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CARBON ADJUSTMENT MECHANISMS: EMPIRICS, DESIGN AND CAVEATS*

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Abstract

This article explores the design of Carbon Adjustment Mechanisms based on an analysis of historical data, the existing literature as well as theoretical considerations. In the empirical analysis we quantify territorial emissions as compared to the CO_2 footprints for countries within the EU-ETS area and globally, we show which (mostly upstream) industries account for the majority of emissions, and identify how their emissions are imported embedded in final or intermediate products from more downstream industries. In an analysis based on gravity equations, we find evidence for carbon leakage in some emission-intensive industries, but only small overall effects. Based on our own evidence and the current literature, we conclude that – if a Carbon Adjustment Mechanism is to be established – focusing on emissions intensive industries could balance excessive bureaucratic burden and carbon leakage mitigation. To be effective, such a system should also extend to embedded emissions in downstream industries to avoid a shift of imports down the value chain. Concerns with regard to international trade relations could be addressed by not implementing Carbon Adjustment Mechanisms unilaterally, but rather using them as the basis for a cooperative approach to climate protection jointly with the most important trading partners.

Keywords: Carbon border adjustment · Carbon leakage · Carbon tax · Climate policy

JEL Classification: Q56 · Q53 · F18 · F14 · F55 · F64

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1 Introduction

The European Union is one of 14 regions worldwide which currently use an Emissions Trading System (ETS) or a carbon tax to put a price on carbon emissions.[1] In 2020, 12.0 % of global greenhouse gas emissions were covered by one of these systems. The EU-ETS covers the emissions occurring in the power generation sector, industrial emissions and emissions in the aviation sector within the borders of the participating countries.[2] In 2018 the coverage extended to 1.75 billion tons of CO_2 emissions or roughly 45 percent of the 3.9 billion tons of CO_2 emitted in the EU-ETS member countries in total. As of November 2020 globally only the price on emissions set by carbon taxes in Finland, Norway, Sweden and Switzerland is significantly higher than the 30 USD per ton of CO_2 in the EU-ETS (World Bank, 2020).

International differences in carbon prices can pose a challenge for companies exposed to international competition and thus indirectly also for success in climate protection. Increases in production cost due to a price on CO_2 emissions can negatively affect the competitiveness of companies located within the EU-ETS area vis-à-vis international competitors located in regions with lower prices on CO_2 emissions or no price at all. As a result, carbon pricing induces incentives for companies to relocate production to regions outside the EU-ETS area. Imports rather than domestic production would then serve final and intermediate demand in the EU. As a matter of fact, this relocation of production would not only reduce value added in the EU, but could even counteract the goal of reducing emissions via carbon leakage. The impact of emissions pricing on international competitiveness and carbon leakage is therefore an important policy challenge for the EU due to its integration into global value chains. In 2019 gross exports and imports between the EU and non-EU states each amounted to slightly more than 2 trillion Euros or 12.5 % of GDP.

In order to mitigate carbon leakage and sustain competitiveness, the EU currently grants companies in emissions intensive and trade exposed industries (EITE industries) a share of emissions allowances for free. As CO_2 prices are expected to increase as a consequence of the European Green Deal and increasingly ambitious climate policies in various member states, the free allocation of allowances might, however, not be sufficient any more to address the challenges of EITE industries within the EU-ETS and mitigate carbon leakage.

Against this background, the discussion on a Carbon Adjustment Mechanism has recently gained momentum within the Roadmap process for the EU Green Deal European Commission (2020). The mechanisms are considered as a measure to mitigate carbon leakage and at the same time an alternative way to counteract distortions in global competitiveness. One approach for carbon adjustment, the Carbon Border Adjustment (CBA), follows the general idea to require importers to purchase emissions allowances to the extent of the CO_2 footprint of imports to create a level playing field for products of domestic or

[1]Number of implemented national or regional emissions trading systems or carbon tax systems in 2020 according to the World Bank Carbon Pricing Dashboard. The European Union is counted as one region. Subnational systems are not counted. Regions that have both a carbon tax and an emissions trading system are only counted once. Counting both carbon tax and emissions trading systems, a total of 33 carbon pricing systems were implemented worldwide, covering 45 national jurisdictions.

[2]The EU-ETS operates in all EU member states and additionally in Iceland, Liechtenstein and Norway.

foreign origin within the EU-ETS area. A comprehensive CBA would also reimburse exporters for the emissions allowances bought equivalent to the CO_2 footprint of exports, which maintains a level playing field for European firms in markets outside the EU ETS area. In particular against the background of recent trade conflicts, there are, however, serious concerns that trade policy considerations stand in the way of a Carbon Adjustment Mechanism implemented at the border (Ismer et al., 2020; Felbermayr and Peterson, 2020; GCEE, 2020). At the same time, challenges to measure the CO_2 footprint may impede a solution that covers the entire carbon footprint. As a consequence of those concerns, various alternative approaches have been proposed that (a) do not adjust at the border but implement a tax on final and intermediate demand (also called "consumption tax" in the literature) and (b) do not address all emissions but only emissions from EITE industries.

Independently of the exact implementation, a Carbon Adjustment Mechanism would shift carbon pricing away from territorial emissions towards the CO_2 footprint of consumption and investment. While 3.8 billion tons of CO_2 were emitted within the EU-ETS area in 2014, the CO_2 emissions caused by EU-ETS-wide final consumption and investment in the same year amounted to 4.4 billion tons of CO_2 (Section 2.1).[3] Thus, the EU is a net importer of CO_2, which implies that pricing the CO_2 footprint of demand and investment would increase the revenues above those from the pricing of territorial emissions. Consequently, beyond the intention to address carbon leakage effectively and maintain competitiveness of particularly affected industries, Carbon Adjustment Mechanisms open up the possibility of raising revenue for the EU budget. As a matter of fact, in 2020 revenues from a Carbon Adjustment Mechanism have already been mentioned explicitly as new own resources in the EU's new Medium-Term Financial Framework for 2021-2027.[4]

When discussing climate policy measures in the EU, it is important to carefully consider their effects in a global context. In 2014 the CO_2 content of final demand in the EU represented only 12.5 % of the roughly 35 billion tons of worldwide carbon emissions. This illustrates that to effectively combat climate change, European climate policy should be designed to facilitate and work towards international cooperation, ideally promoting a global price on carbon (GCEE, 2019; Cramton et al., 2017; MacKay et al., 2015). It is therefore particularly important to assess whether EU climate policy measures promote a more ambitious climate policy in other parts of the world and facilitate the introduction of carbon pricing beyond the EU. In this respect, the introduction of a Carbon Adjustment Mechanism, indeed could reduce the disincentives for countries to introduce their own CO_2 pricing schemes. However, this is only true if the mechanism could distinguish between value added created in countries which have implemented a CO_2 price and those who have not, as well as between different levels of CO_2 prices in different countries, and offset the charge that has already been paid. Ideally, the mechanism would even take other climate policy measures equivalent to specific price levels into account. In

[3] 2014 is the most recent year for which the carbon footprint can be measured using data from the World Input Output database.

[4] Support for the intention to use revenues from the CBA as the EU's own resources is also mentioned in the Draft Report on "Towards a WTO-compatible EU carbon border adjustment mechanism" by the Committee on Environment, Public Health and Food Safety of the European Parliament (2020b).

such a system, emissions embedded in products produced worldwide in regions with different levels of CO_2-prices would be charged equal CO_2-prices when consumed within the EU, with different fractions of the total amount being paid to the EU-ETS area and their countries of origin. This would lower the perceived cost for countries outside the EU ETS to introduce their own CO_2 pricing schemes or to make them more ambitious. To not only reduce costs of introduction but adding additional incentives to do so a Carbon Adjustment Mechanism could be combined with the idea of a Nordhaus-style Climate Club (Nordhaus, 2015). To support developing countries' efforts towards less carbon-intensive economies as well as their participation in global climate efforts, revenues from Carbon Adjustment Mechanisms could be used for fiscal transfers to cooperating developing countries, instead of flowing into the EU budget.

In this article, we discuss current proposals on Carbon Adjustment Mechanisms in the light of empirical findings based on historical data on emissions in Europe and worldwide. In the light of the ongoing policy discussion, in Section 2 we first provide an empirical basis for our analysis. We use historical data to shed light on the differences between territorial emissions and the CO_2 footprint on the national as well as industry level. Second, we provide an overview of how the EU tried to prevent carbon leakage so far by analysing the allocation of free allowances (Section 3.1). An empirical analysis contributes to the quantification of historical carbon leakage and embeds the results into the findings from the literature (Section 3.3). After presenting the empirical and historical framework, we introduce the various currently discussed options to design a Carbon Adjustment Mechanism that allows to (partially) price the carbon footprint instead of territorial emissions (Section 4). In particular, we discuss CBAs at the border and a tax on final and intermediate demand tied to the carbon footprint of goods and services, in combination with free allowances. We evaluate the challenges associated with the implementation of different mechanisms and we assess how the mechanisms would contribute to the objectives of mitigating carbon leakage, maintaining competitiveness, generation of revenues, and international cooperation (Section 5). Our analysis provides additional information for the ongoing debate and discusses whether the benefits in terms of climate protection, competitiveness, revenues, and prevention of carbon leakage could outweigh costs of implementation and negative consequences in the context of international trade policies.

2 Territorial Emissions versus Carbon Footprint

The EU-ETS is a production-based carbon pricing system. Except for the aviation sector, emissions are measured directly at more than 11,000 heavy energy-using installations (power stations and industrial plants). Producers have to surrender allowances that cover their actual emissions independently of whether the produced goods are sold domestically or exported. No charge is, however, levied on the carbon content of imports from outside the EU-ETS area. A different approach would be to price emissions associated with consumption and investment within the EU-ETS area, and thus the inclusion of imports and the exemption of exports from pricing.

In the following we provide details on the structure of territorial emissions as covered by the EU-ETS and the CO_2 footprint of domestic demand (consumption and investment) using industry level input-output data from the World Input Output Database (Timmer et al., 2015) and industry level emissions data from Corsatea et al. (2019).[5] On aggregate the CO_2 footprint of domestic demand is roughly 15 % larger than territorial emissions. Thus, the CO_2 emissions embedded in imports to the EU-ETS area surpass the emissions embedded in exports. A main reason is that the carbon intensity of imports i.e. the carbon embedded in imports relative to the import value is substantially higher than the carbon intensity of exports overall and for each individual industry. Roughly 80 % of the carbon embedded in imports originates from one of only a few emissions intensive industries which consequently merit particular attention. As these industries are located upstream in complex value chains, however, most carbon embedded in imports is not imported directly via goods from these upstream industries but through imports of further processed goods from downstream industries. This complex structure of carbon embedded in imports has to be accounted for in the design of a Carbon Adjustment Mechanism.

2.1 Territorial CO_2-emissions vs. CO_2-footprint of the EU-ETS

In order to empirically assess carbon leakage and the different coverage of production-based versus consumption- and investment-based carbon pricing systems it is useful to distinguish between territorial emissions and the CO_2-footprint of domestic demand. Emissions originating from the household sector, e.g. in the form of heating or individual traffic, are included equally in both measures.

- Territorial CO_2-emissions contain all emissions that originate from sources within a country's territory. They include the direct CO_2-emissions emitted by a country's industries in the production process.

- The CO_2-footprint of domestic demand is derived from a country's domestic final demand, i.e. consumption and investment, and consists of the emissions embedded in domestic final demand for domestic products and imports. As exports are not absorbed domestically, their carbon footprint is not included.

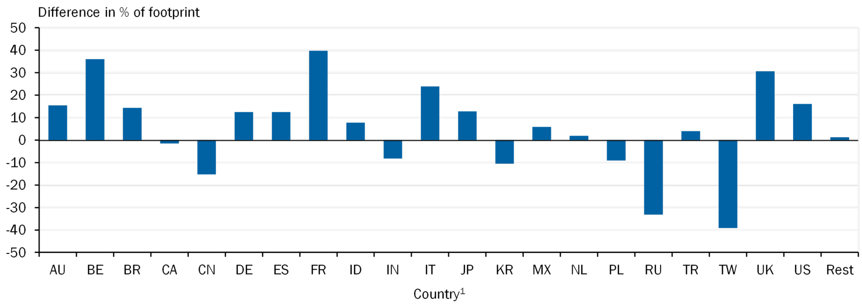
Depending on the composition and amounts of imports and exports, territorial emissions and the CO_2 footprint of domestic demand can differ substantially. If the CO_2 footprint of domestic demand is higher than territorial CO_2 emissions, a country is a net importer of CO_2 emissions. Most countries in the EU-ETS area are net importers of CO_2 emissions, as are most advanced economies (Figure 1). Especially Belgium and France stand out as net importers of CO_2, with the CO_2 footprint surpassing territorial emissions by roughly 35 %. Both countries are among the ones with the largest share of nuclear power in electricity supply worldwide (IAEA, 2020).

The EU-ETS area as a whole is a net importer of CO_2 emissions. While territorial CO_2 emissions as well as the CO_2 footprint of domestic demand in the EU-ETS area have been declining steadily since the introduction of the ETS

[5] A detailed description of the data as well as the methods used to determine the CO_2 footprint can be found in Appendix 1.

Figure 1

Difference between footprint and territorial emissions in 2014



1 – AU-Australia, BE-Belgium, BR-Brazil, CA-Canada, CN-China, DE-Germany, ES-Spain, FR-France, ID-Indonesia, IN-India, IT-Italy, JP-Japan, KR-Republic of Korea, MX-Mexico, NL-Netherlands, PL-Poland, RU-Russian Federation, TR-Turkey, TW-Taiwan, UK-United Kingdom, US-United States, Rest-Rest of the world.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

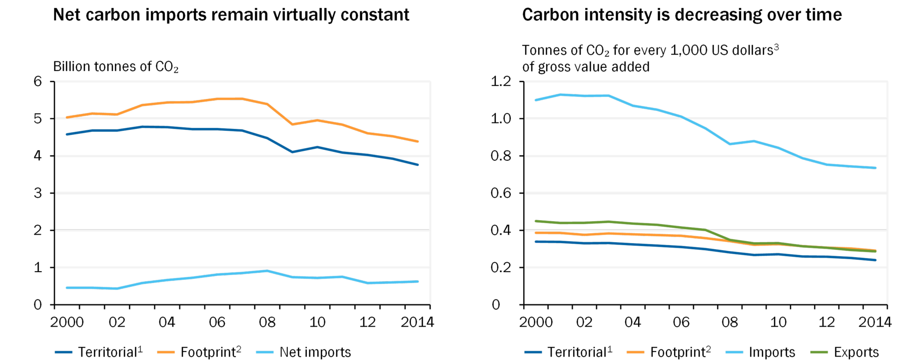
in 2005, net imports have not changed substantially over the years (Figure 2 left). The CO_2 footprint of domestic demand declined by 1.05 billion tons from 2004 to 2014, and territorial emissions by one billion tons. Thus, net imports declined by 50 million tons. Their share of the footprint increased slightly from 12.2 % to 14.2 %.

The decline in territorial emissions occurred despite growth in the territorial value added within the EU-ETS. The CO_2-intensity, i.e. the CO_2 emissions per USD of value added, thus has been declining at a faster rate than territorial CO_2 emissions. Similarly, even though net CO_2 imports have been increasing until 2008 and have not declined substantially below the levels of 2004 and 2005 by the end of our observation period, trade in terms of value added has roughly doubled within the same period. Thus, the CO_2-intensity of imports and exports has declined by roughly 50 % since the early 2000s (Figure 2 right). Interestingly the emissions intensity for all measures began to decline well before the introduction of the EU-ETS in 2005. In general, the CO_2-intensity of imports is much higher than that of exports or territorial production in the EU-ETS area, which is a pattern that can be observed for most net CO_2 importers.

