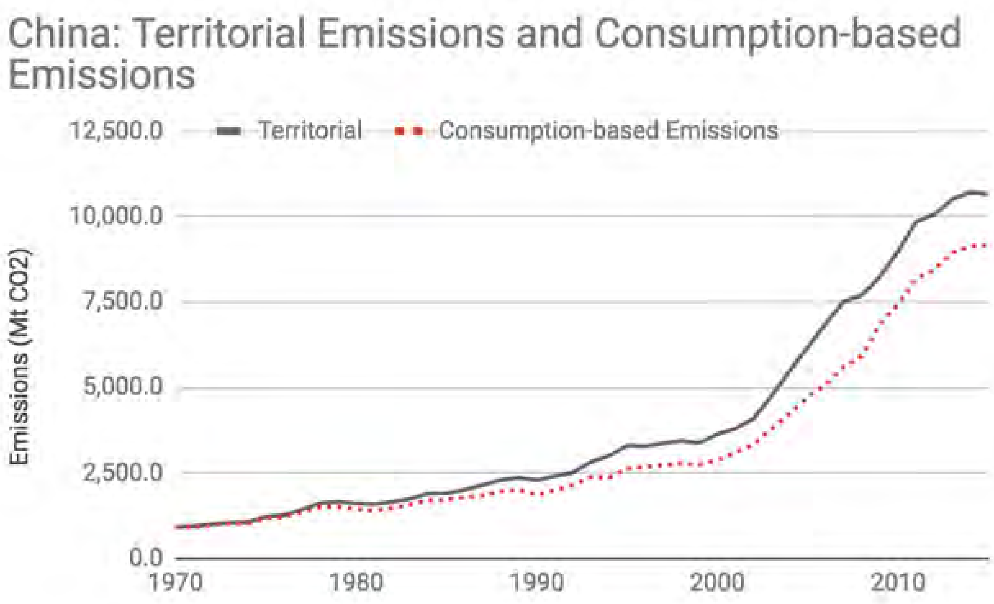


Figure 3.3.1. China's territorial and consumption-based emissions. Note: The gap between territorial and consumption-based emissions is the net export of embodied CO_2.

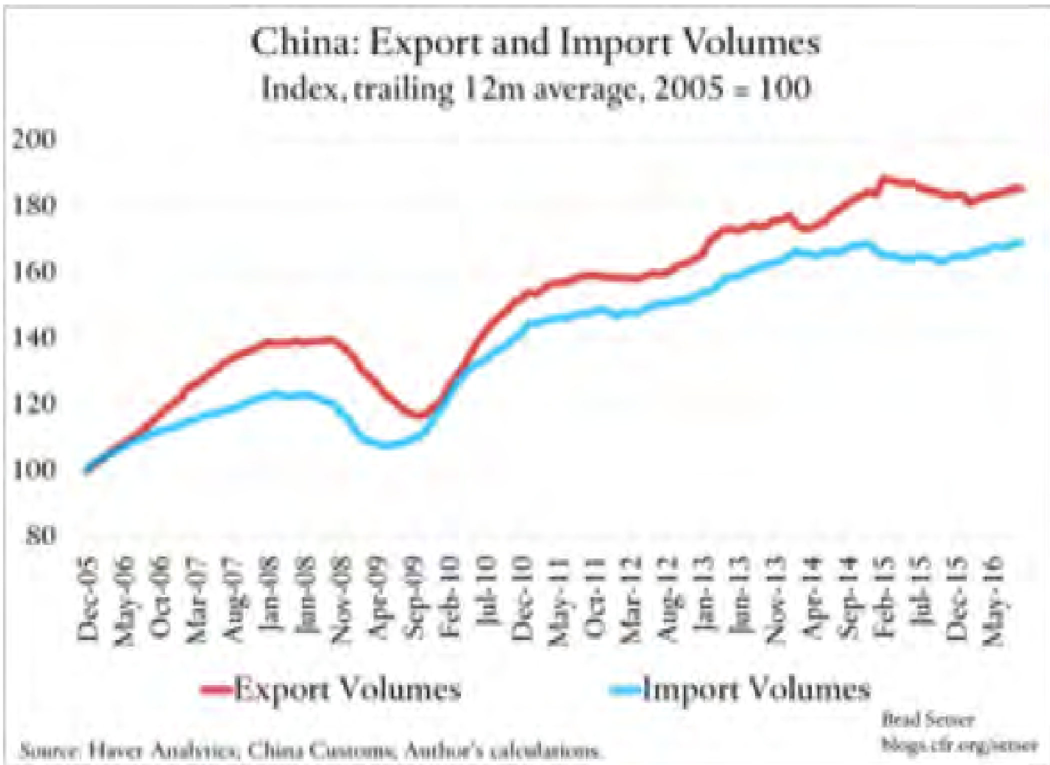


Figure 3.3.2. Chinese import and export volumes in monetary terms, 2005-2016 (Setser 2016)

In China, exports have leveled off in monetary terms, and emissions started to plateau after 2012. This stabilization in emissions is in part due to major policies and programs to improve energy efficiency, shut down old inefficient plants, and shift away from coal. China officially aims to peak its CO_2 emissions by 2030.

A large percentage of emissions from many sectors in China are associated with demand for exports, especially for textiles, toys and recreational products.

For at least 10 sectors (of 123 sectors defined by the Chinese sectoral classification used in the Eora model), more than one third of the sector's Scope 3 emissions are emitted in service of export production (Table 3.3.2). Key sectors in which production for export drives sectoral emissions are toys and recreational products; leather, textiles, and apparel sectors; and office equipment and "other manufacturing products". Emissions-intensive sectors in China like steel and cement represent a larger absolute amount of emissions traded internationally, but the sectors discussed here are more exposed to the carbon loophole due to their orientation towards export.

Table 3.3.2. Top 10 sectors by share of sectoral emissions induced by foreign final demand

Sector	Share of emissions induced by foreign final demand
Toys, athletic and recreation products	65%
Other textiles (not elsewhere classified	52%
Leather, furs, down	48%
Apparel	43%
Cultural goods	42%
Woolen textiles	37%
Instruments & measuring equip	37%
Cultural and office equipment	37%
Knitted fabrics	37%
Other manufacturing products	34%

China's embodied carbon still flows to many of its historic trade partners, but India, Indonesia, and Malaysia are rapidly becoming major importers of embodied carbon from China.

China is a major trading nation and has significant trade relationships with many countries following its entry into the WTO in 2002 (Table 3.4.5). Of the export destinations of embodied carbon from China, the standard set of countries are seen (U.S., European countries, Japan, Korea). A noteworthy item is the rapid rise of India: in 1995 it was only the 19th largest importer of embodied CO_2 from China, but in 2015 it was 7th. The change in suppliers is also significant, with India, Indonesia, and Malaysia not ranking in the top 10 suppliers in 1995 (they were 10th, 13th, and 19th, respectively) but rising to 5th, 7th, and 8th in the ranking in 2015.

China is a net exporter of embodied carbon - volumes of embodied CO_2 imports into China are in total 50% lower than its exports. Korea, Russia, Indonesia, Malaysia, and Kazakhstan stand out as noteworthy suppliers of embodied CO_2 into the Chinese economy.

