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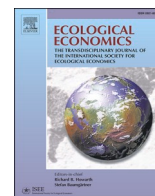
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ANALYSIS

Carbon pricing of basic materials: Incentives and risks for the value chain and consumers

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ABSTRACT

Different options for a reform of the EU Emissions Trading System are discussed to ensure carbon price incentives for mitigation options in the basic materials sector, while minimizing carbon leakage risks. This paper quantifies carbon leakage risks, distributional implications, and additional revenues associated with an import-only border carbon adjustment (BCA), a symmetric (import and export) BCA, and an excise for embodied emissions at a fixed benchmark level in combination with continued free allocation. We estimate the product-level carbon intensities for 4400 commodity groups, compute maximal implied price changes due to full carbon pricing, and calculate cost increases relative to gross value added to assess the scale of carbon leakage risks. We show, first, that around 10% of EU exports and 5% of all domestic manufacturing sales meet the criteria for carbon leakage risk under an incomplete BCA at a carbon price of 30 EUR/t. Second, the distributional implications of consistent carbon pricing of basic materials are small and progressive. Finally, an excise could generate revenues of around 20 billion euros that may be used towards climate action. Our results on potential carbon leakage risks and their mitigation can inform responsible policy making to shape the EU pathway towards climate neutrality.

1. Introduction

The European Union (EU) envisages a shift to climate neutrality by mid-century. This will require the decarbonisation of production of basic materials such as cement, steel, and aluminium, which accounts for around 25% of global CO₂ emissions (IEA, 2017). Decarbonisation will require not only a shift to climate neutral production processes for primary materials (Davis et al., 2018) but also a more efficient material use, substitution with alternative lower carbon materials, and enhanced recycling.¹

To realize this portfolio of mitigation options, a package of policy instruments is being discussed (Climate Strategies, 2019), and effective carbon pricing is considered an important element to cover incremental costs of climate neutral production technologies, as well as to provide financial incentives for the various demand side mitigation opportunities (Goulder and Parry, 2008; Bertram et al., 2015; Stiglitz et al., 2017; Climate Strategies, 2019).

Carbon pricing schemes need to meet two criteria to support the transition to climate neutrality of basic materials: First, carbon costs need to be reflected along the value chain to incentivise the various mitigation options and to ensure incremental costs of climate neutral options can be recovered by producers. Second, concerns about carbon leakage need to be addressed. Carbon pricing could result in carbon leakage if higher domestic carbon costs lead to a replacement of domestic production and emissions with foreign production and emissions. Concerns about carbon leakage can erode the economic and environmental case, as well as political support for carbon price levels necessary to effectively contribute to the transition to climate neutrality.

Historically, carbon leakage risks have been successfully addressed with free allocation of allowances to the energy intensive and trade-exposed (EITE) producers of steel, cement, aluminium, or plastics (Martin et al., 2014; Sato et al., 2015; Branger et al., 2016; Naegele and Zaklan, 2019). However, as a result of international tradability of materials and free allocation, only a fraction of the carbon costs is passed on

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along the value chain to basic material products, components and final products and the incentives for material and energy efficiency or fuel shift at the producers' side are muted (Branger et al., 2015; de Bruyn et al., 2015; Martin et al., 2016; Neuhoff and Ritz, 2019). Therefore, with the current exceptions, carbon pricing fails to provide effective incentives for a transition to climate neutrality.

A variety of options for reforming the European Union Emissions Trading System (EU ETS) are being discussed to resolve the trade-off between consistent carbon pricing (i.e. reflecting embedded emissions of a material or product in its price) and the environmental, economic and political objective of avoiding carbon leakage. These options include border carbon adjustments (BCAs) as an alternative to free allocation, or combining continued free allocation with excise type charge (for an overview of the literature and different policies see de Cendra, 2006; Branger and Quirion, 2014; Böhringer et al., 2017; Cosbey et al., 2019; Felbermayr and Peterson, 2020).

Substantial existing literature has attempted to quantify the effects of these instruments on carbon leakage risks for basic material producers, including indicators such as leakage ratio and its change,² as well as EITE industry output change. These studies typically apply computable general (market) equilibrium (CGE) models with energy-economic constraints, often based on the GTAP database of trade-linked social accounting matrices (Branger and Quirion, 2014; Dong and Walley, 2012). Branger and Quirion (2014) conduct a meta-regression analysis, finding that all other parameters being constant, BCAs reduce leakage ratio by 6 percentage points. The evidence on carbon leakage in EITE industries is less conclusive in research applying econometric models. Branger et al. (2016) find no significant short-term effect of the carbon price on net imports of steel and cement and conclude that there is no evidence of carbon leakage in these sectors. Additionally, Fischer and Fox (2018), who estimate import substitution elasticities and trade intensity to help identify sectors at risk for carbon leakage for 30 EITE/basic material production sectors, do not find any EITE sectors with a high trade intensity but a very low import vulnerability.