The two countries from which most of the net CO_2 imports to the EU-ETS area originate are China and Russia (Figure 3). Both countries overall are net exporters of CO_2. In 2014 the EU-ETS area ran a net trade deficit of 280 million tons of CO_2 with China and 114 million tons of CO_2 with Russia. Other countries, like the United States, realize positive net CO_2 imports from the EU-ETS area. The absolute values of CO_2 emissions by origin and destination differ widely and are hidden behind the smaller variation in net CO_2 trade (Figures A.1 and A.2). We can also identify country specific patterns within the EU-ETS area by calculating the net trade balances of single EU-ETS member countries with the EU-ETS area as a whole. France, for example, realizes net imports of embedded CO_2 emissions from the rest of the EU-ETS member states, possibly due to the low emissions intensity of its power generation sector, while Poland realizes net exports of embedded CO_2 emissions to the rest of the EU-ETS

Figure 2

Territorial emissions and carbon footprint in the EU-ETS area



1 – Carbon emissions caused by the production of goods in EU ETS member states as well as households' direct emissions. 2 – Carbon emissions caused by the production of goods finally used in EU ETS member states as well as households' direct emissions. 3 – At 2010 prices and exchange rates.

Sources: EU Commission, World Input-Output Database, own calculations

member states due to its relatively emissions intensive power generation sector.

Empirical Observation 1 *(i) The EU is a net importer of* CO_2 *emissions. (ii) While China, Russia and India are net* CO_2 *exporters to the EU, the US is a net importer of* CO_2 *from the EU.*

2.2 A disaggregate industry level view on emissions and international trade

A higher CO_2-intensity of imports could be due to differences in CO_2-intensity of imports relative to territorial production in the same industry or a different industry composition of imports and exports, or both. In the following we disaggregate imports and exports into 56 NACE industries included in the World Input Output Database to shed light on the differences in trade composition and emissions intensities.[6] We consider all carbon emissions embedded[7] in the output of a specific industry which takes into account emissions along the whole value chain involved in producing that output. Thus, they consist not only of CO_2 emitted directly during production but in addition also of CO_2 emitted during the production of intermediate inputs, as well as CO_2 emitted during the production of inputs to the production of intermediate inputs.[8]

The industry composition of CO_2 emissions embedded in trade indeed differs substantially between imports and exports (Figure 4). A large share of emissions embedded in imports are concentrated in "textiles, wearing apparel and leather products" (C13-15), "manufacture of computer, electronic and optical products"

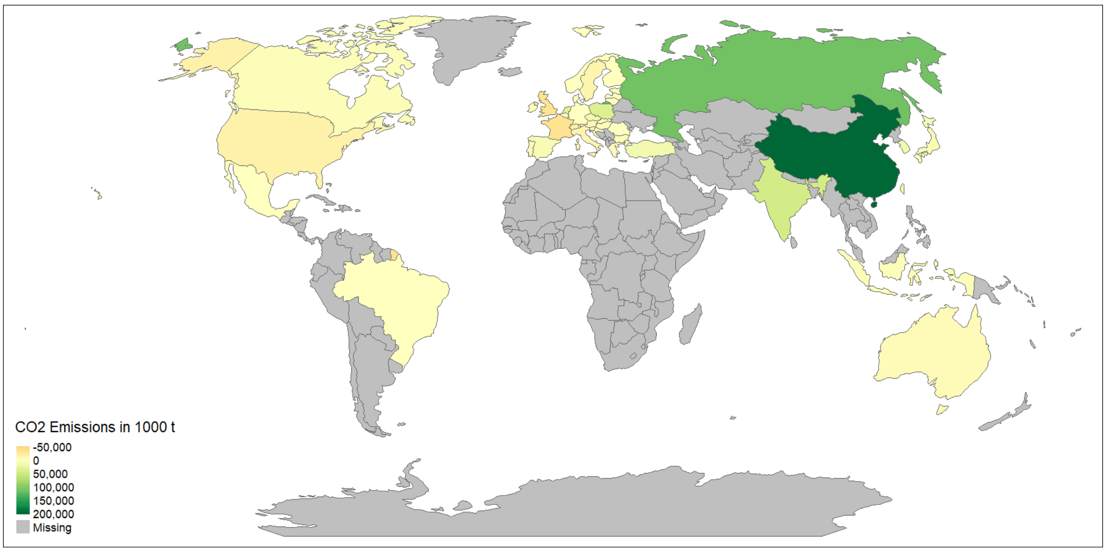
[6]The WIOD mostly distinguishes between NACE two-digit industries. Some industries such are aggregated to the one-digit sector level or to multi-industry aggregates.

[7]We use the terms "CO_2 emissions embedded in..." and "CO_2 footprint of..." interchangeably.

[8]For a detailed description of the methodology see Appendix A.1.

Figure 3

Net trade in CO2 Emissions with EU-ETS area



Countries are colored according to their net CO2 trade balance with the EU-ETS area as a whole. Positive numbers indicate that emissions embedded in exports to the EU-ETS area are higher than emissions embedded in imports from the EU-ETS area. For countries within the EU-ETS area positive numbers indicate that emissions embedded in exports to all other EU-ETS member states are higher than emissions embedded in imports from these states.

(C26), "manufacture of machinery and equipment n.e.c." (C28), "furniture, other manufacturing" (C31_C32) and "motor vehicles, trailers" (C29). The shares of emissions in exports are especially high in "motor vehicles, trailers" (C29) and "manufacture of machinery and equipment n.e.c." (C28). "Water transport" (H50) also exhibits substantial embedded CO_2 exports. Territorial emissions are concentrated in "electricity, gas, steam and air condition supply" (D35).

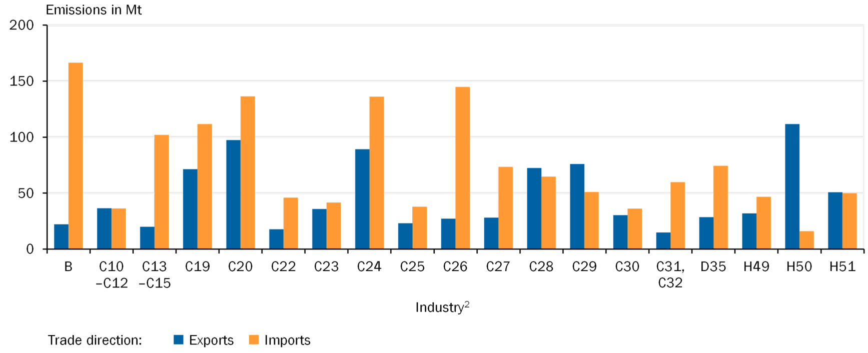
When looking at net imports of embedded CO_2, the textile industry, the computer and electrical equipment industry as well as furniture and other manufacturing stand out as largest net importers. Net CO_2 exports stem primarily from the automotive industry and manufacturing of machinery and equipment as well as water transport.

However, only a very small part of the differences in the CO_2 intensity of exports and imports is explained by differences in their industry composition. Differences in the CO_2-intensity of exports and imports in the same industry are a much more important factor in explaining the difference in the CO_2 intensity of aggregate imports and exports (Figure 5). Industry level emissions intensity in tonnes of CO_2 per 1000 USD of output value is calculated as the amount of carbon emissions embedded in industry output relative to the gross value of industry output. In almost all industries the emissions intensity of imports to the EU-ETS area is substantially higher than the emissions intensity of exports from the EU-ETS area, suggesting that firms and industries from within the EU-ETS area are substantially more energy efficient than firms and industries from outside.

To gauge how much of the difference between the aggregate CO_2 intensity of imports and exports is due to differences in emissions intensity within the

Figure 4

CO_2 footprint[1] of gross exports and imports in 2014

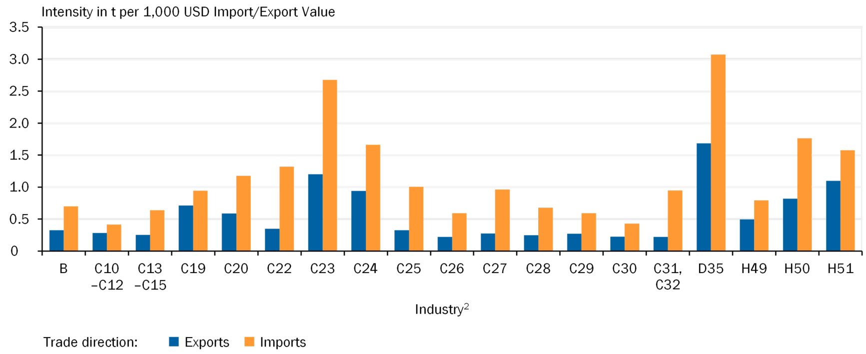


1 – Only emissions occuring in the production process along the supply chain of each industry are considered. For example, emissions from mining and quarrying (B) only consist of emissions that occur directly during the mining and quarrying process or in some production step in the supply chain but not of those resulting from the consumption of fuels produced by the mining and quarrying industry - except if those fuels are used at some point in the production of intermediates to the mining and quarrying industry. 2 – According to the Statistical classification of economic activities NACE Rev. 2 (2008). B: Mining and quarrying; C10–C12: Manufacture of food products, beverages and tobacco products; C13–C15: Manufacture of textiles, wearing apparel and leather products; C19: Manufacture of coke and refined petroleum products; C20: Manufacture of chemicals and chemical products; C22: Manufacture of rubber and plastic products; C23: Manufacture of other non-metallic mineral products; C24: Manufacture of basic metals; C25: Manufacture of fabricated metal products, except machinery and equipment; C26: Manufacture of computer, electronic and optical products; C27: Manufacture of electrical equipment; C28: Manufacture of machinery and equipment n.e.c.; C29: Manufacture of motor vehicles, trailers and semi-trailers; C30: Manufacture of other transport equipment; C31,C32: Manufacture of furniture, other manufacturing; D35: Electricity, gas, steam and air conditioning supply; H49: Land transport and transport via pipelines; H50: Water transport; H51: Air transport.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

Figure 5

Intensity of CO_2 footprint[1] of gross exports and imports in 2014



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Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

same industry as compared to the different industry composition of imports and exports, we use a shift-share decomposition to compare the factual difference to a hypothetical difference between the factual CO_2 intensity of imports and a hypothetical CO_2 intensity of exports. The hypothetical CO_2 intensity of exports is calculated under the assumption that the industry composition of exports was as it is but the CO_2 intensity of each exporting industry was the same as the CO_2 intensity of the corresponding importing industry. Under this assumption the hypothetical aggregate CO_2 intensity of exports is slightly higher than the factual CO_2 intensity of imports. This implies that within industry differences account for slightly more than 100 % of the difference in aggregate CO_2 intensity between imports and exports. Differences in the composition account for slightly less than 1 % of the aggregate difference. A negative covariance term accounts for about -1 % of the aggregate difference.

Empirical Observation 2 *Almost all of the higher* CO_2*-intensity of imports (in tons per 1000 USD import value) compared to the* CO_2*-intensity of exports (in tons per 1000 USD export value) is explained by higher* CO_2*-intensity within the same industry.*

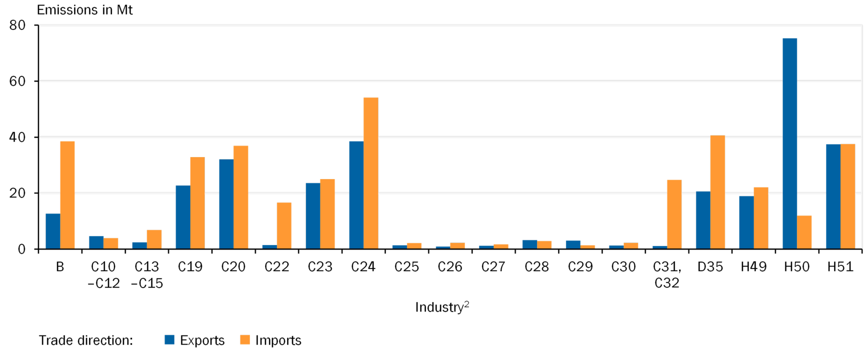
In the analysis of the CO_2-intensity of trade by industry it is important to account for indirect emissions embedded in intermediate products used by the industry under consideration. When only direct emissions of each industry are taken into account the industry structure of emissions embedded in trade looks starkly different (Figure 6). First, it is notable but not surprising that direct emissions are substantially lower than total embedded emissions. On aggregate direct emissions of traded goods amount to only about one quarter of total emissions embedded in trade. Second, the difference between total and direct emissions embedded in trade is substantially larger for more downstream industries such as manufacture of computer, electronics and optical products (C26), manufacture of electrical equipment (C27), manufacture of machinery and equipment n.e.c. (C28) and the automotive industry (C29). In these industries direct emissions embedded in trade are negligible, accounting in each industry for at most 4.5 % of total emissions embedded in trade. For example, while manufacturing of computer, electronics and optical products exhibits the second highest total emissions embedded in imports to the EU-ETS among all 56 industries, it exhibits only the 22nd highest direct emissions embedded in imports to the EU-ETS. The four industries jointly account for roughly 20 % of total emissions embedded in trade but only for 2 % of direct emissions embedded in trade.

Consequently, the direct emissions intensity of trade i.e. the direct emissions embedded in trade divided by the value of gross trade is substantially lower and exhibits a different industry pattern than the total emissions intensity of trade (Figure 7). In particular more downstream industries exhibit a lower direct emissions intensity. For example, while direct emissions in manufacturing of computer, electronics and optical products, amounts only to 0.008 tonnes of CO_2 per 1000 USD import value, total embedded emissions amount to 0.59 tonnes of CO_2 per 1000 USD import value, a difference of nearly two orders of magnitude.

Empirical Observation 3 *Direct emissions embedded in trade are substantially lower and exhibit a different industry pattern than total emissions embed-*

Figure 6

Direct[1] CO_2 emissions of gross exports and imports in 2014

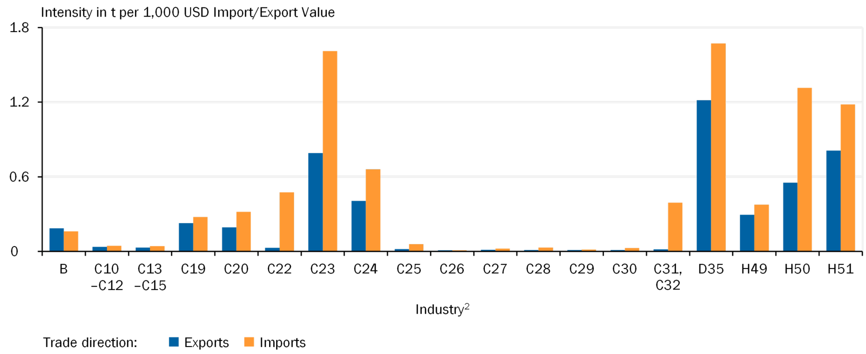


1 – Only emissions occuring directly in the production process of the individual industry for the production of the industry's exports and imports are considered. 2 – According to the Statistical classification of economic activities NACE Rev. 2 (2008). B: Mining and quarrying; C10–C12: Manufacture of food products, beverages and tobacco products; C13–C15: Manufacture of textiles, wearing apparel and leather products; C19: Manufacture of coke and refined petroleum products; C20: Manufacture of chemicals and chemical products; C22: Manufacture of rubber and plastic products; C23: Manufacture of other non-metallic mineral products; C24: Manufacture of basic metals; C25: Manufacture of fabricated metal products, except machinery and equipment; C26: Manufacture of computer, electronic and optical products; C27: Manufacture of electrical equipment; C28: Manufacture of machinery and equipment n.e.c.; C29: Manufacture of motor vehicles, trailers and semi-trailers; C30: Manufacture of other transport equipment; C31,C32: Manufacture of furniture, other manufacturing; D35: Electricity, gas, steam and air conditioning supply; H49: Land transport and transport via pipelines; H50: Water transport; H51: Air transport.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

Figure 7

Intensity of direct[1] CO_2 emissions of gross exports and imports in 2014



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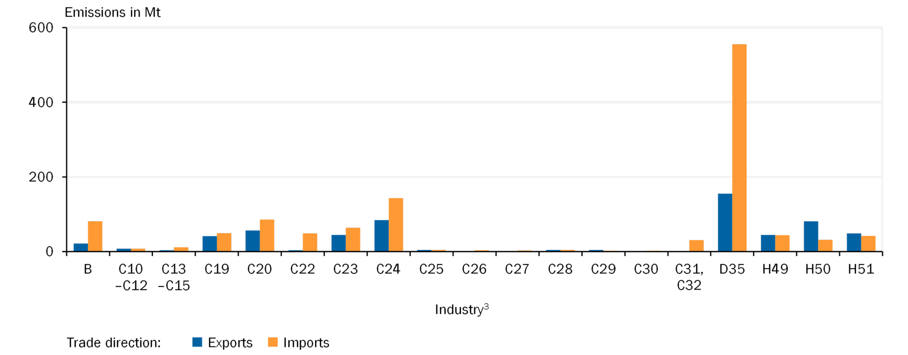
Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations *ded in trade. Downstream industries exhibit much lower emissions intensities when only direct emissions are taken into account, since the major part of embedded emissions originates from intermediate inputs along the value chains.*

2.3 A closer look at emissions intensive and trade exposed industries

Only a few industries account for the bulk of emissions embedded in imports to the EU-ETS area. The seven industries that individually cause the majority of emissions are mining and quarrying (B), manufacture of coke and refined petroleum products (C19), manufacture of chemicals and chemical products (C20), manufacture of rubber and plastic products (C22), manufacture of other non-metallic mineral products (C23), manufacture of basic metals (C24) and electricity, gas, steam and air conditioning supply (D35) (see Figure 8). On aggregate they account for about 80% of imported emissions.