Table 3.3.3. China's trade partners, by import and export of embodied CO_2 (Unit: kt CO_2; Year: 2015)

EXPORTS				IMPORTS			
Consumer	Total emissions exported to this country	Rank in 2015	Rank in 1995	Origin Country	Total embodied emissions originating in this country	Rank in 2015	Rank in 1995
U.S.	502,228	1	1	South Korea	95,451	1	4
Hong Kong	230,927	2	3	Japan	69,777	2	3
Japan	211,508	3	2	U.S.	67,054	3	1
Germany	98,199	4	4	Russia	64,570	4	2
UK	89,358	5	6	India	44,272	5	10
South Korea	79,561	6	5	Germany	27,992	6	5
India	61,141	7	19	Indonesia	19,946	7	13
Canada	54,897	8	9	Malaysia	19,827	8	19
France	54,516	9	7	Australia	18,694	9	8
Italy	43,683	10	8	Kazakhstan	16,144	10	7

3.4. Country Deep-Dive: India

India's CO_2 emissions doubled between 2002 and 2015. The country is increasingly a net exporter of embodied CO_2: in 2015, almost 20% of its emissions were associated with production for export. India's balance of trade in embodied emissions in 2015 was as follows:

Table 3.4.1. India's embodied carbon balance of trade (Unit: $KtCO_2$; Year: 2015)

Territorial emissions from fuel combustion	2,454,968
Embodied in imports	232,722
Embodied in exports	488,312
Embodied in net imports:	-255,590
Consumption-based account:	2,199,378

While India has been a net exporter of embodied carbon since the mid 1990s, the growth of embodied emissions exports has accelerated since 2010. Around 2012, total emissions began to grow faster than consumption-based emissions.

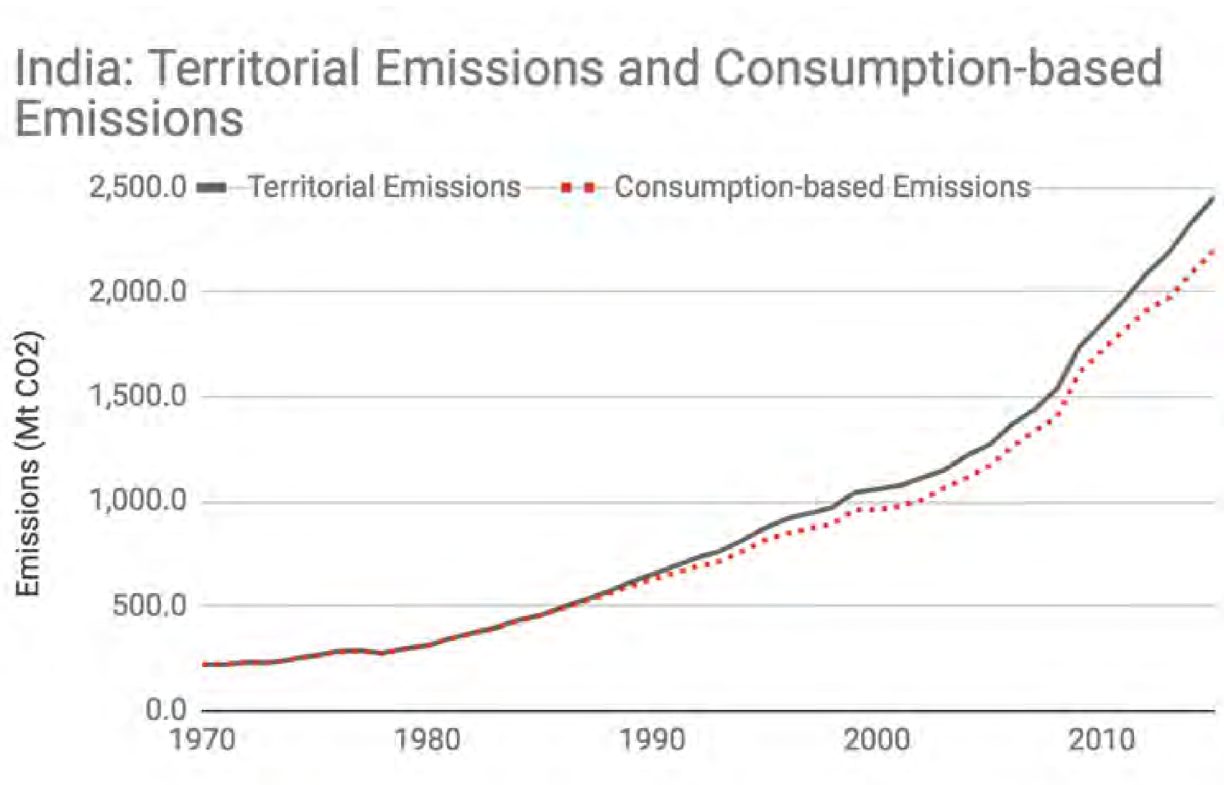


Figure 3.4.1. India's territorial and consumption-based emissions

For some industry subsectors in India, a high percentage of sectoral emissions are associated with production for export

For a number of economically important sectors, including leather and textiles, tea, and electrical appliances, up to 30-50% of the sector's full supply chain emissions (Scope 3 emissions) are attributable to production for export. Compared to more emissions-intensive sectors such as steel and cement, these sectors may be responsible for less absolute emissions in exports; however, due to their trade exposure, they represent an opportunity for downstream consumers to close the carbon loophole by demanding lower carbon forms of a given good.

Table 3.4.2. Top sectors in India, by share of sectoral emissions attributable to production for export (year: 2015)

Sector	Share of emissions induced by foreign final demand
Leather footwear	55%
Leather and leather products	49%
Khadi, cotton textiles (handlooms)	44%
Industrial machinery	42%
Motorcycles and scooters	36%
Bicycles, cycle-rickshaw	34%
Electrical appliances	33%
Tea	31%
Coconut farming and processing	30%
Organic heavy chemicals	29%

The U.S. is the largest importer of embodied carbon from India.

The U.S. is the largest recipient of embodied emissions from Indian goods, importing more than twice as much as the next largest export destination, China. The other top destinations for embodied carbon in Indian exports are the European economies of Germany, France, and Italy, and regional trading partners of Saudi Arabia, the UAE, and Bangladesh. Japan is the fifth largest emissions import and export destination and export destination.

India imports little embodied carbon from European countries, with Russia, South Korea, South Africa, Australia and Malaysia as top importers into India. The only European country that exports a large amount of embodied carbon to India is Germany, which is the 8th largest source of embodied carbon in imports into India.

Table 3.4.3. India's trade partners, by import and export of embodied CO_2 (Unit: kt CO_2; Year: 2015)

EXPORTS				IMPORTS			
Consumer	Total emissions exported to this country	Rank in 2015	Rank in 1995	Origin Country	Total embodied emissions originating in this country	Rank in 2015	Rank in 1995
U.S.	86,845	1	1	China	61,141	1	2
China	44,272	2	11	Saudi Arabia	21,621	2	4
UAE	28,583	3	5	U.S.	18,458	3	1
UK	23,008	4	4	Russia	15,526	4	3
Germany	21,607	5	2	Japan	9,863	5	5
Japan	17,514	6	3	South Korea	8,592	6	11
Saudi Arabia	14,200	7	9	South Africa	8,094	7	9
France	12,315	8	6	Germany	7,407	8	7
Italy	11,419	9	7	Australia	6,519	9	10
Bangladesh	9,692	10	21	Malaysia	5,072	10	21

3.5. Country Deep-Dive: The US and UK

Overall, developed countries are net importers of embodied carbon. The US and UK follow this pattern. But there are some interesting aspects of the trend in these important economies.

In the US, embodied imports accelerated rapidly starting in the early 1990s, but declined very sharply with the 2007 global financial crisis. Both direct emissions within the US (territorial emissions) and embodied emissions have roughly plateaued since the financial crisis. It is too soon to say whether this is the beginning of a lasting de-carbonization trend or only a momentary lull.

The UK's territorial CO_2 emissions have been declining for decades, and it has been one of the few countries able to report a decline in absolute emissions. However, considering the embodied carbon in imports, this apparent success is partly reversed. The total carbon footprint, inclusive of embodied CO_2 in imports, has slightly increased since 1990. As in the US, embodied CO_2 imports were strongly affected by the global financial crisis and have continued to declined slightly even after crash shock.