However, apart from the leakage risk exposure for EITE industries, the existing literature typically does not look at implications of a border carbon adjustment substituting free allowance allocation for the (downstream) manufacturing sector. If carbon costs were fully internalised in basic materials and basic material products sold in the EU due to the combination of full auctioning and BCAs applied only to imports of basic materials and basic material products, then domestic production of components and final products would be exposed to carbon costs in input prices that may not be present to international competitors. Due to the high diversity of the manufacturing sectors regarding their use of basic materials and the share of value added in manufacturing, an analysis with high product resolution is needed to accurately quantify the implications of carbon pricing of materials, trade intensity, and carbon leakage exposure. At the EU level, the PRODCOM database of production and trade (Eurostat, 2020) contains data for around 2000 commodity groups with a material content of more than 50% of cement steel, aluminium, or plastics. For such a high commodity resolution, modelling approaches like CGE are not applicable. Hence, the consequences of a carbon pricing of basic materials that propagates along the value chain for key variables such as carbon leakage risks or distributional implications on household consumption are thus far not well understood at this high level of commodity detail.

This study contributes to the literature by quantifying the effect of consistent industry-wide carbon pricing in the European Union on the following salient economic indicators: (i) price changes of goods, (ii) carbon leakage risks as a result of the price changes of goods along the

² The leakage ratio is defined as the model-calculated emission variation in the rest of the world (no additional climate policy) divided by the emission variation in the climate-policy regime between the climate policy scenario and the counterfactual business-as-usual scenario (Branger and Quirion, 2014).

value chain (including downstream production) and in export markets (proxied by the carbon cost increases in the EU compared to firms in territories without a carbon price relative to value added), (iii) distributional effects among final consumers, and (iv) expected revenues that may be available to support climate action.

We quantify these indicators focussing on the three BCA design options characterized by Ismer et al. (2020), namely, a border carbon adjustment on imports only, with limited coverage of the value chain (Option I), a symmetric (import and export) BCA with a reimbursement for exports and a more extensive coverage of the value chain (Option II), and an excise duty (also labelled climate contribution, Option III). We assume that free allocation of allowances is abolished under Options I and II, such that full carbon cost pass-through is achieved. Under Option III, free allocation is granted to conventional production processes of basic materials in proportion to production volume and the benchmark of conventional processes to avoid double charging from acquiring EU ETS allowances and the excise charge (Ismer et al., 2021).³

We study six key basic materials that could be covered by a BCA or excise, namely cement, steel, aluminium, plastics, pulp and paper. We calculate embodied emissions of each of these materials in around 4400 manufacturing commodity groups. This allows us to calculate product-level price increases due to consistent carbon pricing. We report price increases for four different product categories, namely, basic materials, basic material products, components, and final goods.

To identify which industrial activities may be exposed to a risk of carbon leakage under an incomplete BCA without free allocation, we compute the ratio of carbon costs relative to gross value added (GVA) for 4400 product categories along the value chain. We thus apply the indicator used to assess carbon leakage risk under the EU ETS until 2020 for primary material producers (Directive 2003/87/EC, see Sato et al., 2015) also to basic material products, components and final products. In line with the threshold defined in the EU ETS Directive until 2020, we consider product categories potentially at risk of carbon leakage, where carbon costs relative to GVA exceeds 5%. We also take into account the second indicator under the EU ETS Directive in our analysis, namely a trade intensity (value of imports and exports, divided by the EU market size) of at least 10%.

For an import-only BCA in combination with full auctioning, we find that almost 10% of EU exports meet the criteria for risk of carbon leakage at a carbon price of 30 EUR/t. Moreover, we add to the existing literature by identifying that also components and final products meet the criteria for carbon leakage risk in border carbon adjustments mechanisms that only cover basic materials and basic material products. For a BCA that does not extend to components and final products, we find that 5% of overall sales of EU manufacturing meet the criteria for carbon leakage.