Figure 8

Source[1] industry of CO_2 emissions[2] embedded in exports and imports in 2014



1 – Industry in which the CO_2 emissions embedded in exports and imports were originally emitted during production. 2 – Only emissions occuring in the production process of the individual industry are considered. For example, emissions from mining and quarrying (B) only consist of emissions that occur during the mining and quarrying process, e.g. gas flares, but not of those resulting from the consumption of fuels produced by the mining and quarrying industry. Those emissions are assigned to the industry in which those fuels are consumed during the production process. 3 – According to the Statistical classification of economic activities NACE Rev. 2 (2008). B: Mining and quarrying; C10–C12: Manufacture of food products, beverages and tobacco products; C13–C15: Manufacture of textiles, wearing apparel and leather products; C19: Manufacture of coke and refined petroleum products; C20: Manufacture of chemicals and chemical products; C22: Manufacture of rubber and plastic products; C23: Manufacture of other non-metallic mineral products; C24: Manufacture of basic metals; C25: Manufacture of fabricated metal products, except machinery and equipment; C26: Manufacture of computer, electronic and optical products; C27: Manufacture of electrical equipment; C28: Manufacture of machinery and equipment n.e.c.; C29: Manufacture of motor vehicles, trailers and semi-trailers; C30: Manufacture of other transport equipment; C31,C32: Manufacture of furniture, other manufacturing; D35: Electricity, gas, steam and air conditioning supply; H49: Land transport and transport via pipelines; H50: Water transport; H51: Air transport.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

Not only for the consideration of CO_2 imports, but also when it comes to carbon leakage, those industries are of particular interest. While electricity supply is hardly tradable over large distances, the other industries are potentially exposed to a relocation of production abroad in the wake of rising carbon prices. The six tradable industries, accounted for more than 25 % of territorial emissions in the EU-ETS area (excluding household emissions)[9] and for 4.27 %

[9]In 2014 household emissions accounted for 22% of territorial emissions.

of value added in 2014 (Table 1). Two of them, however, are not particularly emissions intensive within the EU-ETS: Mining and quarrying (B) accounts for a substantial amount of embedded emissions imported simply due to its high level of value added imports. Imports from manufacture of rubber and plastic products (C22) to the EU-ETS area are much more emissions intensive than domestic production. The other four tradable industries with the highest territorial emissions and the highest emissions intensity accounted for 22.6 % of territorial emissions (excluding household emissions) and for 2.26% of value added in 2014. If only territorial emissions were subject to the CO_2 price, in particular those four industries would have to be considered for carbon leakage purposes as they are emissions intensive and have a relatively high trade intensity at the same time. Thus they face particularly strong incentives for relocation of production in response to rising carbon prices.

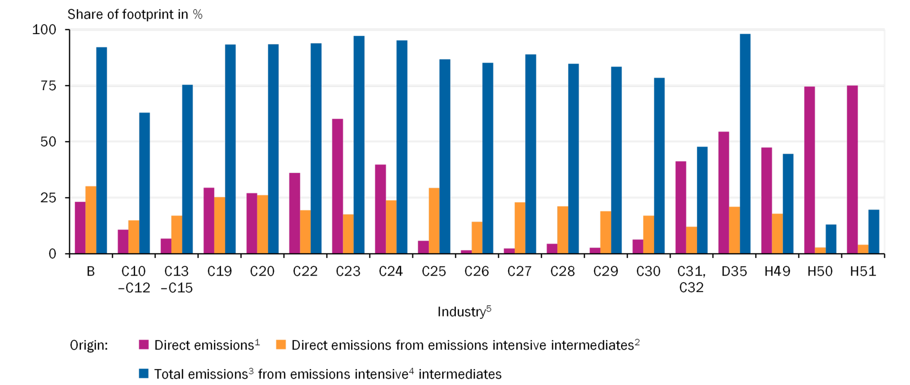
Table 1: Characteristics of selected industries potentially exposed to carbon leakage in the EU-ETS in 2014

Industry	Direct emissions (million tons)	Value added (billion USD)	CO_2 intensity of value added (tons / 1000 USD)	Trade intensity $\frac{\text{Exports+Imports}}{\text{Production}}$
Electricity, gas, steam and air conditioning supply (D35)	1114.4 (37.93% of total excl. households)	322.8 (1.89 % of total)	3.45	4.16 %
Manufacture of other non-metallic mineral products (C23)	198.5 (6.76% of total excl. households)	90.5 (0.53% of total)	2.19	16.7 %
Manufacture of basic metals (C24)	183.2 (6.24% of total excl. households)	89.0 (0.52% of total)	2.06	35.8%
Manufacture of chemicals and chemical products (C20)	143.1 (4.87% of total excl. households)	173.7 (1.02% of total)	0.82	41.0%
Manufacture of coke and refined petroleum products (C19)	140.3 (4.77% of total excl. households)	32.7 (0.19% of total)	4.29	35.9%
Mining and quarrying (B)	59.3 (2.01 % of total excl. households)	218.1 (1.28% of total)	0.27	93.1%
Manufacture of rubber and plastic products (C22)	11.9 (0.41% of total excl. households)	123.2 (0.72% of total)	0.10	23.4%

On the other hand, if the CO_2 footprint would be the yardstick, emissions would be distributed more evenly among the industries. In particular, industries such as the automotive industry (C29) or machinery and equipment manufacturing (C27 and C28) which source intermediate inputs from emissions intensive upstream suppliers exhibit a much higher CO_2 footprint and a much higher embedded emissions intensity (Figure 5). This discrepancy between direct and embedded emissions has been highlighted already for imports and exports. The following analysis focuses on emissions of intermediate goods originating from emissions intensive industries[10] and used in various downstream industries. On the one hand, we specify, separately for each downstream industry, the part of the footprint of imports that is due to intermediate goods directly sourced from emission intensive industries. In a further step we show, again per industry, the part of the footprint of imports that is due to all intermediate goods sourced from emission intensive industries along the entire production chain. As it turns out, emissions from emissions intensive industries contribute substantially to the indirect emissions intensity of imports for all industries (Figure 9).

Figure 9

Composition of the CO_2 emissions footprint of imports in 2014



1 – Emissions occuring directly in the production process of the individual industry for the production of the industry's exports and imports. 2 – Emissions ocurring directly in the production process of emissions intensive intemediates directly used by the industry. 3 – Emissions ocurring directly in the production process of emissions intensive intermediates used in production at some point of the industry's supply chain. 4 – Emissions intensive intermediates are intermediates from the following industries: B, C19, C20, C22, C23, C24, D35. 5 – According to the Statistical classification of economic activities NACE Rev. 2 (2008). B: Mining and quarrying; C10–C12: Manufacture of food products, beverages and tobacco products; C13–C15: Manufacture of textiles, wearing apparel and leather products; C19: Manufacture of coke and refined petroleum products; C20: Manufacture of chemicals and chemical products; C22: Manufacture of rubber and plastic products; C23: Manufacture of other non-metallic mineral products; C24: Manufacture of basic metals; C25: Manufacture of fabricated metal products, except machinery and equipment; C26: Manufacture of computer, electronic and optical products; C27: Manufacture of electrical equipment; C28: Manufacture of machinery and equipment n.e.c.; C29: Manufacture of motor vehicles, trailers and semi-trailers; C30: Manufacture of other transport equipment; C31,C32: Manufacture of furniture, other manufacturing; D35: Electricity, gas, steam and air conditioning supply; H49: Land transport and transport via pipelines; H50: Water transport; H51: Air transport.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

At the aggregate level, 24.5 % of the carbon footprint of imports is due to direct emissions (red bars) and an additional 20 % is due to direct emissions of intermediate inputs directly sourced from one of the seven industries with the highest carbon emissions (green bars).[11] Considering not only direct inputs but the entire upstream value chain, ultimately roughly 79 % of the footprint origi-

[10] As intermediate inputs from emissions intensive industries we consider inputs from mining and quarrying (B), manufacture of coke and refined petroleum products (C19), manufacture of chemicals and chemical products (C20), manufacture of rubber and plastic products (C22), manufacture of other non-metallic mineral products (C23), manufacture of basic metals (C24) and electricity, gas, steam and air conditioning supply (D35).

[11] These industries are mining and quarrying (B), manufacture of coke and refined petroleum products (C19), manufacture of chemicals and chemical products (C20), manufacture of rubber and plastic products (C22), manufacture of other non-metallic mineral products (C23), manufacture of basic metals (C24) and electricity, gas, steam and air conditioning supply (D35).

nates from one of these industries (blue bars). For more downstream industries the share of direct emissions is much lower. Consider for example manufacturing of computers, electronics and optical products (C26), the manufacturing industry with the largest carbon footprint of imports (Figure 4).[12] Direct emissions account only for about 1.5 % of the carbon footprint. Direct emissions of intermediates from the seven most important carbon emitting industries account for 14.2 % of the footprint. Ultimately roughly 85 % of the footprint originates from one of these emissions intensive industries in upstream production.

Empirical Observation 4 *(i) Within the EU-ETS area, the four trade intensive industries accounting for most territorial emissions in 2014 accounted for 22.6 % of emissions (excluding household emissions) and for 2.26 % of value added. (ii) When it comes to imports, emissions from seven emissions intensive industries*[13] *account for 80 % of emissions embedded in imports. 20 % of imported emissions are due to direct emissions of intermediate inputs directly sourced from one of those seven industries with the highest carbon emissions.*

3 Carbon Leakage

As carbon prices are likely to increase due to more ambitious climate policy in upcoming years, the exclusive focus of the EU-ETS on CO_2 emitted within the EU-ETS area is currently reconsidered. Substantial carbon prices could reduce the competitiveness of European firms in domestic and global markets and induce a relocation of carbon intensive production to countries with lower carbon prices or no carbon price at all. As a result, less CO_2 emissions would be subject to the EU-ETS, and imports of carbon intensive goods into the EU-ETS area would increase while exports of carbon intensive goods would decrease. If carbon prices would instead be levied on both, domestic production and imports, while exports would be exempted from carbon pricing, those effects could be alleviated. However, the cost of carbon is only one parameter in the location and production decisions of companies. Thus, it is ex ante unclear whether carbon leakage would occur to a significant extent with higher carbon prices and thus whether a switch towards a mechanism that prices carbon emissions ultimately caused by domestic demand would be a significant improvement as compared to the current regime.

3.1 The current mechanism to countervail carbon leakage

The EU currently tries to countervail carbon leakage by allocating a share of allowances to firms for free. Around 57 % of allowances were auctioned between 2013 and 2020, while the rest was freely allocated[14]. It is important to note that the determination of a CO_2 price is, in principle, independent of whether allowances are being auctioned or freely allocated initially, as long as the total

[12]In mining and quarrying (B), the industry with the largest carbon footprint of imports, direct emissions account for almost 25 % of the footprint. However, direct emissions of intermediates from the seven most important carbon emitting industries in addition account for more than 25 % of the footprint.

[13]For a definition of these industries see Figure 8 and the explanation above that figure.

[14]According to the revised directive 2003/87/EC this share is to remain constant at 57 % in phase 4 of the EU-ETS.

amount of allowances is fixed at the prevailing cap and allowances can be traded after initial allocation. This is the case for the EU-ETS. While a large share of allowances had been freely allocated in the early years of the EU ETS, this share has been reduced substantially over the years. The power generation sector has not been allocated free allowances anymore since 2013 (apart from some exceptions). The share of free allowances in the industry sector has been decreasing from 80 % in 2013 to 30 % in 2020, except for companies in the EITE sectors.

The volume of allocated free allowances for a specific installation is generally determined by four factors (exceptions apply e.g. for the aviation sector or new entrants):

$$\begin{aligned} \text{Allocation} =& \text{Benchmark} \times \text{Historical activity level} \\ & \times \text{Carbon leakage exposure factor} \times \text{Correction factors} \end{aligned} \tag{1}$$

Benchmarks. Specific benchmarks are defined for 52 products, which account for around 75 % of industrial emissions in the EU-ETS (European Commission, 2015). Most benchmarks are set for products in the chemicals (15), pulp and paper (11) and iron and steel (6) industries. If no benchmarks are defined for a product, then benchmarks based on heat production or fuel consumption during the production process (or as fall back: process emissions based on historical emissions) are used as alternatives.

The product benchmarks for the third phase of the EU-ETS (2013-2020) are calculated as the average emission level per unit of product produced by the top 10 % most efficient installations in the EU-ETS in 2007 and 2008. In phase 4 (2021-2030) the benchmarks' value will be updated based on information submitted in 2016. In part 1 of phase 4 (2021-2026), the Commission additionally reduces the benchmark values annually following a flatrate approach to take the scope for efficiency improvements into account. The reduction will be proportional to the difference between the value from 2016 and the one from 2007/2008 (minimum 0.2 % annually and maximum of 1.6 % annually). Product benchmarks apply to every installation producing a specific product independently of geographic location, technology, fuels or raw materials used (ETS Directive Article 10a(2)).

Historical activity level (HAL). The benchmark emissions for the specific product are multiplied with the historical activity level (HAL) of the installation. The default method for phase 3 to determine this level is to calculate the median of the annual production volume of a sub-installation during a specific period. For the third phase of EU-ETS this is either between 2005 to 2008 or between 2009 and 2010. The production quantity is thus set before the start of the relevant phase of the EU-ETS. For the fourth phase the HAL default calculation changed. Now installations can choose either to use 2014-2018 or 2019-2023 as their baseline period and take the arithmetic mean of the annual activity level. For installations which have significantly changed their capacity e.g. through identifiable larger physical changes[15], this capacity change times the historical utilization level is added or subtracted from the historical activity level.

By fixing the historical activity level ex-ante before the start of the ETS phase the free allowances are designed to exert little influence on short-run production decisions, but are rather based on capacities and thus constitute lump-sum subsidies. However, this only applies within a trading period. Across trading periods, firms can increase the subsidy by increasing capacities. The system of free allocations may thus influence production decisions through long-run incentives to increase production quantities. Indeed, Branger et al. (2015) show that companies in the cement industry in the EU-ETS strategically adjusted their output to obtain more allowances through free allocation.

Overall, companies might thus have an incentive to increase capacities and/or production beyond what is optimal. As the emissions cap is decreasing and holding on to freely allocated certificates presents an opportunity cost, those companies will nonetheless have an incentive to decrease their CO_2-intensity. This in turn will decrease the benchmarks for future periods.

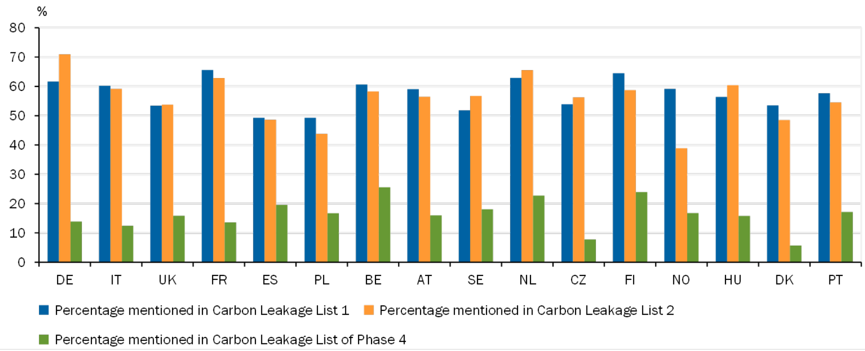
Carbon leakage exposure factor (CLEF). The carbon leakage exposure factor is determined at the 4-digit industry level. If installations are in industries which are mentioned by the carbon leakage list, the CLEF is in principle equal to one. So far, three carbon leakage lists have been published: List 1 and 2 were applied in phase 3, i.e. List 1 from 2013-2014 and List 2 from 2015-2020, and List 3 will be applied in phase 4, i.e. from 2021-2030. For installations in industries not mentioned in the carbon leakage list, the share of free allowances is decreasing over time, from 80 % in 2013 to 30 % in 2020. The share will be further reduced in phase 4, arriving at 0 % by 2030.