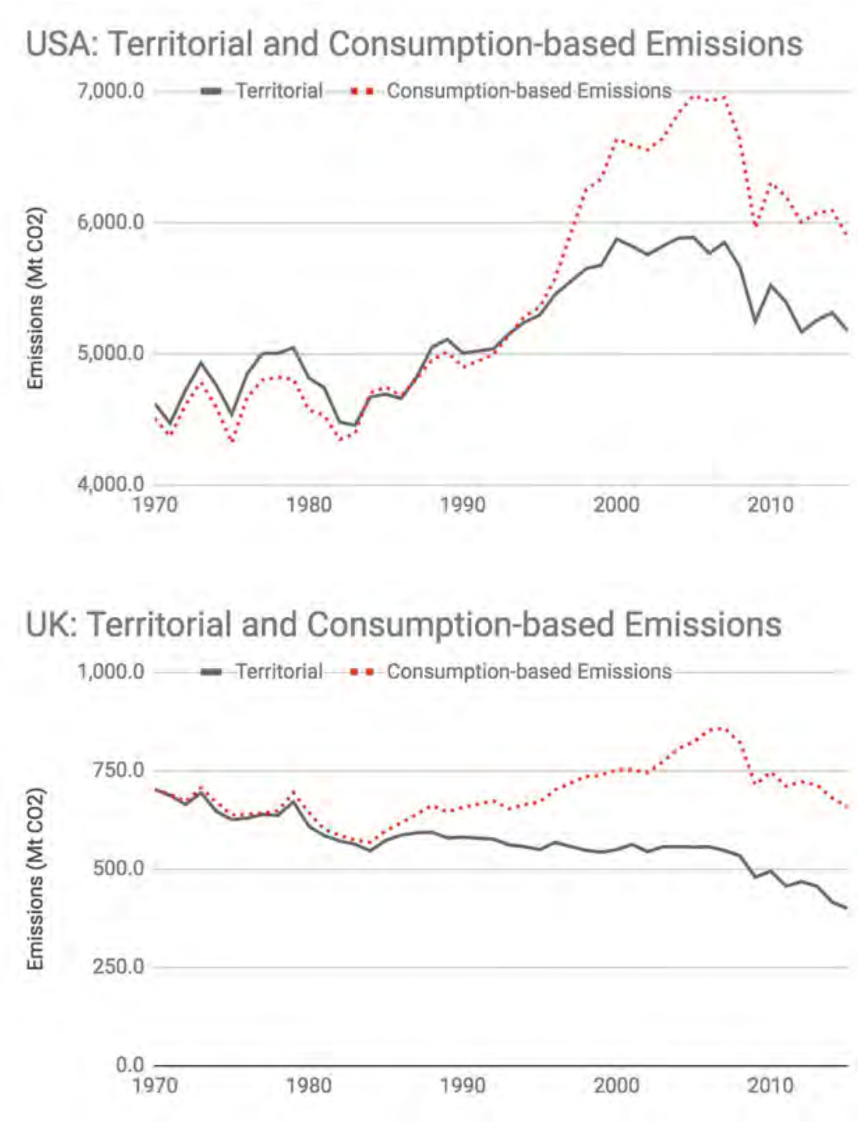
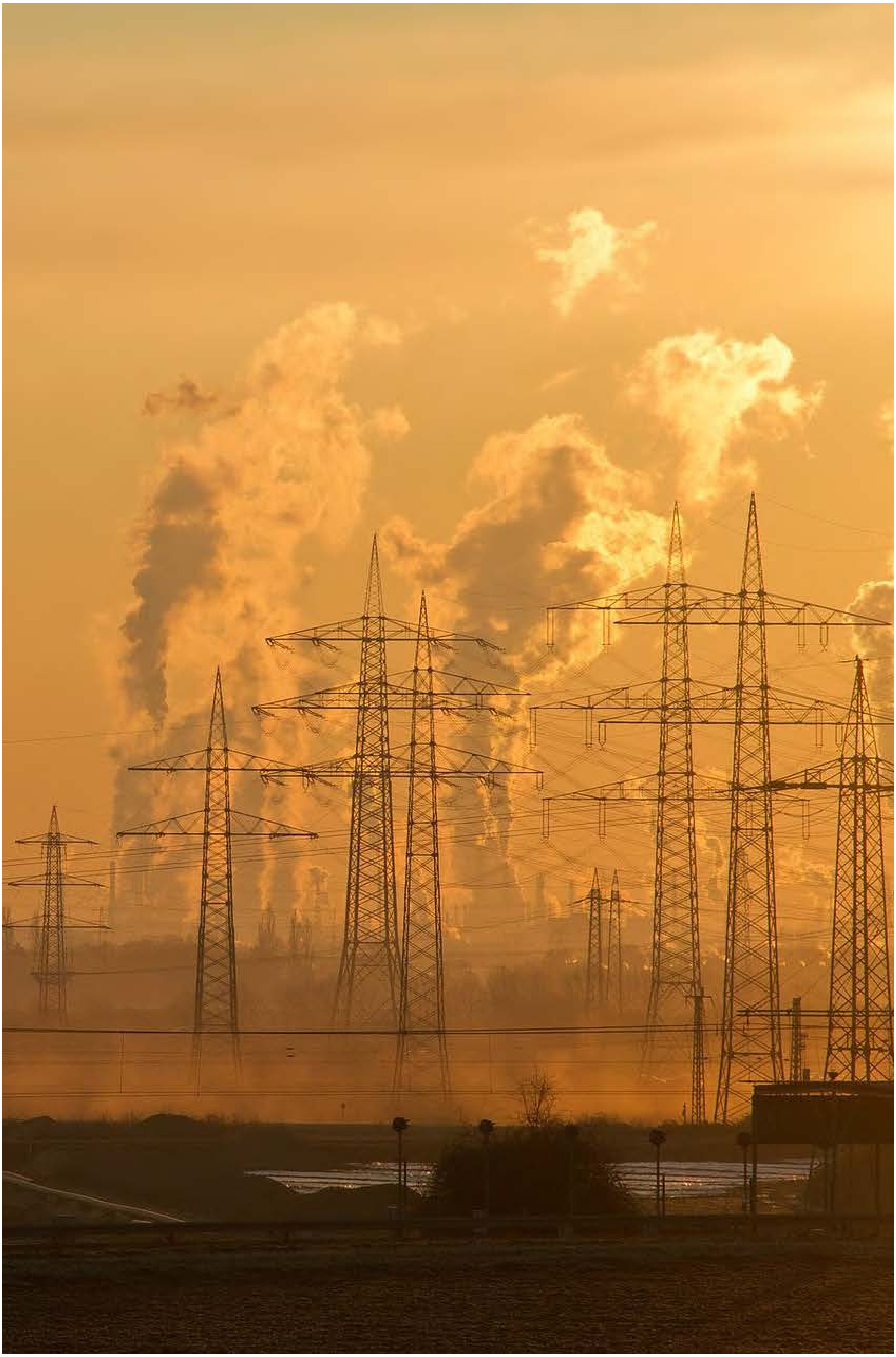


Figure 3.5.1. Territorial and consumption-based emissions in the U.S. and UK



4 Tools using Embodied Carbon Emissions Accounts

Consumption-based emissions accounting can inform policymaking that aims to close the carbon loophole. Many of these policy tools are not entirely new, but to effectively address imported carbon they may require a specific focus on these emissions, therewith building on or expanding existing or emerging policies.

We examine applications of embodied emissions accounting by dividing policy interventions along broad phases of the supply chain: production, the intermediate supply chain, and consumption. Policies listed under Production include those that regulate within national borders, while intermediate products may be traded across borders. Consumption policies address consumption by households, government, businesses, and other actors. A selection of policies is summarized in Table 4.6.1 and briefly further elaborated on in the sections below.

Table 4.6.1. CBA Policy applications by product lifecycle phase

PRODUCTION		
Production	**Intermediate Supply Chain**	**Consumption**
• Point-source and industry-level regulations • Product location at sale • National emissions targets • New metrics for emissions accounting	• Border tax adjustments • Technology transfer policies (offsets) • Best Available Technology standards • Voluntary agreements by trade associations	• Policies targeting household behaviors • Government and business procurement • Retailer certifications and product choice • Information, ranking, and award campaigns

Production Policies and Applications

Production policies aim to address mitigation within national borders. Mitigation policies at the national level and below should be carefully designed to minimize leakage (either through shifting domestic production to carbon-intensive imports or through long-term relocation of production to unregulated regions outside national borders). Carbon pricing can be designed to reduce leakage. Under an emissions trading system, there is a tradeoff between providing industries with free emissions allowances in order to prevent carbon leakage, and achieving the emissions reductions goals of the ETS. Other studies recommend adjusting consumption-based accounting for carbon pricing to better incorporate trade balance and specialization (Jakob and Marschinski 2013).

The ClimateWorks report “Europe’s Carbon Loophole” (Becque et al. 2018) provides greater elaboration on potential key policy actions.

National emissions reduction policies can be guided by consumption-based accounting, including the inventories in the studies covered previously as well as new metrics such as technology-adjusted consumption-based accounting (TCBA), which adjusts for the carbon intensity of export sectors around the world (Kander et al. 2015). Simply increasing consumption-based accounting can also help countries determine their role in the carbon loophole, as well as identifying key sectors and geographies that drive carbon leakage (Minx et al. 2009). At present, fuel and GHG suppliers in California and some parts of the United States as well as several companies in France are the only firms subject to mandatory reporting of indirect and embodied emissions. A number of countries provide voluntary, government-initiated reporting on their embodied emissions, mostly through MRIO analysis, such as the UK, France, Sweden, and Denmark. Mandatory sustainability reporting for businesses and countries can help increase awareness and use of CBA approaches to GHG management.

Intermediate Supply Chain Policies and Applications

Intermediate supply chain policies aim to address products that are traded across borders. CBA can be used to close the carbon loophole between developed and developing countries through financial transfers to developing countries for emissions reduction projects (a.k.a. offsets). Some studies have shown that offsets are a cost-effective mechanism for reducing carbon leakage (Springmann 2014). There are many offset programs around the world, such as the Clean Development Mechanism and REDD+.

Border tax adjustments (BTAs) are another commonly discussed policy for closing the carbon loophole at national borders. BTAs would essentially tax imported products based on their carbon intensity. To date, no country has implemented BTAs (possibly out of concern for violation of WTO trade rules), but the EU has discussed taxing import of energy-intensive goods as part of the emissions trading system reform, and carbon BTAs were considered in the past. Given that BTAs can put exporting countries at a disadvantage, some studies have recommended that BTAs be combined with revenue redistribution to the exporting countries and technology transfer deals (K. Steininger et al. 2014).

Another main example of interventions in the supply chain is voluntary sustainable trade programs, which mostly address agricultural and forestry products whose production has been associated with deforestation (and therefore carbon emissions) in developing countries. Examples include commodity-specific roundtables, such as the Roundtable on Sustainable Palm Oil or the Roundtable on Sustainable Beef, which engage industry stakeholders and provide standards for production. There are also numerous certification schemes for products, such as the Fair Trade label.

Consumption Policies and Applications

Consumption policies aim to address end use of products by households, government, businesses, and other actors. Many countries have policies and/or programs in place that indirectly address embodied carbon of imported goods by reducing consumption of carbon-intensive products. Sustainable procurement programs set standards for goods consumed by a given institution, often government agencies or individual businesses. These procurement guidelines can be voluntary or mandatory. For example, in Denmark, the central government is required to procure sustainable timber for their buildings, furniture, and paper products. There is also a voluntary Green Public Procurement initiative organized by the European Commission for governments in the EU to implement as they desire. The Buy Clean Act in California requires state agencies to consider the embodied emissions in steel, glass, and other building materials when contracting for state-funded infrastructure projects. While non-mandatory, many behavioral policies and labeling campaigns target household consumers, encouraging them to make environmentally responsible purchasing and consumption choices.

Going forward, countries should increase awareness of the carbon loophole and the need to address these emissions. Following acknowledgment, policymakers can adopt a consumption-based accounting framework to begin to annually measure and report their embodied emissions footprint. Finally, countries can adopt policies that target production, the intermediate supply chain, and consumption as discussed above.

5 Conclusions

This report has provided up-to-date data, information, and analysis of the embodied carbon trade worldwide. Using the Eora model, we have summarized the state of embodied emissions and highlighted key trends using the latest data. Furthermore, we have conducted several deep-dive studies for key regions of the world (China and India) and industrial sectors (steel and cement industry) that are highly entangled in the carbon loophole.

Around one quarter of global CO_2 emissions are embodied in imported goods, thus escaping traditional climate regulations. This proportion has been growing over time. Since carbon intensity varies between countries and sectors, as new climate policies emerge, the loophole could be widened further. This has already occurred with air pollution: despite strong, successful air quality legislation in the US and EU starting in the 1970s, global air pollution in total has continued to grow. The carbon loophole could allow the same to occur with GHG emissions.

Many large countries have a significant imbalance in import or export of embodied emissions. Emissions transfers from developing countries to the U.S. and EU appear to have plateaued in recent years, but whether this is a peak or just a pause remains to be seen. Instead, growth in the trade of embodied carbon is mostly occurring through South-South transfers, or trade among countries outside of Europe and North America. Embodied emissions transfers among these countries have risen even while transfers to North America and Europe have stabilized.

Our sectoral deep-dive studies showed that there are significant inter-regional and extra-regional flows of carbon embodied in commodity steel, value-added steel, cement, and clinker trade worldwide. China is the largest net exporter of embodied carbon in commodity steel to outside of Asia. China accounts for 40% of the carbon embodied in global commodity steel extra-regional trade and 27% of carbon embodied in the overall commodity steel trade. Except for China, Japan, and The Commonwealth of Independent States (CIS), other regions of the world are net importers of carbon embodied in commodity steel. The embodied carbon of traded steel is divided almost evenly between commodity steel and steel-containing goods.

Cement and clinker are also traded far outside of their regions of production - around 50% and 60% of the embodied carbon in the cement and clinker trade is extra-regional, respectively. Given its rapid development, Africa is the largest net importer of embodied carbon in both cement and clinker. The top three largest flows of embodied carbon in the cement trade are from the EU, China, and Other Asia regions to Africa. The EU28 region is the largest net exporter (31% of total) and Africa is the largest net importer (48% of total) of the embodied carbon in the clinker extra-regional trade.

Much of the apparent success in decreasing domestic emissions has been more than offset by an increase in embodied emissions in imports. Unless consumption-based accounting is used, countries may meet their Paris Agreement targets while being responsible for increasing emissions abroad, as occurred with the Kyoto Protocol. The EU as a group nearly succeeded in meeting its target (due both to intentional action and to economic recession), and Russia and the former Soviet states reduced emissions even beyond their Kyoto targets. During the period of Kyoto (1990-2011), while Annex B countries reduced territorial emissions by 1.59Gt/yr, nearly that same amount, 1.67Gt/yr, was embodied in net imports back in to those countries.

In many countries, the magnitude of embodied emissions transfers is on par with that of their original Kyoto reduction target. The United Kingdom and Poland are perhaps the most striking cases for how outsourcing emissions-intensive production has helped countries meet their targets. Both countries report reductions that exceed their targets, however, once emissions embodied in their imports are included, they no longer achieve these targets. Similar outsourcing can also be observed for countries that either have failed to meet their targets, such as the U.S. and Japan, or that have met their Kyoto targets even including emissions embodied in imports, such as Russia. Remarkably, in all cases, changes in emissions embodied in imports are comparable to or larger than changes in domestic emissions. Thus, under a consumer responsibility principle, developed countries have not recorded a decrease from 1990 levels, but rather an increase.