The share of value added covered by the carbon leakage lists decreases significantly in phase 4 (Figure 10). Among the larger member states, the share of value added by the industries mentioned on the carbon leakage list surpasses 20 % only in Belgium, the Netherlands and Finland in phase 4. In phase 3 the share was above 60 % also in Germany and France. There are two industries where 100 % of the value added is covered by a carbon leakage list in both, phase 3 and phase 4: "Mining of metal ores" and "Manufacture of coke and refined petroleum products". There are several industries where the coverage dropped from 100 % to (almost) zero, like manufacture of pharmaceutical products, computer, electric, electrical and optical equipment or machinery (Table A.2). 72.6 % of free allowances were allocated to sectors on the carbon leakage list 2 from 2015 to 2019. Only in industries related to beverages and wood, the majority of the allowances were not freely allocated because the sub-industries were included in the carbon leakage list, but for other reasons. In those industries related to metal products, mining and plastic products, the share that was due to a sub-industry being included in the carbon leakage list was below 90 %, in all other industries above that value (Table A.2).

[15] The necessary significant capacity change is defined by at least one identifiable physical change in the technical operation, not the substitution of already existing assembly lines. In addition, either the capacity must change by at least 10 % compared to the original activity level or the recalculation of the allowances per year would result in a change of 50,000 allowances per year, representing at least 5 % of the preliminary annual allocated allowances (Source: p.58 handbook EU ETS or Guidance Document 7 EU).

Figure 10

Share of gross value added of industries mentioned on carbon leakage lists across member states[1]



1 – Only larger member states depicted, with a share of total gross value added (GVA) in the EU of at least 1 %. Before the matching process: NACE-Codes for the list of the period 2013–2014 were recoded to NACE Rev. 2 according to European Commission (2020b), in carbon-leakage lists the Prodcom-Codes were converted to NACE Rev. 2 Codes (4-digit) and letter codes were added. In the matching process of the two datasets, a dummy variable was created for each period of the carbon-leakage lists, which is one if the 4-digit NACE-Code is part of the list, and zero if not.

Sources: European Commission (2020b), own calculations

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Correction factors. As the emissions cap of the EU-ETS decreases every year and the total share of 57 % of allowances to be auctioned is fixed in 2003/87/EG, the amount of allowances available for free allocation is limited and decreases over time (Figure 11).

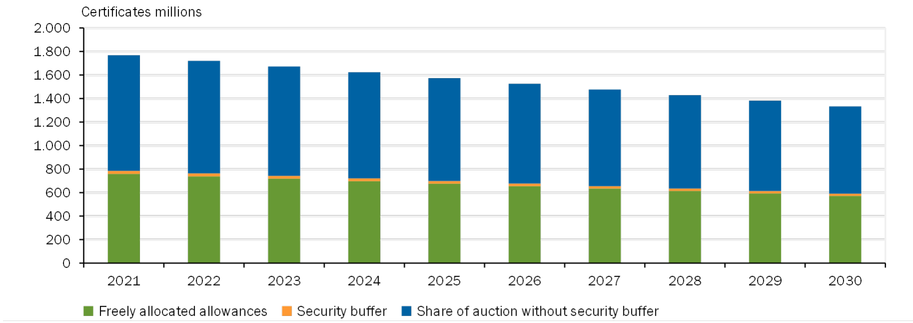
This is achieved by various correction factors. The linear reduction factor resembles the annual reduction in the total amount of allowances, which is 1.74 % in phase 3 and 2.2 % in phase 4 each year. Furthermore, after all operators have been applied for free allowances in accordance with the allocation rules, the sum of the determined individual freely allocated allowances can turn out to be higher than the total number of allowances available for free allocation. In order to comply with the limit, the calculated allocation amounts for all plants are reduced by a uniform percentage, the cross-sectoral correction factor. According to BMU (2018) this factor was 11 % per year on average during phase 3 of the EU-ETS. In phase 4, in order to avoid the application of such a factor, additional flexibility is added through a "safety buffer". Up to 3 % of the total budget will be additionally available for the free allocation if this is necessary to avoid using a correction factor.

3.2 Free allocation of allowances in phase 3

A large share of allowances is allocated to the aviation sector and to the combustion of fuels. This share is, however, sharply decreasing over time. While in phase 2 from 2008-2013 in total 62 % of free allowances were allocated to combustion of fuels, the share in phase 3 (from 2013-2020) was only 27 %. In 2019, only 21 % of freely allocated allowances went to combustion of fuels. The share of allowances freely allocated to aviation was 2 % in phase 2 and 4 % in phase 3. The remaining shares of free allowances are allocated to industrial installations.

Figure 11

Cap share in the 4th trading period



Source: BMU

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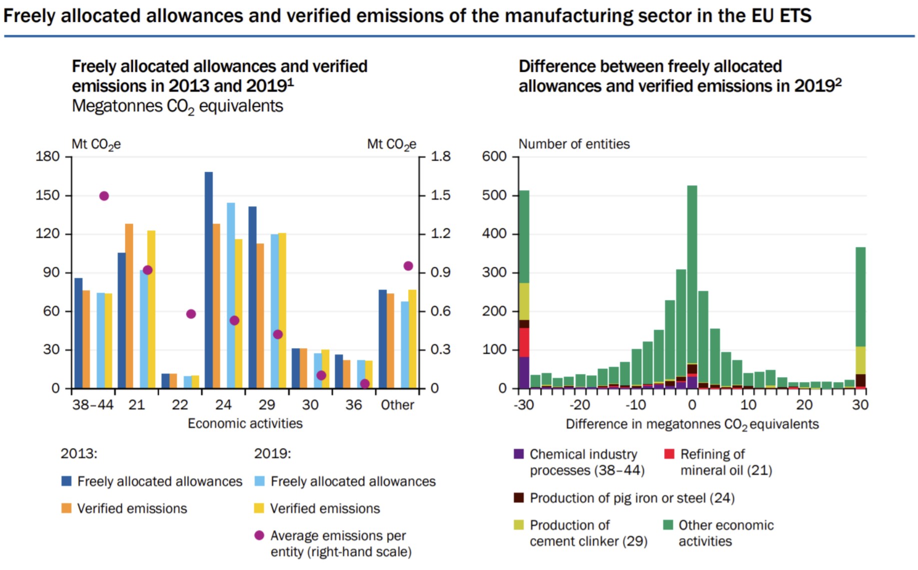
Within the industry sector, in phase 3 the largest share is allocated to the production of pig iron and steel, to coking plants and oil processing, to the production of cement and the chemical industry (Figure 12). In all those areas, except for the refining of mineral oil and the production of lime, the allocated free allowances approximately matched or were larger than the observed verified emissions in 2013 and (to a smaller extent) in 2019.

Individual installations can receive a larger amount of free allowances than they actually need to cover their verified emissions, for example if the carbon intensity of production decreases substantially or their production levels decrease. This is reflected in the distribution of the difference between freely allocated allowances and actual verified emissions (Figure 12). On aggregate, this applies particularly to the steel sector which receives substantially more allowances for free than needed to cover verified emissions. More details on the distribution of the difference across installations can be found in the Appendix (Table A.1). Martin et al. (2014) conclude that the current allocation results in "substantial overcompensation for given carbon leakage risk".

Across the EU-ETS area, in absolute terms, most free allowances in the industry sector have been allocated to Germany, Italy, France and Spain (Figure 13 top). However, relative to the total amount of verified emissions of a country, others like Sweden, Lithuania, Belgium, France and Finland were among the ones with the highest shares in 2019. Relative to the total value added of a country in 2019, the highest amount of free allowances was allocated to Luxembourg, Cyprus, Romania, Bulgaria, Netherlands and Lithuania. France, Germany, Italy and the UK were the countries with the smallest amount of free allowances relative to total value added.

Total verified emissions were significantly higher than the total amount of freely allocated allowances in 2013 and 2019 across all EU-ETS member states. However, considering only the industry sector in some countries, the amount of freely allocated allowances was higher than the verified emissions. While in 2013 the amount of freely allocated allowances was substantially higher than verified emissions in many countries in the industry sector, in 2019 the same

Figure 12



1 – The only economic activities included are those that have received freely allocated allowances and – under the classification of activities applicable since 2013 – belong to the manufacturing sector. 38–44-Production of nitric acid, adipic acid, glyoxal and glyoxylic acid, ammonia, bulk chemicals, hydrogen and synthesis gas, soda ash and sodium bicarbonate, 21-Refining of mineral oil, 22-Production of coke, 24-Production of pig iron or steel, 29-Production of cement clinker, 30-Production of lime, or calcination of dolomite/magnesite, 36-Production of paper or cardboard, Other-Production of glass, ceramics, primary aluminium, pulp, mineral wool, carbon black, gypsum or plasterboard, secondary aluminium, production or processing of ferrous metals and non-ferrous metals, metal ore roasting or sintering; other activity opted-in under Art. 24 Directive 2003/87/EC. 2 – Entities that have been assigned to the categories presented in the data set according to the old classification prior to 2013 have been assigned to categories as presented by the European Environment Agency for emissions from 2017.

Sources: European Commission, European Environment Agency, own calculations

was true only for Sweden, Finland and the Czech Republic (Figure 13 bottom). Other countries like Austria or the United Kingdom were allocated significantly less allowances than verified emissions.

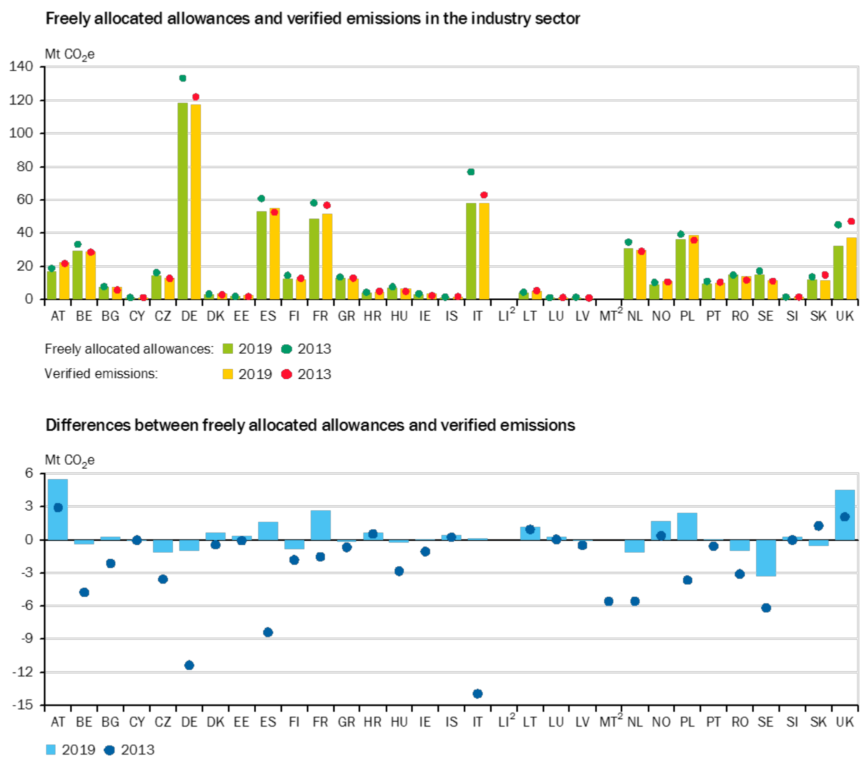
Empirical Observation 5 *(i) A small number of industries receive the bulk of free allowances. (ii) Within the industry sector, the largest share is allocated to the production of pig iron and steel, to coking plants and oil processing, to the production of cement and the chemical industry. (iii) The amount of free allowances assigned to a country and industry deviates from its verified emissions. Over the years, the positive difference was reduced in the industry sector and the amount of freely allocated allowances fell below verified emissions.*

3.3 Indications for Carbon Leakage

The decreasing EU-ETS emissions cap will, by construction, induce a continued decline of territorial emissions in the EU-ETS area in the future. Consequently, the price of emissions certificates will likely increase. On the one hand, the increasing price on carbon emissions induces producers within the EU-ETS area to become more efficient as there is an incentive to invest in a transition towards less CO_2 intensive production technologies. On the other hand, production of emissions intensive products in the EU-ETS becomes increasingly expensive.

Figure 13

Freely allocated allowances and verified emissions in the industry sector in 2013 and 2019[1]



1 – AT-Austria, BE-Belgium, BG-Bulgaria, CY-Cyprus, CZ-Czech Republic, DE-Germany, DK-Denmark, EE-Estonia, ES-Spain, FI-Finland, FR-France, GR-Greece, HR-Croatia, HU-Hungary, IE-Ireland, IS-Iceland, IT-Italy, LI-Liechtenstein, LT-Lithuania, LU-Luxembourg, LV-Latvia, MT-Malta, NL- Netherlands, NO-Norway, PL-Poland, PT-Portugal, RO-Romania, SE-Sweden, SI-Slovenia, SK-Slovakia, UK-United Kingdom. 2 – No data available.

Sources: European Commission (EAA), own calculations

For these products carbon leakage might occur, i.e. production might relocate to regions where emissions are less costly, while consumption will still be taking place in the EU-ETS area. Consequently, the carbon footprint would decline at a slower pace than territorial emissions.

So far, the carbon footprint in absolute terms declined at a similar pace as territorial emissions in the EU-ETS area (Section 2.1). This implies, in particular, that net carbon imports were not declining by a substantial amount. Those observations could raise concerns that carbon pricing not only in theory but also in practice has led to carbon leakage and a deterioration of competitiveness in carbon intensive industries. The patterns might, however, be due to other contemporaneous events such as the substantial increase in world trade between 2000 and the financial crisis and the subsequent decline in trade growth.[16] Furthermore, other country specific policies and developments such as the accession of China to the WTO might have affected trade flows.

[16] World exports grew at an annual rate of 5.3 per cent between 2000 and 2008. Between 2008 and 2014 world export growth roughly halved and grew at an annual rate of 2.7 per cent.

In order to analyse the effect of carbon pricing on trade flows and embedded carbon emission we construct a data set that allows us to eliminate these confounding factors from the analysis. In particular, we use input and output data from the 43 countries included in the World Input-Output Database for 56 industries for the years between 2000 and 2014. During this period coverage with ETS extends to the EU-ETS beginning in 2005 and its expansion to Bulgaria and Romania in 2007, to Norway in 2008 and to Croatia in 2013. While Kazahkstan and New Zealand also introduced an ETS in the period we analyze, neither is included in the World Input Output Database. We add information on carbon emissions from Corsatea et al. (2019), on carbon pricing from the World Bank Carbon Pricing Dashboard and on participation in trade agreements from the CEPII gravity equation database (Head et al., 2013).