The Paris Agreement, struck in 2015, sets voluntary emissions targets for 2020 and beyond. The EU, for example, has extended its original Kyoto target to now aim for a 40% reduction in emissions below 1990 levels by 2030. Given the discrepancy between Kyoto Protocol targets and actual consumption-based emissions, countries' progress in meeting their Paris targets must be reconciled with their embodied emissions in the future. Otherwise, the trend of decreasing territorial emissions while increasing total carbon footprint is likely to continue.

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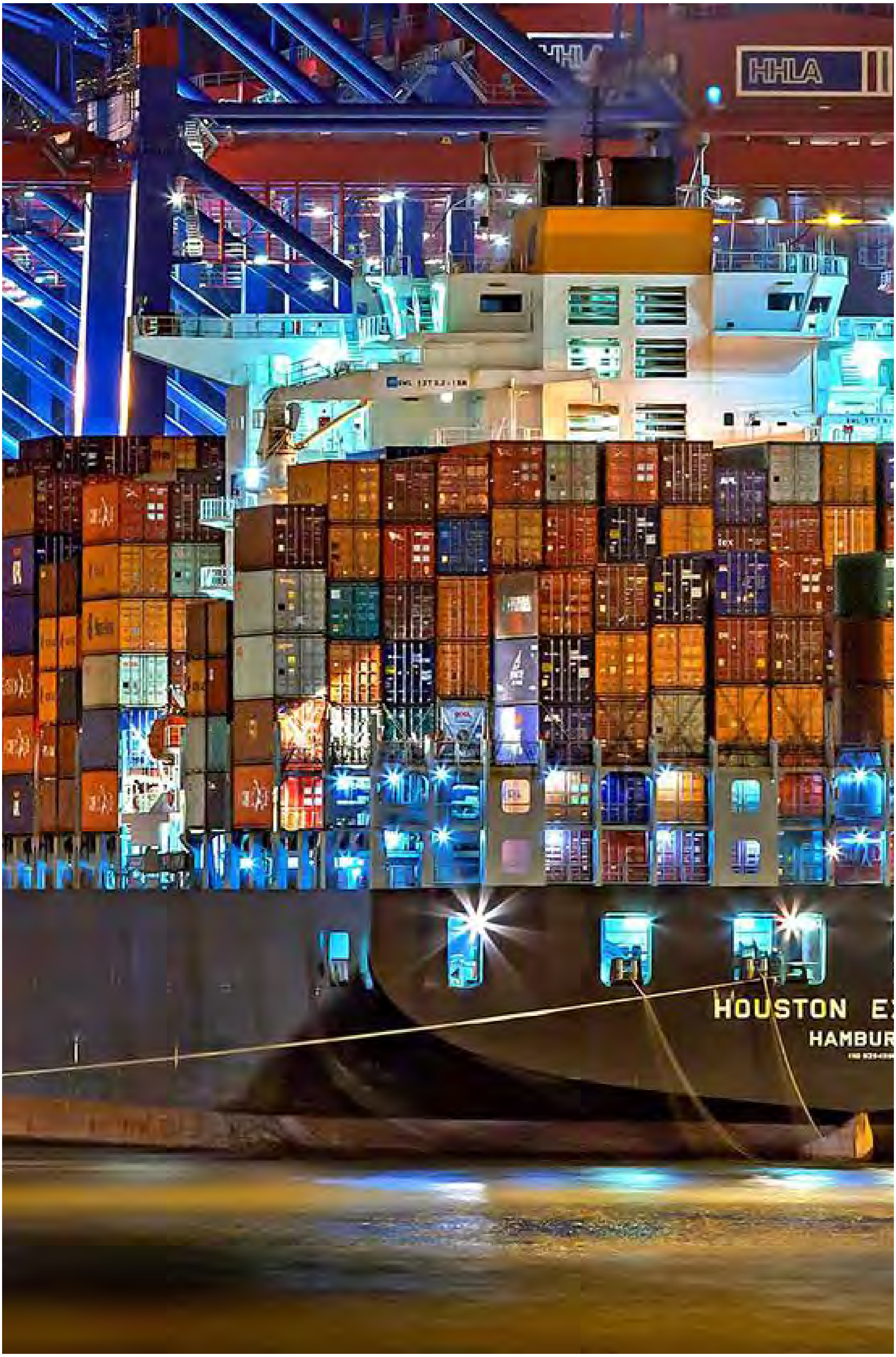
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Appendices

Appendix 1. List of Acronyms

AIIOT	Asian International Input-Output Tables
BTA	Border tax adjustment
CBA	Consumption-based accounting
CH4	Methane
CIS	Commonwealth of Independent States
CO_2	Carbon dioxide
EE-MRIO	Environmentally extended multiregional input-output
ETS	Emissions trading system
GHG	Greenhouse gas
GRAM	Global Resource Accounting Model
Gt	Gigaton
GTAP	Global Trade Analysis Project
ICIO	Inter-Country Input-Output Database
IMF	International Monetary Fund
IPCC	United Nations Intergovernmental Panel on Climate Change
IO	Input-output
LCA	Life cycle assessment
MRIO	Multiregional input-output
Mt	Megaton
NOx	Nitrogen oxides
OECD	Organisation for Economic Cooperation and Development
ODS	Ozone-Depleting Substances
PBA	Production-based accounting
SO_2	Sulfur dioxide
SOX	Sulfur oxides
TCBA	Technology-adjusted consumption-based accounting
UNFCCC	United Nations Framework Convention on Climate Change
WIOD	World Input-Output Database
WTO	World Trade Organization

Appendix 2. List of Figures and Tables

Appendix 3. Data and Methods Used in this Report

A3.1. Global MRIO method

Carbon footprints for nations were calculated using the Eora multiregional input-output database (MRIO) using the standard Leontief demand-pull environmentally-extended input-output model. National total footprints were taken from the year 2015, the most recent year available.

The calculation of carbon footprints using an MRIO database is described in many papers, including Kanemoto et al. 2016; Peters et al. 2011; Kanemoto et al. 2012; and Wiedmann 2009. The Eora MRIO is available online at worldmrio.com and is described in Lenzen et al. 2012. Footprints in each country consider gross final demand, not just household final demand, i.e. they are inclusive of government purchases and change in inventories.

The general framework consists of connecting inventories of primary emissions in each sector in a standard multi-regional input-output (MRIO) model in order to track embodied GHG emissions to the country of final consumption. The framework extends monetary transactions between sectors and between countries into embodied carbon emission flows. The territorial carbon emissions associated with production (p) in country s, F(p)s, can be decomposed into embodied emissions in consumption, in imports, and in exports. Following the formulation in Kanemoto et al 2012 the equation may be written:

$$\underbrace{F^{(p)s}}_{production} = \sum_{ri} f_i^r \left[\underbrace{\sum_{tj} L_{ij}^{rt} y_j^{ts}}_{consumption} - \underbrace{\sum_{t\neq s,j} L_{ij}^{rt} y_j^{ts}}_{imports} + \underbrace{\sum_{t\neq s,j} L_{ij}^{rs} y_j^{st}}_{exports} \right]$$

where f is carbon intensity (factor intensity), L is the Leontief inverse (Leontief 1970), y is final demand, i and j are sector of origin and destination, and r and s are exporting and importing country. t is the country of last sale in the consumption and imports terms and t is the country of final consumption in the exports term.