We estimate several gravity equations familiar from the international trade literature following Aichele and Felbermayr (2015) who use these specifications[17] to estimate the carbon leakage effects of participation in the Kyoto Protocol.

$$lny_{imxt} = \alpha_1 DETS_{mxt} + \beta POL_{mxt} + FE_{mt} + FE_{xt} + FE_{imx} + \epsilon_{imxt} \quad (2)$$

y_{imxt} is the outcome of interest e.g. the bilateral flow of CO_2 emissions embedded in imports of industry i to country m from country x. $DETS_{mx}$ measures differential ETS implementation i.e. it is an indicator that takes the value 1 if the importer country has an ETS in place and the exporter country does not. It takes the value 0 if either both have an ETS in place or both don't, and it takes the value -1 if the importer country has no ETS in place while the exporter country does. The variables in POL_{mx} control for trade policies of the importer-exporter pair, in particular joint WTO membership, joint free trade agreements and joint EU membership. We also include country year fixed effects and an importer-exporter-industry fixed effect. The coefficient of interest α_1 measures the percentage change in the outcome variable if countries are differentially exposed to ETS regimes and is identified from variation within country-pair by industry cell over time that is not explained by time variation at the aggregate country level. Furthermore, we estimate a second set of gravity equations to investigate whether the effect of ETS coverage varies by carbon intensity.

$$\begin{aligned} lny_{imxt} = &\alpha_1 DETS_{mxt} + \alpha_2 DETS_{mxt} \times CINT_{ix} + \beta POL_{mxt} \\ &+ FE_{mt} + FE_{xt} + FE_{imx} + \epsilon_{imxt} \end{aligned} \quad (3)$$

We include the interaction between differential ETS exposure ($DETS_{mxt}$) and the initial average carbon intensity of industry i in export country x during the years 2000 to 2003 ($CINT_{ix}$).[18] A positive coefficient for this interaction

[17] Similar regressions to investigate carbon leakage induced by the EU-ETS have been performed by Naegele and Zaklan (2019). Their regressions include a larger set of countries but only three time periods. Apart from an ETS dummy they also include emissions cost from direct emissions and indirect emissions duet to intermediate consumption of electricity corrected for the allocation of free allowances.

[18] We use the carbon intensity at the beginning of the observation period to measure initial carbon intensity before industries could react to the introduction of an ETS. We average over the years 2000 to 2003 to evade potential outliers of carbon intensity in a single year.

Table 2: ETS implementation and footprints of value added and CO_2 emissions

	log VA footprint		log CO_2 intensity		log CO_2 footprint	
	(1)	(2)	(3)	(4)	(5)	(6)
$DETS_{mxt}$	-0.080***	-0.080***	0.112***	0.103***	0.032***	0.023***
	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)	(0.004)
$DETS_{mxt} \times CINT_{ix}$		-0.000		0.006***		0.006***
		(0.000)		(0.001)		(0.001)
Joint FTA membership	0.051***	0.051***	0.001	0.001	0.051***	0.051***
	(0.006)	(0.006)	(0.007)	(0.007)	(0.009)	(0.009)
Joint WTO membership	0.023	0.023	-0.009	-0.012	0.017	0.014
	(0.031)	(0.031)	(0.028)	(0.028)	(0.042)	(0.042)
Joint EU membership	0.119***	0.119***	0.005	0.004	0.124***	0.123***
	(0.006)	(0.006)	(0.008)	(0.008)	(0.009)	(0.009)
Country-year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,349,474	1,349,474	1,340,085	1,340,085	1,341,069	1,341,069
No. of countrypair-sectors	90118	90118	89667	89667	89667	89667
Adj. R^2	0.620	0.620	0.412	0.412	0.149	0.149
F-stat	981.681	980.367	873.436	869.888	216.745	216.139
RMSE	0.411	0.411	0.521	0.520	0.615	0.615

Standard errors in parentheses
* p<0.1, ** p<0.05, *** p<0.01

term suggests that the effect of carbon leakage is stronger for more carbon intensive industries. In the first set of regressions we analyse the effect of differential ETS exposure on the origin of value added embedded in final demand[19] and the origin of the carbon footprint of final demand. The dependent variables are value added, the carbon footprint of final demand of country m which has been generated by industry i in country x, and the corresponding carbon intensity of value added.

The results indicate that, after controlling for trade policy indicators and fixed effects, the value added embedded in final demand that originates from countries without an ETS decrease by 8 % after the introduction of an ETS. At the same time, however, the CO_2 footprint of final demand in country m (with ETS) originating from production of industry i in country x (without an ETS) increases by 3.2 %. Consequently, the carbon intensity of value added embedded in final demand of country m originating from industry i in country x increases by 11.2 %. There is some heterogeneity across industries, as the carbon intensity of value added originating from country x, as well as the carbon footprints, increase more strongly in more carbon intensive industries.

In the second set of regressions we analyse the effect of differential ETS exposure on the more traditional measure of gross imports, as well as CO2 intensity and CO2 footprint of gross imports.

These regressions use similar measures of imports, carbon footprint of imports and carbon intensity of imports as Aichele and Felbermayr (2015). The

[19]This measure is calculated in a fashion similar to the corresponding measure in the OECD TIVA database (OECD, 2019).

Table 3: ETS implementation, gross imports and their carbon content

	log imports		log CO_2 intensity imports		log import CO_2 footprint	
	(7)	(8)	(9)	(10)	(11)	(12)
$DETS_{mxt}$	-0.087***	-0.086***	0.041***	0.031***	-0.046***	-0.054***
	(0.006)	(0.006)	(0.001)	(0.002)	(0.006)	(0.007)
$DETS_{mxt} \times CINT_{ix}$		-0.001		0.007***		0.006**
		(0.002)		(0.001)		(0.003)
Joint FTA membership	0.059***	0.059***	-0.001	-0.002	0.057***	0.057***
	(0.015)	(0.015)	(0.003)	(0.003)	(0.015)	(0.015)
Joint WTO membership	-0.125	-0.125	0.003	-0.001	-0.123	-0.126
	(0.080)	(0.080)	(0.019)	(0.019)	(0.080)	(0.080)
Joint EU membership	0.147***	0.147***	0.007**	0.007**	0.155***	0.155***
	(0.014)	(0.014)	(0.003)	(0.003)	(0.014)	(0.014)
Country-year effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,294,016	1,294,014	1,292,727	1,292,727	1,292,727	1,292,727
No. of countrypair-sectors	87836	87834	87675	87675	87675	87675
Adj. R^2	0.343	0.343	0.766	0.766	0.142	0.142
F-stat	293.170	292.682	2657.249	2657.566	100.683	100.504
RMSE	0.951	0.951	0.188	0.188	0.963	0.963

Standard errors in parentheses
* $p<0.1$, ** $p<0.05$, *** $p<0.01$

dependent variable are gross imports to importing country m from industry i in exporting country x, and the respective footprint of those imports, as well as the carbon intensity. The results indicate that, after controlling for trade policy indicators and fixed effects, imports decrease by 8.6 % after the introduction of an ETS. At the same time the carbon footprint of imports decreases by 4.6 %. The carbon intensity of imports increases by 4.1 %. There is some heterogeneity across industries, with more carbon intensive industries experiencing a stronger increase in carbon intensity of imports and a weaker decrease of the carbon footprint of imports.

The significant coefficients on the interaction term between differential ETS exposure and the average carbon intensity of industry i in export country x imply that the effect of ETS coverage on leakage differs across industries. To investigate this further, we run the regressions (7), (9) and (11) separately for all manufacturing industries in the WIOD database, mining and quarrying as well as electricity production. The results show that there is indeed substantial heterogeneity across industries, with the effect on the carbon footprint of imports varying between an increase of more than 13 % for printing and reproduction of recorded media and coke and refined petroleum products to less than -14 % for rubber and plastic products. Similarly, the range of the effect on import values is quite heterogeneous with some industries showing positive effects i.e. an increase in imports from non-ETS countries to ETS countries and others showing negative effects. For almost all industries, however the effect on the CO_2 intensity of imports is unambiguously positive implying an increase in the CO_2 intensity of imports from non-ETS countries to ETS countries after the latter have introduced an ETS.

Table 4: ETS implementation, sector by sector analysis

		(13) log imports	(14) log CO_2 intensity	(15) log import CO_2 footprint
(C18)	Printing and reproduction	0.092***	0.045***	0.137***
	of recorded media	(0.034)	(0.005)	(0.034)
(C19)	Coke and refined petroleum products	0.116**	0.020***	0.135**
		(0.053)	(0.006)	(0.053)
(C24)	Basic metals	0.060*	0.044***	0.105***
		(0.035)	(0.005)	(0.036)
(C30)	Other transport equipment	0.033	0.042***	0.075**
		(0.038)	(0.005)	(0.038)
(B)	Mining and quarrying	0.005	0.045***	0.051
		(0.042)	(0.009)	(0.042)
(C20)	Chemicals and chemical products	-0.012	0.052***	0.040
		(0.024)	(0.006)	(0.024)
(C17)	Paper and paper products	0.031	-0.003	0.028
		(0.034)	(0.006)	(0.035)
(C13-C15)	Textiles, wearing apparel	-0.021	0.027***	0.006
	and leather products	(0.028)	(0.005)	(0.028)
(D35)	Electricity, gas, steam	-0.111***	0.111***	0.001
	and air conditioning supply	(0.035)	(0.007)	(0.036)
(C21)	Basic pharmaceutical products	-0.077**	0.059***	-0.019
	and pharmaceutical preparations	(0.038)	(0.006)	(0.038)
(C28)	Machinery and equipment n.e.c.	-0.094***	0.061***	-0.033
		(0.021)	(0.005)	(0.021)
(C10-C12)	Food products, beverages	-0.049*	0.008	-0.041
	and tobacco products	(0.026)	(0.005)	(0.026)
(C27)	Electrical equipment	-0.105***	0.040***	-0.065***
		(0.024)	(0.004)	(0.024)
(C25)	Fabricated metal products,	-0.145***	0.077***	-0.068***
	except machinery and equipment	(0.022)	(0.005)	(0.022)
(C16)	Wood, products of wood and cork;	-0.134***	0.044***	-0.090***
	articles of straw and plaiting materials	(0.028)	(0.006)	(0.028)
(C29)	Motor vehicles, trailers	-0.116***	0.026***	-0.090***
	and semi-trailers	(0.029)	(0.005)	(0.030)
(C23)	Other non-metallic mineral products	-0.125***	0.012**	-0.113***
		(0.025)	(0.006)	(0.026)
(C31+C32)	Furniture; other manufacturing	-0.189***	0.068***	-0.121***
		(0.025)	(0.005)	(0.024)
(C26)	Computer, electronic and optical products	-0.116***	-0.009*	-0.126***
		(0.027)	(0.006)	(0.028)
(C22)	Rubber and plastic products	-0.174***	0.029***	-0.145***
		(0.026)	(0.006)	(0.025)

Sectors are shown in descending order of the coefficients on their imports' CO_2 footprint. Each cell is the result of a separate regression of the variable in the uppermost row on differential ETS implementation, trade policy controls (joint FTA, WTO and EU membership), a full set of country by year effects and country-pair effects. The sample is limited to include only observations of the respective industry. Heteroskedasticity-robust standard errors are clustered at the country-pair level (in brackets). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

3.3.1 Carbon leakage in the literature

The results of our analyses are well within the range of conclusions of other analyses in the literature. Zachmann and McWilliams (2020) and Felbermayr and Peterson (2020) review the literature of ex-ante simulation studies and of econometric studies analysing ex-post data and document evidence for carbon leakage in some industries but overall mixed evidence for carbon leakage in response to environmental policies at the aggregate level. Analyses of the EU-ETS, such as for example Naegele and Zaklan (2019), tend to find no or little evidence for carbon leakage. Studies including countries worldwide and more comprehensive environmental regulation policies, such as Aichele and Felbermayr (2015) who analyse carbon leakage resulting from participation in the Kyoto Protocol, tend to find some limited evidence for carbon leakage.

Empirical analysis of ex-post data can, however, only evaluate carbon leakage and the shift of economic activity in response to existing policies. For the assessment of possible effects of a more ambitious climate policy it is therefore also important to consider modelling studies that analyse hypothetical climate policy scenarios with higher carbon prices than observed in ex-post data. The leakage rates found in these studies vary widely and depend on the scenarios considered and the assumptions made. A meta-analysis by Branger and Quirion (2014) of 25 simulation studies dealing with the effects of climate policy measures on carbon leakage summarizes these results in a coherent manner. Their meta study mostly focusses on computable general equilibrium (CGE) models, but they also include some partial equilibrium models. With the help of meta-regressions, they capture the effects of various assumptions in the 25 studies considered, that present a total of 310 estimates of carbon leakage and production relocation. The leakage rates are between 5 % and 25 % (mean: 14 %) without CBA and between -5 % and 15 % (mean 6 %) with CBA. Ceteris paribus, the leakage rate is reduced by 6 percentage points on average by the implementation of CBA. The meta-analysis as well as other studies show that (i) leakage rates decrease with the size of the "coalition of the willing" that implements more ambitious climate policy, that (ii) a more ambitious climate policy e.g. represented by higher CO_2 prices, leads to higher leakage rates, (iii) leakage rates increase for higher substitution elasticities between domestic and foreign products and (iv) the greater the importance of the EITE industries in the status quo.

Partial equilibrium models that consider particularly emission- and trade-intensive (EITE) industries and fix macro aggregates exogenously find higher leakage rates of up to 90 % (Zachmann and McWilliams, 2020). These higher leakage rates may not be reflected in the aggregate general equilibrium numbers, for example due to a low overall importance of those industries. This fact is illustrated by disaggregating economy-wide carbon leakage rates in CGE models. In the CGE simulation of Kuik and Hofkes (2010), for example carbon leakage in the steel industry accounts for about half of economy-wide carbon leakage. All in all, these findings seem to suggest that measures against carbon leakage and the associated shift of value creation should rather be focused on the EITE industries. The share of value added by the EITE industries and the share of emissions from the EITE industries in the total emissions are therefore decisive factors with regard to the design of a carbon adjustment. However, a CBA just for EITE industries could lead to a shift of imports down the value chain towards products intensively using EITE output as intermediate input as has been observed as a result of previous tariffs levied on upstream industries.[20]

Furthermore, in many of the ex-ante simulation studies employing CGE models a second indirect channel of carbon leakage is driving the results (Zachmann and McWilliams, 2020). This second channel works through reductions in international energy prices and is independent of whether territorial emissions or the carbon footprint are priced. The results seem to be similar for the aggregate and the industry level in ex-post as well as ex-ante studies. However, the studies do find relatively higher effects for especially energy-intensive and trade exposed industries. Finally, most studies on carbon leakage do not account for the fact that carbon pricing induces energy-saving technological innovations that can even spill over abroad (Gerlagh and Kuik, 2014). Thus, those models might overestimate carbon leakage.

Overall, the literature on environmental regulation points to other factors outweighing the effects of higher carbon prices or environmental regulations in the location decisions of firms. Dechezleprêtre and Sato (2017) survey the extensive literature on the competitiveness effects of environmental regulation which result from differences in the stringency of environmental regulation between firms, sectors and regions/countries. Overall the literature finds that differences in environmental regulation can "lead to small, statistically significant adverse effects on trade, employment, plant location, and productivity in the short run". They argue however, that the magnitude of the effects seems to be small compared to other factors affecting trade and location decisions such as market access and local human capital. Differential stringency of environmental regulation seems to be an important factor only for some very energy-intensive sectors with limited ability to pass through cost increases to customers.

Empirical Observation 6 *(i) Our analysis of ex post data shows evidence for carbon leakage due to differential ETS coverage in (some) EITE industries, but no clear aggregate effects. Overall, the carbon intensity of imports tends to be slightly higher after the introduction of an ETS. (ii) Modelling studies suggest mild effects for the overall economy. Substantial effects for EITE industries are possible. (iii) Overall, other factors seem to outweigh the location decision of firms.*

4 Pricing the carbon footprint

In the previous section we have presented evidence that carbon leakage in the EU-ETS[21] remained limited so far. However, with more ambitious climate policy, higher CO_2 prices, and fewer free allocations this might change. One possibility to counteract carbon leakage is to price the carbon footprint instead of territorial emissions, as consumption is less mobile than production. Since,

[20] Zachmann and McWilliams (2020) illustrate this point with the example of US steel and aluminum tariffs which substantially reduced steel and aluminum imports but led to an increase in imports of products using steel and aluminum as inputs such as steel nails and aluminum wire.

[21] While the empirical analysis looks at the differential exposure to an ETS in general, the variation that identifies the parameter stems from the introduction of the EU-ETS in 2005 and its expansion to Bulgaria and Romania in 2007, to Norway in 2008 and to Croatia in 2013. While Kazahkstan and New Zealand also introduced an ETS in the period we analyze, neither is included in the World Input Output Database.

as shown in Section 2.1, the carbon footprint is larger than territorial emissions within the EU-ETS, a switch to pricing the footprint will also raise additional revenue for the European budget or other purposes. In the following sections, we discuss various options to price the carbon footprint either for all products or just for the emissions intensive and trade exposed (EITE) industries.