The number of sectors defined by emissions inventories (following the IPCC guidelines) is generally less than the number of products individuated by the Eora MRIO. In this case the emissions from a broadly defined sector are attributed amongst daughter sectors using sectoral gross output as a pro-rating scheme, unless superior sector-wise emissions data are available. For key countries (U.S., China, India), these sector-wise emissions factors are checked manually.

There are several papers and reports that provide an introduction to the the calculation of consumption-based accounts using MRIO:

- Wiedmann, T. (2009). Editorial: Carbon Footprint and Input-Output Analysis - An Introduction. Economic Systems Research, 21(3), 175–186. https://doi.org/10.1080/09535310903541256
- Schaffartzik, A., Sachs, M., Wiedehofer, D., & Eisenmenger, N. (2014). Environmentally Extended Input-Output Analysis. (U. of K. Institute for Social Ecology, Ed.). Vienna.

- Kitzes, J. (2013). An Introduction to Environmentally-Extended Input-Output Analysis. Resources, 2(4), 489–503. Retrieved from http://www.mdpi.com/2079-9276/2/4/489
- Eurostat Input-Output Manual - Along with the UN SNA, the canonical reference manual.
- Input-Output Analysis: Foundations and Extensions - The textbook by Miller and Blair
- Prof Lenzen's MRIO lecture video series

This report focuses just on CO_2 as a greenhouse gas (GHG). CO_2 is the dominant greenhouse gas, responsible for >70% of total radiative forcing (IPCC 2007, Table 2.1). The other non-CO_2 anthropogenic GHGs will have slightly different trade profiles, as those gases are implicated in a slightly different set of products. For example, CH_4 emissions are greater from agricultural production, particularly beef and rice production. So embodied flows of CH_4 will follow trade flows of those CH_4-goods, in the same way as embodied flows of CO_2 follows CO_2-intensive goods. Furthermore, some non-CO_2 GHGs are more difficult to attribute to an economic production activity; for example, CO_2 emissions from biomass burning or land use change. As of the time this report was written, properly allocating non-GHG emissions to sectors and products was an active area of research. In sum, while the flows of non-CO_2 GHGs represent a minority share of total GHG emissions, in future study is is important to consider these other GHG gases alongside CO_2.

A3.2. 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 CO_2 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 2018). The latest year for which the cement and clinker trade data were available on UN Comtrade was 2014. 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 (WBCSD/CSI 2018). The latest year for which the CO_2 intensity for cement and clinker production was available in the GNR database was 2015.

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, 2015, 2016, 2017). For the commodity steel, the latest year for which the trade data were available was 2016, whereas for value added steel, the latest data were for 2013. The CO_2 intensity of steel production in different regions/countries were obtained or estimated based on various sources (Hasanbeigi et al. 2016, JRSF 2016, Pal et al. 2014, Lisienko et al. 2015, Erickson 2013, IEA 2015, IEA 2012).

Appendix 4. Additional results tables and graphs

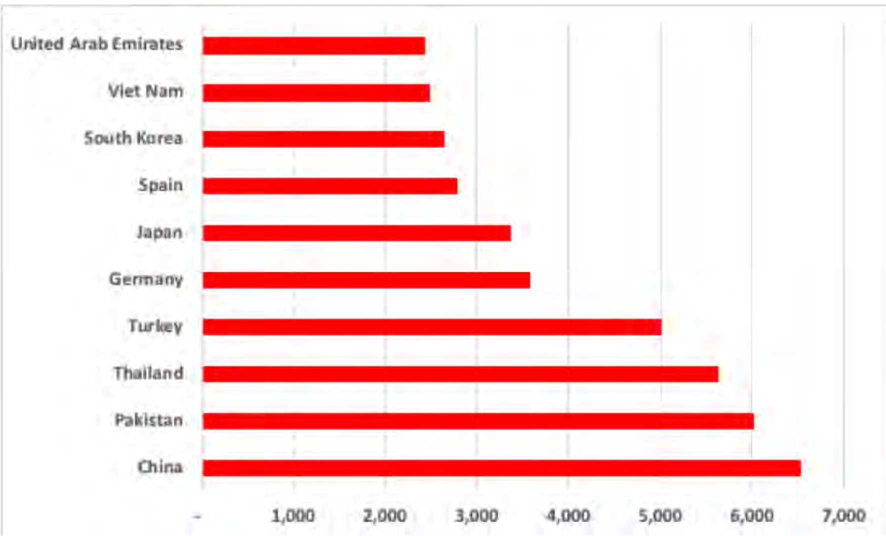

Figure A.4.1. Top 10 exporters of CO_2 emissions embodied in the cement trade (kton CO_2), 2014

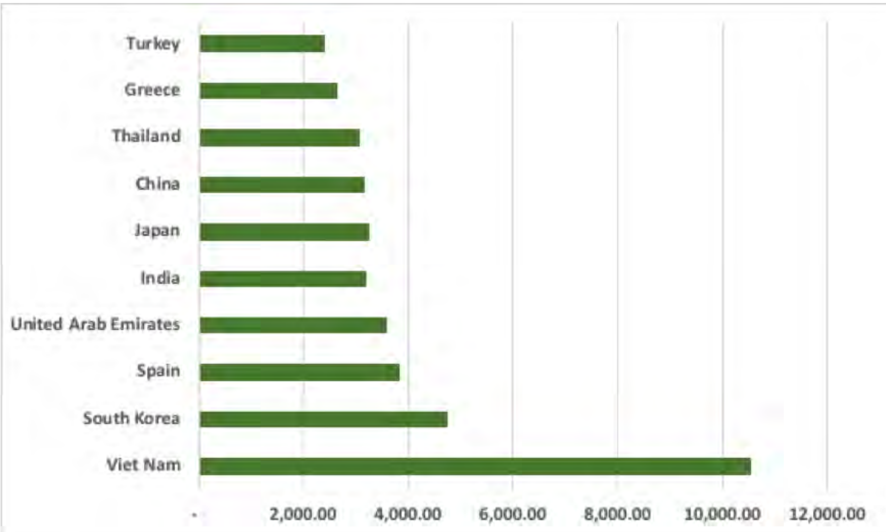

Figure A.4.2. Top 10 exporters of CO_2 emissions embodied in the clinker trade (kton CO_2), 2014

Table A.4.1. Top 20 trade flows of Portland cement among countries in 2014 (UN 2018)

Reporter	Flow	Partner	Amount (tons cement)
Pakistan	Export	Afghanistan	4,091,766
Thailand	Export	Myanmar	3,600,985
Thailand	Export	Cambodia	3,535,335
Oman	Import	United Arab Emirates	3,183,943
Singapore	Import	Japan	3,125,603
Japan	Export	Singapore	2,959,255
Canada	Export	U.S.	2,727,471
U.S.	Import	Canada	2,282,648
Sri Lanka	Import	India	2,270,517
Iraq	Import	Iran	2,075,749
Kuwait	Import	United Arab Emirates	1,846,618
United Arab Emirates	Export	Kuwait	1,815,683
Portugal	Export	Algeria	1,787,355
U.S.	Export	Canada	1,786,113
Algeria	Import	Portugal	1,699,945
Myanmar	Import	Thailand	1,647,734
Belarus	Export	Russian Federation	1,589,700
Russian Federation	Import	Belarus	1,502,060
China	Export	Mongolia	1,472,213
India	Export	Sri Lanka	1,471,115

Table A.4.2. Top 20 trade flow of Clinker among countries in 2014 (UN 2018)