4.1 Two general options to price the carbon footprint

The EU-ETS sets a cap on the quantity of emissions. Within such a system, there are two options to price the carbon footprint within the ETS area: i) a Carbon Border Adjustment (Option "CBA") or ii) a tax on goods proportional to their CO_2 footprint in combination with allocation of free allowances to ensure the quantity target (Option "Tax+Allowances").

Given the EU already implemented the EU-ETS to price territorial CO_2-emissions, adding a CBA mechanism would be the natural extension of the system in order to price the carbon footprint. The basic idea is that importers also need to surrender certificates reflecting the CO_2-content of imported goods and exporters receive certificates to the extent of the CO_2-content of their exports. However, limited CBA mechanisms without the compensation for exports are also discussed, which would price a mixture of carbon footprint and territorial emissions. With a CBA, importing firms would need to purchase emissions certificates to the extent of the CO_2-content of the imported products sold within the EU-ETS area. The carbon content of foreign production would thus be priced similarly to that of domestic production. As the full CBA mechanism (i.e. including the exemption of exports) would establish a level playing field for companies on domestic as well as global markets outside the EU ETS area, the introduction of the CBA would plausibly be associated with an abolishment of the free allocation of allowances (also to comply with the principle of non-discrimination under GATT Art. III). If a CBA, however, would be limited to imports in combination with an abolishment of free allocation of allowances, it would negatively affect the competitiveness of EU-based firms that are exporters and currently receive free allowances in markets outside the EU ETS area. As territorial emissions are lower than the carbon footprint of consumption, the introduction of a CBA would probably need to be accompanied by an adjustment of the total amount of allowances available in the EU-ETS. This has already been discussed at the European level (European Parliament, 2020a). Furthermore, the EU-ETS would not be suited anymore to precisely reach the current emissions reduction targets of the EU, as the emissions covered by the EU-ETS would differ from the basis used in the definiton of those reduction targets.

The introduction of a CBA mechanism is practically challenging. In particular, compatibility with international trade law and potential political trade countermeasures are discussed controversially (Section 5.2). Against this background, an alternative option has been proposed recently: the introduction of a tax proportional to the CO_2-footprint of final and intermediate goods in combination with the allocation of free allowances.[22] The tax would be imposed on all goods from industries which are entitled to receive free allowances, independently of whether they are intermediate or final goods, and both for imported and domestically produced goods. Böhringer et al. (2017) show that such a "Tax + Allowances" mechanism in theory can be designed to be equivalent to a full CBA. However, a range of assumptions, for example regarding the level of the tax, the amount of freely allocated allowances or the treatment of imports and exports, are necessary for the equivalence to hold in the model framework. Especially the very specific assumptions for the level of the tax would practically be incompatible with an emissions trading system where the price is changing continuously and is determined by supply and demand.[23] In order to replicate a full CBA with this mechanism, taxes and the OBR rate would have to be continuously adjusted. Furthermore, the informational requirements for this mechanism might be similar to a full CBA as the carbon footprint would have to be determined for domestically purchased goods and imports, whereas in a full CBA the footprint of imports and exports must be determined.

In practice, the tax would most likely work similarly to the VAT. Tax rates would be set at the product level proportional to a benchmarked CO_2 footprint and be paid by sellers to the tax authority for domestic sales and borne by domestic buyers. Similarly to the process of input tax deduction for VAT, taxes paid on intermediate inputs could be offset when taxes are paid on sales.

An additional consideration for the introduction of a tax alongside OBR stems from the fact that in a system like the EU-ETS in which the amount of free allowances received depends on past output, firms have an incentive to increase production. Böhringer et al. (2017, 2019) discuss this distortion at length and show that OBR are similar to a production subsidy. In the current system this mechanism works over a longer horizon, as currently the amount of free allowances depends on historical production levels which resemble capacity rather than actual production output. Nevertheless, dynamic incentives are present as higher output at the beginning of the trading period leads to more emissions allowances in the future (Section 3.1). Thus, the introduction of a tax has an additional benefit in a system with OBR. By reducing demand for goods that are excessively supplied due to OBRs, the introduction of a tax can be welfare improving (Böhringer et al., 2019).

[22] Böhringer et al. (2019) discuss a version of this mechanism as "smart hedging against carbon leakage". They argue that in order to countervail incentives to increase output associated with output based free allocation of allowances it is optimal to introduce a tax on the final and intermediate goods that receive free allowances irrespective of the origin of these goods. Felbermayr and Peterson (2020) discuss the option to expand free allocation and a tax to all industries in order to replicate the full CBA. A similar design is discussed in Böhringer et al. (2017).

[23] The theoretical framework in Böhringer et al. (2017) models certificates with a fixed price and free allocation of certificates, which means it basically models a carbon tax and a production subsidy that is tied to the tax rate. Thus, in the theoretical model the free allocation has no effect on the price of certificates. However, in the EU-ETS the free allocation affects the price of certificates, pushing it up, as the free allocation pushes the demand curve for certificates up. In the simulated model an ETS like system is modelled by fixing the total amount of emissions and adjusting the tax and subsidy rates until in equilibrium total emissions equal the fixed cap.

4.2 Carbon adjustment for selected sectors

Given the challenge to measure the carbon footprint for all products (Section 5.1), mechanisms with limited “broadness”, i.e. a limited number of industries for which direct emissions are being taken into account, are discussed for both systems, CBA as well as Tax+Allowances. For example, the currently announced plan of the European Commission suggests to start a CBA system with selected industries and to extend the range over time (Von der Leyen, 2019). Droege and Fischer (2020), among others, suggest that a CBA limited to imports in EITE industries most prone to carbon leakage would suffice, as simulation studies indicate that such a design is sufficiently effective in countervailing carbon leakage (Böhringer et al., 2012, 2018). An initial CBA mechanism would in this context apply only to direct emissions from the production of EITE industries' imports. Similarly a tax in an equivalent Tax+Allowances system would only be set for goods from EITE industries and only refer to the direct emissions from the production of these goods. Such a system focusing only on direct emissions in a few sectors, parallel to the EU-ETS, would create a mixture of pricing territorial emissions and carbon footprint.

Let us briefly assess to which extent the CO_2 footprint of imports would then be covered. Direct emissions of the seven most emissions intensive industries account for roughly one quarter of the CO_2 footprint of imports (Section 2.3). In particular emissions from electricity (D35) are not imported directly, but are typically embedded in imported goods. While ultimately about 80 % of emissions embedded in imports originate from one of seven emissions intensive (EI) industries (Figure 8),[24] a large part of emissions are embedded in imports of downstream industries such as "textiles, wearing apparel and leather products" (C13-15), "manufacture of computer, electronic and optical products" (C26), "manufacture of machinery and equipment n.e.c." (C28), "furniture, other manufacturing" (C31_C32) and "motor vehicles, trailers" (C29) (Figure 4). Production of these industries' final output involves complex value chains, which implies substantial complexity in calculating their carbon content. However, as most CO_2 is ultimately emitted in only a few upstream industries, it could be sufficient to track the use of intermediates from these sectors with high direct emissions intensity and price the emissions that ultimately stem from these sectors to cover the bulk of imported emissions.

Tracking carbon emissions from emissions intensive industries along the whole value chain might nonetheless prove to be too complex. An intermediate approach could be to focus on direct intermediate inputs from emissions intensive industries, which together with direct emissions from these industries account for about 45 % of the carbon footprint of imports (Section 2.3). For example, automobile manufacturers would then have to purchase emissions allowances for the emissions occurring in the production of steel or aluminum directly used as an input to automobile production. They would not have to purchase allowances for the emissions occurring in the production of copper that is used in the production of electric wires which are then used as an input in

[24] These industries are mining and quarrying (B), manufacture of coke and refined petroleum products (C19), manufacture of chemicals and chemical products (C20), manufacture of rubber and plastic products (C22), manufacture of other non-metallic mineral products (C23), manufacture of basic metals (C24) and electricity, gas, steam and air conditioning supply (D35).

automobile production. Tracking carbon emissions would thus be limited to one step in the value chain, substantially reducing complexity.

Note that a mechanism that applied only to direct emissions from EITE industries would induce incentives for firms to shift CO_2 imports down the value chain. Such a shift down the value chain will most likely occur in industries that intensively use EITE products as inputs. Those effects cannot be addressed in simulation studies as Böhringer et al. (2012, 2018), since they do not distinguish at which levels of the value chains emissions originating from EITE industries are imported. A shift of imports down the value chain would result if certificates would need to be surrendered or a tax would need to be paid e.g. for the import of steel, but not for products where steel is an input. Then intermediate production steps might be moved abroad and products down the value chain imported.[25] This shift could potentially lead to more carbon leakage and a more substantial relocation of economic activity than without the limited Carbon Adjustment Mechanism. A mechanism that also tracks the carbon content of (direct) intermediate inputs from emissions intensive industries embedded in imports, might have the potential to countervail this effect to a certain extent. The choice regarding the "deepness" i.e. the number of previous steps in the value chain for which direct emissions are taken into account, thus involves a trade-off between increased complexity and reduced relocation and value chain shifting risks. Increasing deepness of the Carbon Adjustment Mechanism likely re-duces relocation risk,[26] while it increases complexity.[27] In the light of those re-location risks, an attractive option may be the announcement of a deepening of the Carbon Adjustment Mechanism over time, where a vagueness on the timeline that will be implemented need not hurt. This is even more true since relocations of value creation steps are medium- to long-term decisions that are on-ly taken if a profit can be expected from them in the long run.

When reducing the broadness of a Carbon Adjustment Mechanism, potentially distortive effects would also need to be considered. If only some industries are reimbursed for their exports in a Carbon Adjustment Mechanism there would be incentives that distort production and CO_2 emissions towards those industries and products.

5 Challenges in implementation

The introduction of a Carbon Adjustment Mechanism is accompanied by various challenges, which also depend on the specific design of the mechanism. The main challenges concern the complexities associated with the measurement

[25]A similar shift of imports down the value chain has been observed as a result of the introduction of tariffs on steel and aluminum imports by the US (Zachmann and McWilliams, 2020).

[26]As noted in section 3.3, other factors besides carbon costs affect the location decision of firms. However, ceteris paribus a higher discrepancy between carbon costs for domestic production and carbon costs for imports increases the relocation risk. The additional amount of the carbon footprint that is covered, and thus the additional reduction in carbon cost differences between domestic production and imports by increasing the deepness of a CBA is decreasing in the deep-ness of the CBA. Thus, the additional reduction in relocation risk is also decreasing.

[27]The added complexity might be reduced by using benchmarks (see section 5.1) for determining the carbon footprint of intermediate inputs at more remote steps of the value chain e.g. intermediate inputs used in the production of intermediate inputs.

and credible identification of the CO_2 footprints of goods and services on the one hand and trade policy concerns on the other. In particular, moving from production-based to consumption- and investment-based pricing involves substantial hurdles with respect to measurement and credible identification of the carbon content of goods and an increased bureaucratic burden. Moreover, details of the implementation may induce different economic incentives for firms, depending on their emissions intensity, their trade intensity and their position in the value chain. Furthermore, as levies on imports in an CBA could be interpreted as illegitimate trade policy measures, the implications for international trade and international relations have to be taken into account when balancing the up- and downsides of different systems.

5.1 Credible identification of carbon footprints and bureaucracy

Any mechanism that goes beyond the coverage of direct emissions involves the measurement of carbon emissions embedded in intermediate inputs used in the production chains of imports. A CBA applied to the full carbon footprint of goods and services would require tracking carbon emissions occurring along the whole value chain i.e. direct emissions occurring in the production of imports, as well as all emissions occurring along the production chains of imported goods and services. For exports, the domestic emissions plus emissions of intermediate products and imports along the value chains would need to be measured. In a Tax+Allowances system, the information for exports would not be necessary, but the CO_2 emissions along the whole value chains of all domestically sold products.

While the average carbon footprint of industries and countries can be calculated using international input output tables and industry level information on carbon emissions, the exact measurement of the carbon footprint is substantially more complex for individual products of individual firms. Complexity arises, among other issues, due to long value chains, international trade of intermediate inputs and various production technologies along value chains.

Tying the amount of emissions allowances to be purchased to the individual carbon footprints of firms' products would require the disclosure of individual importing firms' value chains, the identification of direct emissions at each step of the value chain and their verification by officials which could prove to be a substantial administrative burden. In addition, firms might be reluctant (Zachmann and McWilliams, 2020) or not able[28] to disclose their full value chains. An alternative would be the development of an acknowledged certification system by which individual firms could authorize an independent institution to determine their emissions footprint and require certification of their intermediate suppliers. Either option would, however, prove to be a costly non-tariff barrier and put a burden particularly on smaller firms. Currently several new options based on blockchain technology are explored to track information along value chains. Those technologies could in a medium-term also be used to reduce costs and improve credibility of the measurement of carbon emissions along a product's value chain (Andoni et al., 2019).

[28]In particular more remote steps of the value chain e.g. the intermediate suppliers of their own intermediate suppliers might not be known to firms.

One approach to reduce complexity, particularly for smaller firms, for which the disclosure of individual footprints is too costly, could be the use of benchmarks e.g. the average carbon footprint per Euro production value in the relevant group of firms/products. Coarse benchmarks at the industry-by-country level can be calculated readily from international input output tables. More fine-grained benchmarks at the product-by-country level would be preferable, as they are more targeted, but involve more complexity in their calculation. A Carbon Adjustment Mechanism based on such benchmarks would go some way to reduce price distortions between domestic products and imports.

Absent any mechanism which allows importers to prove a lower emissions intensity than the benchmark, however, importers do not have an incentive to individually lower their emissions intensity as the reduction would not affect the number of allowances that need to be purchased. These incentives could be provided if default benchmarks were combined with an adjustment mechanism by which importers could prove a lower emissions intensity in order to reduce the required number of allowances. A related, more involved adjustment mechanism is discussed by Felbermayr (2019): Starting from a benchmark value, firms who can prove a lower carbon footprint than the benchmark value only have to purchase allowances according to this lower carbon footprint. Their carbon emissions and production value are then removed from the calculation of the benchmark value, resulting in a higher benchmark for all remaining firms. Subsequently additional firms whose carbon footprints are lower than the new benchmark value would have an incentive to disclose their true carbon footprint.

A mechanism limited to selected industries, direct emissions or emissions embedded in direct intermediates only, could substantially reduce the bureaucratic burden. This would for example be achieved by limiting the mechanism to emissions intensive industries where methods to measure direct emissions already exist and which are located upstream in the production network i.e. require only few previous production steps. For these industries direct emissions make up more than 25 % and up to 60 % of the respective carbon footprint, and direct inputs from those emissions intensive sectors an additional 20 % to 30 %. Expanding the Carbon Adjustment Mechanism to sectors which intensively use direct inputs from emissions intensive industries could strike a balance between comprehensive coverage and administrative and measurement burden. Such an approach could, however, potentially lead to the relocation of production steps further down in the value chain. In this regard, the announcement to step by step include further production steps could help (Section 4.2).

An additional suggestion by some authors (e.g. Böhringer et al., 2017) to reduce the administrative burden involved in the calculation of benchmarks at the product level for emissions intensive industries is to use the benchmarks already in place for the free allocation system. For the free allocation system in the EU-ETS however, benchmarks are currently calculated at the production level i.e. they only benchmark the direct emissions of a specific production stage and thus would primarily be feasible for Carbon Adjustment Mechanisms limited to direct emissions in certain industries.

5.2 International trade law and politics

An important argument against introducing a CBA is the potential incompatibility with international trade rules, especially WTO law, and the threat of retaliatory trade measures. A legal or political incompatibility at the international level could trigger trade conflicts and increases uncertainty for investors and companies. Against this background, the European Commission emphasized that the system "should be fully compliant with World Trade Organization rules" (Von der Leyen, 2019). There is a growing literature pointing to a possible legal feasibility of a CBA within WTO law, if the design and implementation satisfies certain requirements (Mehling et al., 2019; Hillman, 2013; Pauwelyn, 2013). Those, however, might contradict some design elements of a theoretically optimal CBA and prove cumbersome upon actual implementation. Furthermore, there might still remain a high degree of uncertainty about the legal feasibility and a wide range of open questions.

It appears unclear if the two basic principles of the WTO "most favoured nation principle" and "national treatment" are compatible with an envisaged CBA. According to the "most favoured nation principle", basically all countries need to be treated similarly. It seems that this could possibly impede that CO_2 levies differ with respect to the CO_2 intensity in the country of origin or make it impossible to account for CO_2 prices already paid in the source country. However, this differentiation would be necessary to induce the intended incentives for other countries to introduce a (more ambitious) carbon pricing. According to the principle of "national treatment", imported products need to be de-facto (not only de-iure) treated as favourably as domestic products. This might possibly result in cumbersome design and administrative challenges. For example it could be required that the price on CO_2 content of imports needed to be equal or lower than the price for domestic products, or that if domestic producers would receive a part of their allowances for free, the same degree of free allowances needed to be granted to importers to have a non-discriminatory system.

Some argue that narrowing down the CBA might improve the chances of it being compatible with WTO law. Those limits might, however, counteract some of the goals of the CBA. For example, a CBA seems to be more likely in line with the WTO Agreement on Subsidies and Countervailing Measures, if only imports were addressed but exports would not benefit from the system, since the exemption of exports under a CBA might qualify as an export subsidy. However, if a CBA did not exempt exports, but at the same time OBRs were abolished, competitiveness of firms located in the EU-ETS area on international markets would decrease as compared to the current system. The WTO rules have an exemption for environmental measures. Narrowing down the CBA only to carbon intensive goods might possibly contribute to CBAs being classified as such a measure. However, as shown above such a system might risk shifting imports into exempted industries .

In general, the legal feasibility and detailed design requirements to comply with WTO or other law is intensively discussed and disputed even among legal experts. However, apart from the specific legal assessment, it also might matter how a Carbon Adjustment Mechanism is perceived by trading partners and whether it triggers retaliatory measures. Retaliation could happen independently of whether the actual implementation is in line with trade law or not. Trading partners could, for example, argue a CBA to be a protectionist tariff, especially if the mechanism did not differentiate between particular countries based on whether a climate protection scheme is in place or not.

Also in the absence of retaliatory actions there might be barriers to trade emerging from the introduction of a Carbon Adjustment Mechanism. The measurement of carbon content could constitute a substantial non-tariff barrier if importing companies need to prove their emissions through the whole value chain. This might be especially problematic for smaller companies.

Overall, trade policy considerations could lead to a preference to build on existing instruments. The free allocation of allowances and national taxes are both already in place in different forms in EU-ETS member countries. Both are therefore likely less prone to get in conflict with trade law or trigger retaliatory measures.

The damage to the European economy already of the threat of retaliation is potentially substantial. Thus, setting up a system that could initiate or intensify trade conflicts might reduce expected value added within the EU-ETS more than a potential relocation of production due to higher CO_2 prices. Policy makers need to carefully balance the risks and it might be appropriate to consider other options which do not involve a shift from production- to consumption/ investment-based pricing, probably based on the currently working mechanism based on the allocation of free allowances, or mechanisms focused on global cooperation described in the following section.

5.3 Emissions reduction worldwide and global cooperation

Carbon emissions intensity is very heterogenous across the world (Figure 14). As the EU accounts for only around 10 % of worldwide emissions, one of the overarching goals of EU climate policy must be to work towards an internationally coordinated approach to reduce emissions. The most effective instrument would be a global price on CO_2 emissions. Steps towards a global price could be the introduction of separate CO_2 prices in different regions worldwide. In the context of global cooperation, a Carbon Adjustment Mechanism could promote or at least facilitate the introduction of carbon pricing in regions outside the EU – if appropriately designed.

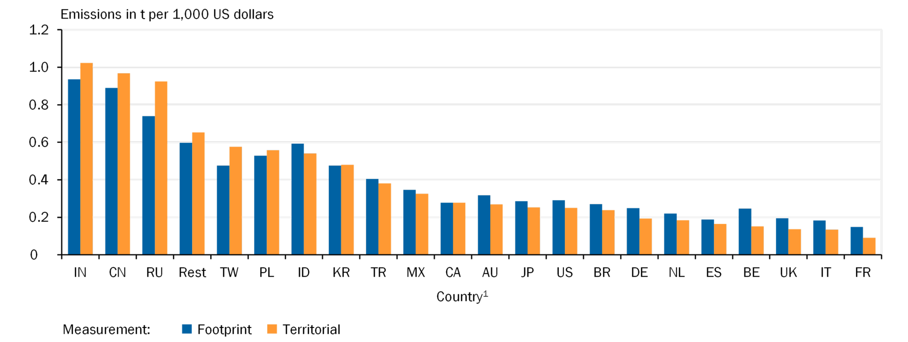
The effect of an introduction of a Carbon Adjustment Mechanism on the introduction of CO_2 prices in other countries crucially depends on the possibility to differentiate between countries with different CO_2 price levels within the Carbon Adjustment Mechanism, i.e. to take into account whether there is a comparable CO_2 pricing regime in a particular foreign country or not. However, as described above this might be legally challenging.

If the Carbon Adjustment Mechanism needed to be ignorant of whether a foreign country had an own CO_2 pricing scheme or not, companies in a foreign country with CO_2 pricing would need to pay twice for CO_2 emissions (if exports from the respective country are not exempted) and thus be in a less favourable position than companies from countries without CO_2 pricing. This makes it less attractive for countries outside the EU to introduce an own carbon pricing scheme. Thus, regarding a contribution to worldwide climate cooperation, the possibility to condition the CO_2 price charged based on climate policies established in the source countries is key.

If the Carbon Adjustment Mechanism would be able to discriminate between imports from different countries, the question arises how to measure the ambition of a country's climate policy. In the easiest case, if another region also introduced an ETS covering the same sectors as the EU-ETS, one could

Figure 14

Emissions intensity by country in 2014



1 – IN-India, CN-China, RU-Russian Federation, Rest-Rest of the world, TW-Taiwan, PL-Poland, ID-Indonesia, KR-Republic of Korea, TR-Turkey, MX-Mexico, CA-Canada, AU-Australia, JP-Japan, US-United States, BR-Brazil, DE-Germany, NL-Netherlands, ES-Spain, BE-Belgium, UK-United Kingdom, IT-Italy, FR-France.

Sources: Corsatea et al. (2019), World Input-Output Database 2014, own calculations

calculate the difference in CO_2-prices. However, in practice, countries choose very different climate policy approaches, with and without pricing emissions in various sectors and in various ways. Finding a robust methodology to measure climate policy ambition across countries might thus be difficult (Cosbey et al., 2019).

Assuming the measurement would be possible, both, a CBA and a Tax+Allowances scheme could take differences in CO_2-prices into account. In case of CBA the amount of certificates an importer needed to surrender would vary with the country of origin and the amount of certificates a exporter received would depend on the destination country. In case of Tax+Allowances, the tax would need to vary depending on where the product is produced and in which countries the links of the value chain were located. If exact measurement would be feasible, payments could be tied to CO_2 footprints directly and CO_2-prices paid abroad could be offset.

In this case, companies from countries which introduced CO_2-prices or increased them would not be in a worse position. Such a system would eliminate one disincentive for the introduction of carbon pricing. Domestic companies, companies from countries with CO_2-pricing and companies from countries without CO_2-pricing would all face the same carbon price for selling products within the EU-ETS.

Even in case measurement of carbon footprint was not possible at the product level, the Carbon Adjustment Mechanism could provide incentives for foreign companies to reduce their emissions intensity, either by giving companies the opportunity to prove that their emissions are lower than the benchmark and then setting a lower carbon content for those importers (Section 5.1).

Finally, it may be attractive to combine the idea of a Climate Club (Nordhaus, 2015) with a Carbon Adjustment Mechanism. Climate Clubs are a group of countries with climate policies that are agreed to have comparable ambition. Vis-à-vis non-member states, countries within the club set no bilateral adjustments of CO_2-prices but a common (possibly quite high) CO_2-price, in order to "punish" the absence of climate policy measures. Within a Climate Club, no Carbon Adjustment Mechanism would be necessary. However WTO compatibility of such clubs is even more unlikely than in the case of Carbon Adjustment Mechanisms (Pauwelyn and Kleimann, 2020) as they are based on plain tariffs.

In contrast to Climate Clubs a Carbon Adjustment Mechanism would not actually "punish" countries which do not introduce a CO_2 pricing scheme, but rather treat them equally as domestic companies. When it comes to connecting the regions where carbon pricing exists, however, the idea of climate clubs could lead the way. While it is unlikely to achieve similar ambition levels among a large number of various emission intensive economies worldwide on ambitious timelines, it may be feasible to proceed stepwise. Countries that want to cooperate and pool their ambitions could first agree on a common joint minimum CO_2 price on carbon emissions, but in return renounce internal carbon adjustments within their "Climate Club". At the external borders with states outside the Climate Club, a Carbon Adjustment Mechanism could be implemented. In this way, the convergence towards similar ambitions within the Climate Club could be combined with a solution for carbon adjustments at the borders with non-members. This way the original idea of "Climate Clubs" could be moved towards a more likely compatibility with WTO law. Countries outside the club would have an incentive to join the climate club, since they could then benefit from lower bureacratic burden and non-tariff barriers as well as shifting the revenues from pricing CO_2 embedded in traded goods from the budget of the Climate Club into the own budget. In addition, if the area of the Climate Club was a net CO_2 importer, revenues from carbon adjustments could be used to offer incentives to countries outside the club to reduce their emissions and join the Climate Club.

6 Conclusions

In this article, we discuss current proposals on Carbon Adjustment Mechanisms in the light of the current literature as well as own empirical findings based on historical data on carbon emissions in Europe and worldwide.

In an extensive empirical analysis we first shed light on the differences between territorial emissions and the CO_2 footprint in the EU-ETS area as compared to other countries worldwide. While the EU is a net importer of emissions, countries like China, Russia or India are net CO_2 exporters. A detailed analysis at the industry level yields that across almost all industries, the CO_2 intensity of imports to the EU-ETS area is higher than the CO_2 intensity of exports. As it turns out, this largely explains the overall higher CO_2 intensity of imports. We then particularly focus on emission intensive and trade exposed industries, due to their important role in the context of carbon leakage and carbon adjustments. The four industries that are potentially most exposed to carbon leakage account for 22,5 % of total emissions (excluding emissions from households) in the EU-ETS area, but only for 2.6 % of value added. With respect to CO_2 imports, we show that seven emissions intensive industries directly account for 20 % of imported emissions. Taking into account the entire value chains of imports, 80 % of emissions embedded in imports ultimately originate from those seven emissions intensive industries.

In a second step, we provide an overview of how the EU tried to prevent carbon leakage so far. We review the past practice of allocating free allowances to carbon intensive and trade exposed industries, among others. We show that a small number of industries received and still receive the bulk of free allowances. Within the industry sector, the largest share is allocated to the production of pig iron and steel, to coking plants and oil processing, to the production of cement and the chemical industry. In the past, the amount of free allowances assigned to a country and industry deviated from the verified emissions. Over the years, this difference was reduced and today, most countries and industries receive fewer allowances than their verified emissions. Based on data from the World Input-Output Database and the World Bank Carbon Pricing Dashboard we provide an empirical analysis in order to quantify historical carbon leakage. Our analysis shows evidence for carbon leakage due to differential ETS coverage in (some) emission intensive and trade exposed industries, but no clear aggregate effects. Overall, the carbon intensity of imports tends to be slightly higher after the introduction of an ETS. We also place our analysis in the literature and discuss results of some modelling studies, which suggest mild effects for the overall economy, but also show that substantial effects for emission intensive and trade exposed industries are possible. Overall, other factors may well outweigh the location decision of firms, such as market access and local human capital (Dechezleprêtre and Sato, 2017).

Based on the empirical insights and the current literature, we discuss various options to design a Carbon Adjustment Mechanism that allows to (partially) price the carbon footprint instead of territorial emissions. In particular, we discuss CBAs as well as a tax on final and intermediate demand tied to the carbon footprint of goods and services, in combination with free allowances. We argue that a focus on selected emission intensive industries could balance excessive bureaucratic burden and mitigation of carbon leakage in case a Carbon Adjustment Mechanism is to be implemented. However, there may be serious concerns in case of only aiming at direct imports from emission-intensive industries, as such an approach could lead to a relocation of downstream value creation stages abroad. On top of this, direct imports from emissions intensive industries account for only 20 % of imported CO_2 emissions. If emissions from emissions intensive industries that are embedded in final and intermediate products were also included, the Carbon Adjustment Mechanism would capture 80 % of imported emissions instead. Since the measurement of CO_2 emissions along the value chains is still likely to be a challenge in the near future, a step-by-step approach would be advisable. It is conceivable to start with a coverage of direct imports of emissions intensive industries or direct imports as well as direct emissions of intermediate inputs directly sourced from one of those industries with the highest carbon emissions. In order to prevent relocation of more downstream production stages in the future, the prospective inclusion of further more upstream stages in the value chain should be announced at an early stage. Technological progress will very likely make the implementation of more comprehensive coverage possible in the future.

Implementing a Carbon Adjustment Mechanism also comes with legal challenges. In particular, compliance with international trade law is critical. Even in the case of compatibility with WTO rules, however, the implementation of a Carbon Adjustment Mechanism could be interpreted by trading partners as the establishment of trade barriers and therefore trigger retaliatory measures accordingly. Against this background, it could be preferable to implement a Carbon Adjustment Mechanism not unilaterally, but to strive for a joint approach with important trading partners. One possibility would be to link the idea of a "cooperation of the willing" in a Climate Club (Nordhaus, 2015) with Carbon Adjustment Mechanisms. Countries cooperating in the Climate Club could, even if initially there are different levels of ambition in climate policy, agree on a common minimum price on carbon emissions and then no carbon adjustment would be necessary within the Club. In the external relationships with third countries, however, Carbon Adjustment Mechanisms could be used at the individual borders.

References

Aichele, R. and G. Felbermayr (2015): "Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade," *Review of Economics and Statistics*, 97, 104–115.

Andoni, M., V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. McCallum, and A. Peacock (2019): "Blockchain Technology in the Energy Sector: A Systematic Review of Challenges and Opportunities," *Renewable and Sustainable Energy Reviews*, 100, 143–174.

BMU (2018): "Die Reform des EU-Emissionshandels für die 4. Handelsperiode," Tech. rep., Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit.

Böhringer, C., E. J. Balistreri, and T. F. Rutherford (2012): "The role of border carbon adjustment in unilateral climate policy: Overview of an Energy Modeling Forum study (EMF 29)," *Energy Economics*, 34, S97–S110.

Böhringer, C., J. C. Carbone, and T. F. Rutherford (2018): "Embodied carbon tariffs," *The Scandinavian Journal of Economics*, 120, 183–210.

Böhringer, C., K. E. Rosendahl, and H. B. Storrøsten (2017): "Robust policies to mitigate carbon leakage," *Journal of Public Economics*, 149, 35–46.

——— (2019): "Smart hedging against carbon leakage," CESifo Working Paper 7519.

Branger, F., J.-P. Ponssard, O. Sartor, and M. Sato (2015): "EU ETS, free allocations, and activity level thresholds: the devil lies in the details," *Journal of the Association of Environmental and Resource Economists*, 2, 401–437.

Branger, F. and P. Quirion (2014): "Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies," *Ecological Economics*, 99, 29–39.

Corsatea, T. D., S. Lindner, I. Arto, M. V. Roman, J. M. Rueda-Cantuche, A. V. Afonso, A. F. Amores, and F. Neuwahl (2019): "World Input-Output Database Environmental Accounts. Update 2000-2016," Tech. rep.

Cosbey, A., S. Droege, C. Fischer, and C. Munnings (2019): "Developing guidance for implementing border carbon adjustments: Lessons, cautions, and research needs from the literature," *Review of Environmental Economics and Policy*, 13, 3–22.

Cramton, P., A. Ockenfels, and S. Stoft (2017): *An International Carbon-Price Commitment Promotes Cooperation*, chap. 12, 221–241.

Dechezleprêtre, A. and M. Sato (2017): "The impacts of environmental regulations on competitiveness," *Review of Environmental Economics and Policy*, 11, 183–206.