Reporter	Flow	Partner	Amount (tons cement)
Viet Nam	Export	Bangladesh	6,215,747
Sri Lanka	Import	India	1,773,271
Thailand	Export	Bangladesh	1,512,996
Australia	Import	Japan	1,477,908
Japan	Export	Australia	1,445,905
India	Export	Egypt	1,310,140
Indonesia	Import	Viet Nam	1,264,288
China	Export	Australia	1,187,700
United Arab Emirates	Export	Kenya	1,181,175
Australia	Import	China	1,129,326
Nepal	Import	India	1,124,100
Kuwait	Import	Iran	1,091,128
Viet Nam	Export	Other Asia	1,088,039
United Arab Emirates	Export	Egypt	1,052,979
Chile	Import	Rep. of Korea	1,002,929
Malaysia	Import	Viet Nam	979,116
Viet Nam	Export	Indonesia	959,473
India	Export	Sri Lanka	952,558
Peru	Import	Rep. of Korea	905,217
Rep. of Korea	Export	Chile	897,460

Table A.4.3. Top 20 importing countries of commodity steel in 2016 (Worldsteel 2017)

Rank	Top Importing Countries	Total imports (Mt steel)
1	European Union (28)	40.4
2	United States	30.9
3	Germany	25.5
4	South Korea	23.3
5	Italy	19.6
6	Vietnam	19.5
7	Thailand	17.6
8	Turkey	17
9	France	14.6
10	China	13.6
11	Belgium	13
12	Indonesia	12.6
13	Mexico	12.5
14	Poland	10.1
15	India	9.9
16	Spain	9.4
17	Egypt	9.2
18	Netherlands	8.4
19	Taiwan, China	7.9
20	Canada	7.7

Appendix 5. State of knowledge for tracking embodied carbon

A5.1. Methodology for Tracking Embodied Carbon

Input-output analysis is an economic accounting method developed in the 1970s by Leontief (Leontief 1974) that documents the financial flows between sectors, and can be used to follow supply chains. Input–output accounting can attribute pollution associated with production to final consumers, making it a foundational tool for calculating carbon footprints. Multiregional input-output (MRIO) tables can be used to estimate consumption-based inventories of CO_2 and other greenhouse gas emissions. In this report, the Eora global MRIO is used to gain a high-level view of the carbon loophole. Eora represents a new generation of high-resolution input-output models that are detailed enough for policy use. The choice of Eora over other available MRIO models, and a review of the reliability of MRIO-based accounts are both discussed below.

Life cycle analysis (LCA) was the first method used to conduct embodied emissions accounting. LCA -- a process-based, or bottom-up method -- looks in detail at all stages along a production or supply chain, and quantifies the emissions from each stage. While LCA can deliver highly accurate results for particular products and processes under study, the system or study boundaries are defined arbitrarily. LCA results are often not directly comparable and cannot be summed.

To comprehensively account for international flows of embodied carbon, national-level accounts are needed. Ahmad and Wykoff (2003) from the OECD prepared one of the earliest estimates of embodied CO_2 in international trade using the national-average carbon intensity of each country to estimate the embodied carbon in exports. The original National Footprint and Biocapacity Accounts from the Global Footprint Network (2005) were another early effort. Their approach was to apply embodied emissions intensities (embodied CO_2/kg) multipliers taken from LCA studies to the physical volume of trade in goods between countries, though this analysis still suffered from the boundary issues of LCAs discussed above.

Lenzen (2001, 2004), Weidmann et al. (2007), Lutz (2005), Turner et al. (2007), Tukker et al. (2006) were some of the earliest studies using input-output analysis to calculate embodied emissions. Input-output accounting, with refinement, is the primary accepted method for calculating CBA (consumption based accounting) today. Input-output analysis was extended early on to account for flows between regions (countries or states, depending on the model's scope), and to additionally track nonmonetary inputs to production (including land, and pollution emissions), to form what is today referred to as environmentally extended multi-regional input-output accounts (EE-MRIO). EE-MRIOs attribute emissions to a primary production activity (mining, smelting, growing paddy rice, and so on), then track those associated goods through monetary supply chains consisting of potentially many trade and transformation steps. The standard method to attribute emissions to consumers is called the Leontief demand-pull model, so called because in this approach one starts with a given consumption bundle (such as for a household or business) and uses the Leontief inverse model to "pull" production, and with it embodied carbon, to satisfy that demand bundle (Schaffartzik et al 2014, Kitzes 2013, Leontief 1986, and Wiedmann 2009a).

A5.2. Measuring Embodied Carbon with MRIO Models

Early studies estimated the carbon footprint of nations using simply a domestic input-output model and then making a simple domestic technology assumption about the embodied carbon content of imports, by assuming that imports had the same carbon intensity as domestic production or that they had world-average carbon intensity.

Since around 2010, global MRIOs have become available. Global MRIOs are continually seeking to add more sectoral detail and more regional/country-level resolution. Higher resolution in both these regards makes the model more accurate. Multiregional input-output (MRIO) models are recognized as the best available tool for tracking embodied carbon in traded goods. For analysis at the sectoral, national, and international scale, they are preferable to LCA-based approaches because they do not suffer from boundary issues and double-counting risk. MRIO results have been used to recommend targets and policies based on embodied carbon. Tukker et al. (2013) provides a useful overview of the main global MRIO databases (recreated in Table 1).

Database Name	Countries	Detail (Industries x Products)	Time	Extensions
EORA	Around 150	Variable (20-500)	1990-2009	Various
EXIOBASE	40	200 x 200	2000, 2007	30 emissions types, 60 energy carriers, water, land, 80 resources
WIOD	40	35 x 59	1995-2009	Socio-economic and environmental accounts
GTAP-MRIO	129	57 x 57	1990, 1992, 1995, 1997, 2001, 2004, 2007	5 greenhouse gases, land use, energy volumes, migration
GRAM	40	48 x 48	2000, 2004	Various
AIIOT	Asia-Pacific (8-10 countries)	56 x 56 through 76 x 76	1975-2005	Employment
OECD ICIO	57	37 x 37	1995, 2005, 2008-2011, 2015-2016	CO_2, value-added

Eora (Lenzen, Kanemoto et al. 2012, Lenzen, Moran et al. 2013) avoids the labor-intensive assembly process used by other MRIOs by using of a high degree of automation and sophisticated data-handling algorithms. The result is a model covering all 189 countries of the world with a variable degree of sectoral resolution ranging from 26 sectors for the lowest resolution countries to >400 sectors of detail for the major economies (UK, U.S., Japan). The use of heterogeneous classifications allows the model to primarily use official national data and offer high sectoral detail.

EXIOBASE (Tukker, de Koning et al. 2013; Wood 2015) is the product of several million Euros of investment over three EU projects, bringing the project to the current version, EXIOBASE3.

WIOD (Dietzenbacher, Los et al. 2013) is a simple and effective MRIO covering the 40 largest economies in the world plus a Rest of World trade partner. WIOD has lower sectoral detail than other MRIOs (only 35 sectors per country) and has not released GHG satellite accounts more recent than 2012. It is relatively easy to use - unlike the other models, it can be effectively run in Excel - and is popular among economists.

GTAP (Narayanan et al 2008) is a collection of IO tables for 140 countries/regions. At least two MRIOs have been constructed using these IO tables: the MRIO used by Peters and Andrews for their papers (Peters 2008A, 2008B, Hertwitch 2009, Andrew 2013, Davis et al 2011, Peters 2011a, 2011b), and the EU-funded OpenEU model (Weinzettel, Steen-Olsen et al. 2011, Galli, Weinzettel et al. 2012). GTAP has its roots in agricultural economics so it has a slightly higher sectoral detail than other models on agricultural commodities.

The **GRAM** model (Wiebe et al 2012) from 2012 covers OECD member states and key trading partners. The Asian Input-Output database (**AIIOT**) (Meng et al 2013) was an MRIO with a focus on trade within Asia developed by Japan's development agency, IDE-JETRO. These models were advanced at the time they were published, but have effectively been superseded by the current generation of global MRIOs.

The **OECD ICIO** database uses the OECD's collection of country-level input-output tables for 57 countries and 37 industries. ICIO also has unique data on 'trade in value-added'. Using IEA data on fuel combustion, Wiebe and Yamano (2016) extended ICIO to include CO_2 emissions that can be used for consumption-based accounting.

Recently there are some early attempts to build nested models. One is a model that places a sub-national IO model of the Chinese provinces inside the Eora global model (Wang 2015). Bachmann et al (2015), Wenz (2015), and the SNAC approach of Edens et al (2015) are also notable examples. A more ambitious approach is the Virtual IELab project by Lenzen's group (Lenzen et al 2014). This is spiritual successor to the Eora model. The IELab offers a software framework for a multiply-nested ultra high resolution global model. The IELab software has been developed using Australia as a test case, and is being built out one country at a time.

A5.3. Why Eora?

The Eora input-output model provides a current, comprehensive, and high-level view of global traded carbon. The Eora model also features high sectoral detail, which provides the starting point for the sector-specific deep dive analysis above. The model distinguishes from 26 to 500 sectors in each of 189 countries. The analysis of embodied carbon in traded goods is calculated from an EE-MRIO table using the widely accepted Leontief input-output method. Whereas previous models mostly cover aggregated regions or just a subset of countries, Eora includes all UNFCCC countries for the years 1970 to 2011, with improved detail such as non-CO_2 emissions and confidence estimates for all results. Eora's increased resolution does not alter its basic results on embedded emissions (Davis and Caldeira, 2010; Peters et al., 2012), but it does give policymakers more detailed results that can inform their decision-making.

The Eora MRIO (worldmrio.com) used in this project has several advantages over other models:

1. It tracks every country in the world (190 countries), while other models use aggregated regions
2. It provides a comprehensive annual time series (1970-2015)
3. It provides the highest level of sectoral detail, with a total of 15,000 sectors / 5 billion supply chains across 190 countries

4. It is built using sophisticated optimization methods to reconcile conflicting data, so every result datapoint is accompanied by an estimate of its reliability.

The Eora database is regularly used in academic research on embodied carbon. The main two papers presenting Eora have been cited 750 times. The same methodology used for generating carbon footprints can also be applied to study other embodied/indirect flows, such as air pollution, virtual water, land use, and material flows. In economic contexts the footprint concept is used to study value-added stages along global supply chains, and Eora has been used by the UN Commission on Trade and Development to build their Global Value Chain Database, and by the IMF for their annual World Economic Outlook.

A5.4. Key Points of Uncertainty in the MRIO models

Eora does have some areas of uncertainty. Eora has higher uncertainty about embodied emissions transfers due to trade in services because the data on trade in services is less detailed. Another limitation of Eora is poorer data availability for the years 1970 to 1989. For those years, the MRIO is built by extrapolating from the 1990 MRIO table using the constrained optimization method described in Lenzen et al., 2012a. In addition, Eora can only be as accurate as its underlying data. Official Chinese CO_2 emissions estimates may be unreliable to the degree of over a gigaton within a single year (Guan et al. 2012); however to our knowledge no better alternative currently exists.

Recent years have seen a proliferation of global MRIO tables that are used with the standard Leontief model to calculate consumption-based footprints for countries. While these accounts ostensibly seek to reach the same result – a global production and consumption database with explicit representation of trade, combining the economic and trade statistics published by major statistical bureaus – due to various implementation details there is nevertheless appreciable divergence between results as published by various research groups. Here we summarize the results from key studies why these models diverge (Moran and Wood (2014), Owen et al (2014), Owen et al (2016), Steen-Olsen et al (2014), Steen-Olsen et al (2016), Kanemoto et al 2012, and Inomata and Owen (2014)).

CBA accounts consist of three main components: a transactions matrix matrix **T** describing the economic structure, an environmental stressors matrix **S** describing the per-sector direct environmental impacts of production, and a consumption bundle **Y** describing the composition of the demand bundle whose footprint is being measured. The total CBA footprint is a function of these three variables. Across various reported CBA results, the consumption bundles for each country are quite consistent. There is some minor variation across models, due to different classification schemes, a certain degree of data conflict and uncertainty, and some issues around disaggregation of final demand. The biggest source of uncertainty in final demand is changes in inventory: different models and modelers make different assumptions about how these should (or should not) be amortized (Peters et al. 2012).

The transactions matrix (also called a flows matrix, or if the transactions are expressed not in absolute value but in as fractions of one unit of output a technical coefficients matrix) documents the transactions between various sectors within and across countries. This is the most complex part of the MRIO to assemble. There are several challenges. Countries do not use the same sectoral classification for their official IO tables. Globally, the sum of reported exports does not equal the sum of reported imports, and the difference is very significant (~30%). Often two or more agencies publish official data which should report the same value for the same flow (e.g. total national GDP), but do not. Finally, trade statistics document exports per sector, and imports per sector, but most often these are simply totals so some estimation is needed to allocate exports of one sector amongst import sectors in the receiving country. These issues are well understood and solving them is the primary work of MRIO builders.

Surprisingly, despite these significant challenges in assembling the core of the MRIOs, the transactions matrix is not the largest source of disagreement among CBA results. The major source of disagreement is actually the environmental stressor accounts. This is where GHG emission are attributed to primary production activities. There are several major reasons for disagreement: 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), different data sources for emissions, and the allocation of emissions to sectors.

A5.5. Summary of the MRIO Literature

Carbon leakage (i.e. the carbon loophole) is a substantial and growing problem, especially since leakage shifts CO_2 emissions from developed to developing countries. The initial Kyoto Protocol discussions did not prioritize carbon leakage as it was anticipated to be a minor issue (Intergovernmental Panel on Climate Change, 1995). However, many recent studies have shown that up to 30% of global emissions are linked to production for export (Aichele and Felbermayr, 2012; Andrew et al., 2013; Davis and Caldeira 2010; Caldeira and Davis, 2011; Chen and Chen, 2011; Hertwich and Peters, 2009; Nakano et al., 2009; Peters and Hertwich, 2008b; Peters et al., 2011a, 2011b). When using consumption-based accounting instead of a territorial emissions inventory, it is evident that the UK's total carbon footprint increased 12% between 1992 and 2004, not decreased by 5% as the territorial emissions accounting indicates. This is because increasing consumption in the UK was supplied by emissions-intensive imports, not domestic production (BBC News, 2008; Wiedmann et al., 2008, 2010). In China, nearly 30% of the country's emissions in 2005 were linked to production for export (Feng et al., 2013; Weber et al., 2008; Davis and Caldeira 2010). Since export production has driven much of its emissions growth (Minx et al., 2011), China has argued that responsibility for emissions should lie with the final consumers of goods as well as the producer (BBC News, 2009; Information Office of the State Council of China, 2011; Leggett, 2011).

For non-CO_2 GHGs, this burden-shifting effect is similar and, in some cases, stronger than for CO_2. In addition, the same pattern of emissions displacement has historically already occurred for air pollution - despite aggressive legislation of SO2, NOx and particulate matter in major emitting countries, total global air pollution emissions have increased (Kanemoto et al. 2014).

A5.6. Alternative Approaches to Attributing Responsibility for Emissions

The firms and jurisdictions in which the emissions occur have the greatest immediate control over those emissions, but the responsibility for emissions can be attributed otherwise. For a while, there was much discussion about historical responsibility - which argued that responsibility for abatement should be allocated not based on shares of current emissions but instead based on cumulative historical emissions. Another suggested approach was shared producer-consumer responsibility (Gallego 2006, Lenzen 2006). This proposed a framework for allocating responsibility amongst multiple parties along a multi-stage supply chain from emitter to consumer.

Businesses are often more concerned with carbon supply chain risk rather than responsibility. This perspective uses the exact same tools as for allocating responsibility: instead of taking some moral or legal responsibility for upstream emissions, business are often more concerned with potential regulation or costs associated with carbon-intensive stages of upstream supply chains.