Droege, S. and C. Fischer (2020): "Pricing Carbon at the Border: Key Questions for the EU," *ifo DICE Report*, 18, 30–34.

European Commission (2015): "EU ETS Handbook," Tech. rep.

——— (2020): "EU Green Deal (carbon border adjustment mechanism)," https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12228-Carbon-Border-Adjustment-Mechanism, accessed: 2020-12-15.

European Parliament (2020a): "Opinion of the Committee on Economic and Monetary Affairs for the Committee on the Environment, Public Health and Food Safety towards a WTO-compatible EU carbon border adjustment mechanism (2020/2043(INI))," Opinion, European Parliament, Committee on Economic and Monetary Affairs, version from 11.12.2020.

——— (2020b): "Towards a WTO-compatible EU carbon border adjustment mechanism (2020/2043(INI))," Draft report, European Parliament, Committee on the Environment, Public Health and Food Safety, version from 07.10.2020.

Felbermayr, G. (2019): "Grenzausgleich: Für Klima und Wirtschaft," Kiel Focus 11/2019, ifw Kiel.

Felbermayr, G. and S. Peterson (2020): "Economic assessment of Carbon Leakage and Carbon Border Adjustment," Briefing for the inta committee.

GCEE (2019): "Dealing with Structural Change," Annual report 2019/20, German Council of Economic Experts.

——— (2020): "Overcoming the Coronavirus Crisis Together; Strengthening Resilience and Growth," Annual report 2020/21, German Council of Economic Experts.

Gerlagh, R. and O. Kuik (2014): "Spill or leak? Carbon leakage with international technology spillovers: A CGE analysis," *Energy Economics*, 45, 381–388.

Head, K., T. Mayer, et al. (2013): "Gravity equations: Toolkit, cookbook, workhorse," *Handbook of international economics*, 4, 131–195.

Hillman, J. (2013): "Changing Climate for Carbon Taxes: Who's Afraid of the WTO?'(2013)," The gmf climate and energy policy paper series, German Marshall Fund.

IAEA (2020): "Nuclear Share of Electricity Generation in 2019," https://pris.iaea.org/PRIS/WorldStatistics/NuclearShareofElectricityGeneration.aspx, accessed: 2020-12-15.

Ismer, R., K. Neuhoff, and A. Pirlot (2020): "Border Carbon Adjustments and Alternative Measures for the EU ETS: An Evaluation," Diw berlin discussion paper no. 1855.

Kuik, O. and M. Hofkes (2010): "Border adjustment for European emissions trading: Competitiveness and carbon leakage," *Energy policy*, 38, 1741–1748.

MacKay, D. J., P. Cramton, A. Ockenfels, and S. Stoft (2015): "Price carbon—I will if you will," *Nature*, 526, 315–316.

Martin, R., M. Muûls, L. B. De Preux, and U. J. Wagner (2014): "Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme," *American Economic Review*, 104, 2482–2508.

Mehling, M. A., H. van Asselt, K. Das, S. Droege, and C. Verkuijl (2019): "Designing border carbon adjustments for enhanced climate action," *American Journal of International Law*, 113, 433–481.

Naegele, H. and A. Zaklan (2019): "Does the EU ETS cause carbon leakage in European manufacturing?" *Journal of Environmental Economics and Management*, 93, 125–147.

Nordhaus, W. (2015): "Climate clubs: Overcoming free-riding in international climate policy," *American Economic Review*, 105, 1339–70.

OECD (2019): "Guide to OECD's Trade in Value Added (TiVA) Indicators, 2018 edition," Tech. rep.

Pauwelyn, J. (2013): "Carbon leakage measures and border tax adjustments under WTO law," in *Research handbook on Environment, Health and the WTO*, Edward Elgar Publishing.

Pauwelyn, J. and D. Kleimann (2020): "Trade Related Aspects of a Carbon Border Adjustment Mechanism. A Legal Assessment," Briefing for the inta committee.

Timmer, M. P., E. Dietzenbacher, B. Los, R. Stehrer, and G. J. De Vries (2015): "An illustrated user guide to the world input–output database: the case of global automotive production," *Review of International Economics*, 23, 575–605.

Von der Leyen, U. (2019): *A Union that Strives for More: My Agenda for Europe: Political Guidelines for the Next European Commission 2019-2024*, Publications Office of the European Union.

World Bank (2020): "Carbon Pricing Dashboard," https://carbonpricingdashboard.worldbank.org/, accessed: 2020-12-15.

Zachmann, G. and B. McWilliams (2020): "A European carbon border tax: much pain, little gain," Tech. rep., Bruegel.

Appendix

A.1 Direct and embedded emissions – Data and Methodology

Data on the input-output structure and value added are taken from the World Input-Output Database (Timmer et al., 2015). This database contains harmonized input-output tables for 44 countries[29] and 56 industries for the years 2000 to 2014. Carbon emissions data are taken from Corsatea et al. (2019) who constructed environmental accounts for the World Input-Output Database for the years 2000 to 2016.

Data on carbon pricing are taken from the World Bank Carbon Pricing Dashboard (World Bank, 2020) and the EUTL emissions registry. The World Bank provides data on emissions trading systems and carbon taxes around the world. Data on trade policy is taken from the CEPII gravity equation database containing country-pair by year data on joint membership in free trade agreements, the WTO and regional trade agreements (Head et al., 2013).

The emissions along the value chain that are induced by final demand for an industry's goods can be determined using input output analysis in combination with data on industry level emissions intensity. Using data from the World Input Output Database we can calculate the Leontief matrix whose entries $L^{c,i}_{d,j}$ for each industry i from each country c provide the total direct and indirect inputs required from industry j from country d along the whole value chain in order to produce one USD worth of final output. These data can be combined with direct emissions data for each of the country-industry pairs (d, j) to calculate total emissions embedded in the production of country-industry (c, i). Using the direct emissions data and data on total output of each country-industry pair (d, j) we can calculate the emissions intensity $e_{d,j}$ in tonnes per million USD of output for each pair. Multiplying these emissions intensities with the required inputs from sector (d, j) for producing one million dollars of final output of sector (c, i) and summing over all input sectors (d, j) gives total emissions embedded in one million USD of final output of sector (c, i).

$$EmbEm_{(c,i)} = \sum_{d \in C} \sum_{j \in I} L^{c,i}_{d,j} \cdot e_{d,j} \tag{4}$$

Embedded emissions usually differ from direct emissions by a substantial amount. Direct emissions of industries which produce mainly intermediate goods are higher than emissions embedded in final demand for their goods. Industries belonging to this group are electricity production, production of chemicals or production of basic metals. Industries which require many are more downstream, i.e. use many intermediate goods, and produce mainly for final use such as car manufacturing or construction, or which produces mainly

[29] 43 individual countries and the "rest of the world" as an aggregate.

investment goods, exhibit much higher embedded emissions than direct emissions. Construction for example uses intermediates such as concrete and steel sourced from industries with very high direct emissions.

While total embedded emissions might just be low due to final demand only being a small fraction of total output, we can also compare the respective emissions measures in relation to a suitable output measure. The direct emissions capture the amount of CO_2 that is emitted by an industry directly in the production process. The suitable output measure is the value that is added by the industry directly in the production process i.e. the value added. Consequently, the direct emissions intensity is given by tons of CO_2 per thousand USD of industry value added. Embedded emissions capture all the CO_2 that is emitted by the industry itself as well as by intermediate producers in order to produce an industry's final demand. So, the suitable output measure related to embedded emissions is the value of final demand. Thus, embedded emissions intensity is measured in tons of CO_2 per thousand USD of industry final demand.

A.2 Supplemental Graphs

Figure A.1

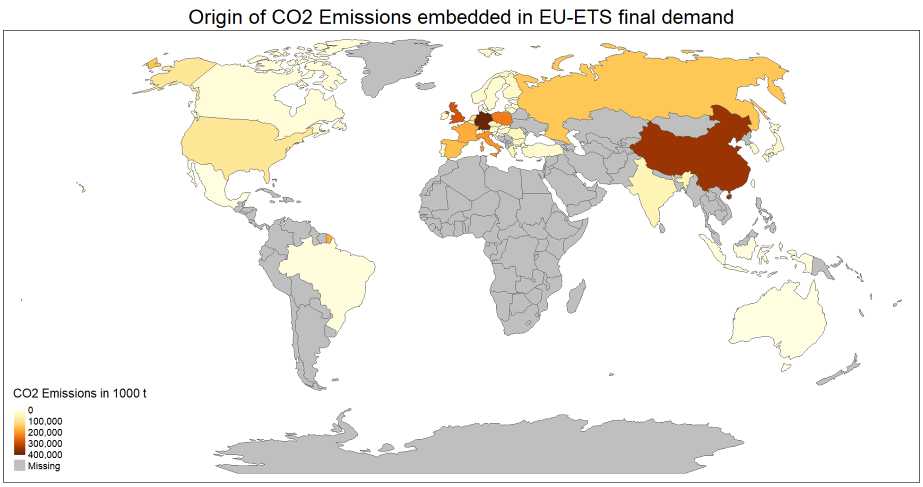
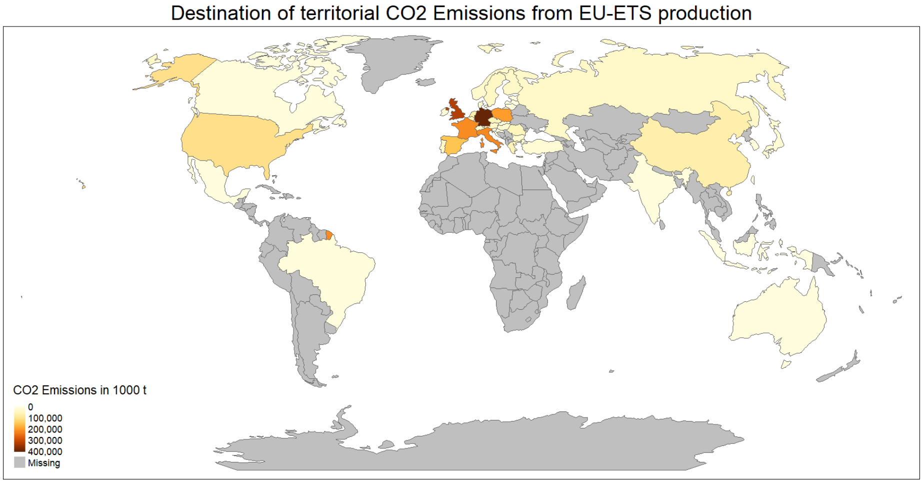


Figure A.2


Destination of territorial CO2 Emissions from EU-ETS production
CO2 Emissions in 1000 t
0
100,000
200,000
300,000
400,000
Missing

A.3 Supplemental Tables

Table A.1: Distribution of difference between freely allocated allowances and verified emissions by installation

Main Activity Code	Description	n (%)	Sum	Mean	Median	< 0 (%)	> 0 (%)	-30 (%)	30 (%)
10	Aircraft operator activities	3.3	-2621	-8.4	-0.8	79.5	20.5	25	1.3
20	Combustion of fuels	57.5	-43131	-7.8	-3.6	74.2	24.3	18.2	1.9
21	Refining of mineral oil	1.3	-2268	-18.7	-30	83.5	15.7	63.6	5
22	Production of coke	0.2	112	6.6	11.8	41.2	58.8	17.7	41.2
24	Production of pig iron or steel	2.2	198	1	0.3	46.2	52.4	11.1	14.9
25	Production or processing of ferrous metals	2.4	-294	-1.3	-0.8	54.9	45.1	5.2	2.2
29	Production of cement clinker	2.3	-703	-3.2	-6.9	54.7	45.3	44	32.3
30	Production of lime, or calcination of dolomite/magnesite	2.8	-1030	-3.9	-3.7	58.3	40.2	18.2	9.1
31	Manufacture of glass	3.5	-3291	-10	-7.6	82.4	17.3	12.1	0.3
32	Manufacture of ceramics	8.7	-1301	-1.6	-0.6	56.2	42.4	1.6	0
35	Production of pulp	1.7	318	1.9	-0.7	53.9	45.5	9.1	17.6
36	Production of paper or cardboard	5.5	-556	-1.1	-2.1	60.7	38.2	11.9	15.7
Aluminum	26,27	0.6	-654	-10.7	-7.7	86.9	13.1	32.8	8.2
Chemicals	38,39,40,41,42,43 4.3	794	1.9	1.7	43.5	56	20.1	23.7	
Others	1,6,8,23,28,33,34,37,44,99	3.7	-1085	-3.1	-0.2	63.7	31.2	9.6	6.2
Total		100				68.4	30.2	16.8	5.1

Notes: EUTL converted to the new names (based on EAA table). All installation which have NA in allowances allocation or verified emissions ignored and only rows which have values for verified emissions (46% of dataset is remaining: 153554 installations). Only 2013 (10773) and 2019 (9564). Outliers above 30 and below -30 cut off and counted in respective columns as -30 and 30.

Table A.2: Share of value added (VA) covered by carbon leakage lists (CL) accross industries

NACE industry	Share of value added (%)	Share of VA mentioned on CL 1	Share of VA mentioned on CL 2	Share of free allowances allocated due to CL 2
Mining of coal and lignite	0.35	79.14	79.14	100
Extraction of crude petroleum and natural gas	1.14	100.00	100.00	100
Mining of metal ores	0.05	100.00	100.00	99.1
Other mining and quarrying	0.51	88.95	60.21	81
Mining support service activities	0.29	100.00	0.00	0.0
Manufacture of food products	7.67	29.76	37.31	93.5
Manufacture of beverages	2.06	45.49	45.49	53.2
Manufacture of tobacco products	0.27	0.00	0.00	0.0
Manufacture of textiles	1.04	100.00	100.00	100
Manufacture of wearing apparel	0.84	100.00	100.00	100
Manufacture of leather and related products	0.66	100.00	100.00	100
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	1.50	47.75	8.63	1.6
Manufacture of paper and paper products	2.08	63.76	40.40	96.8
Printing and reproduction of recorded media	1.29	0.00	0.00	0.0
Manufacture of coke and refined petroleum products	1.48	100.00	100.00	100
Manufacture of chemicals and chemical products	6.14	95.39	93.67	99.8
Manufacture of basic pharmaceutical products and pharmaceutical preparations	4.47	100.00	100.00	100
Manufacture of rubber and plastic products	3.76	61.03	14.16	87.2
Manufacture of other non-metallic mineral products	3.01	49.18	64.45	100
Manufacture of basic metals	2.96	88.86	88.86	100
Manufacture of fabricated metal products, except machinery and equipment	7.73	28.13	38.85	73
Manufacture of computer, electronic and optical products	3.46	100.00	100.00	100
Manufacture of electrical equipment	4.17	98.37	100.00	100
Manufacture of machinery and equipment n.e.c.	9.64	100.00	100.00	100
Manufacture of motor vehicles, trailers and semi-trailers	9.51	4.59	68.57	94.3
Manufacture of other transport equipment	3.21	100.00	88.47	98.6
Manufacture of furniture	1.48	24.36	54.92	
Other manufacturing	2.06	100.00	100.00	100
Repair and installation of machinery and equipment	2.77	100.00	0.00	
Electricity, gas, steam and air conditioning supply	9.54	0.00	0.00	
Water collection, treatment and supply	1.57	0.00	0.00	
Sewerage	0.74	0.00	0.00	
Waste collection, treatment and disposal activities; materials recovery	2.45	33.96	0.00	
Remediation activities and other waste management services	0.09	0.00	0.00	
Total	100.00	57.28	58.41	72.6

Notes: Before the matching process: NACE-Codes for the list of the period 2013-2014 were recoded to NACE Rev. 2, in Carbon-Leakage lists the Prodcom-Codes were converted to NACE Rev. 2 Codes (4-digit) and letter codes were added. In the matching process of the two datasets, a dummy variable was created for each period of the carbon-leakage lists, which is one if the 4-digit NACE Code is part of the list, and zero if not. GVA was calculated for each sector at 2-digit-NACE-level. The last column was calculated using the official EU data (EUTL) and a table from CADMUS for the recoding to match each installation with a 4digit Nace code. Then using the carbon leakage lists (source: EU), each installation was given a carbon leakage list dummy.