We show that the distributional consequences of consistent carbon pricing for basic material production are limited and progressive. Using German household expenditure data, we estimate consumers to spend below 0.2% of total disposable income at a carbon price of 30 EUR/t, with the share slightly increasing by income decile. Finally, we estimate revenues from a BCA or excise that may be available to support for example climate action. They are substantial even at relatively moderate carbon costs of 30 EUR/t. The excise duty (climate contribution, Option III) has the highest overall revenues. An import-only BCA

³ Free allowance allocation would be done at a benchmark based on the top 10% of production assets in terms of material output per carbon emissions and directly linked to the production volume of the preceding year (dynamic output-based allocation). This would be a change relative to the current EU ETS allocation rules (Branger et al., 2015). Under output-based allocation, only emissions exceeding the benchmark contribute to marginal cost and could be reflected in material price changes. As these emissions tend to be small compared to the base emissions for which free allowances are granted, they are ignored in the calculation.

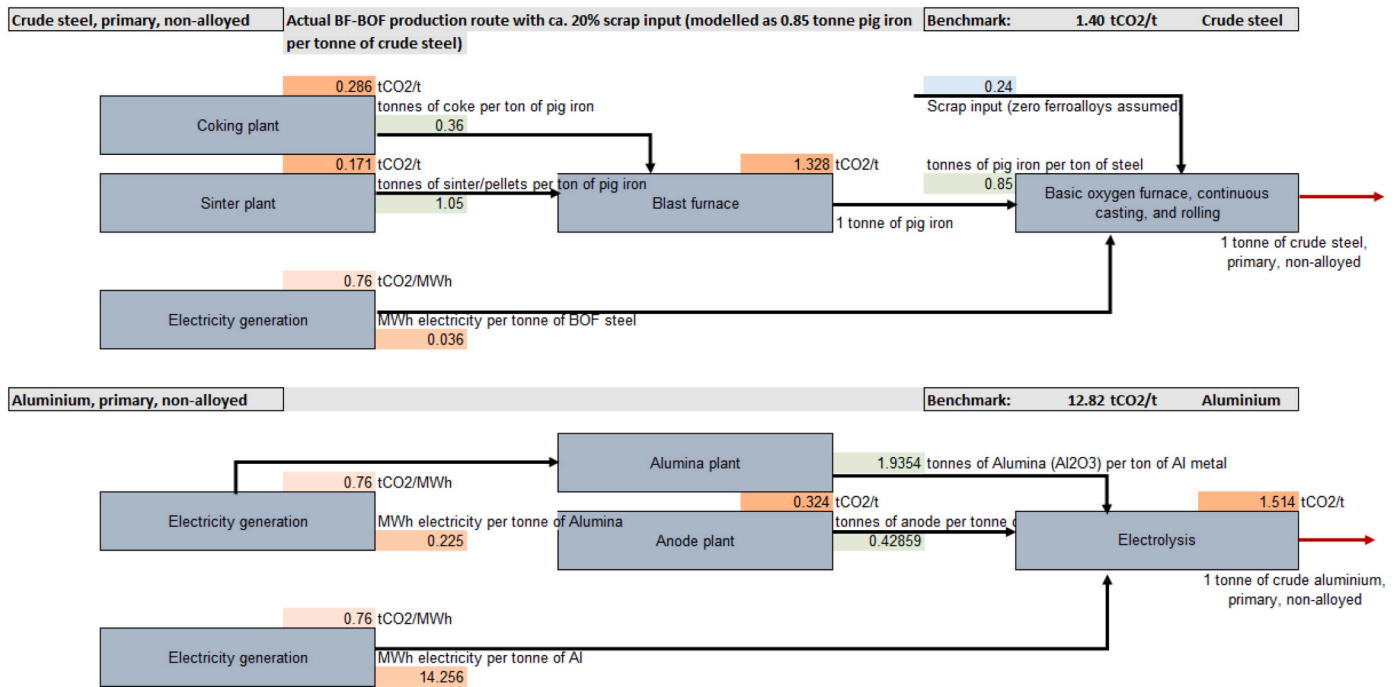


Fig. 1. Construction of product-level CO₂ benchmarks with simplified supply chains.

Here, the examples of crude steel (basic oxygen furnace (BOF) route with ~20% scrap input) and primary aluminium are shown. EU-ETS process and electricity benchmarks are combined with mass balance and process data.

(Option I) has the second highest revenues, much of which is generated by increased auctioning revenues. The symmetric BCA (Option II) has the lowest revenues due to the existence of export rebates. Moreover, a significant share of revenues of both BCAs is at risk of resource shuffling, i.e. the less emissions-intensive materials produced abroad may be directed or merely allocated on paper towards the European market to reduce carbon costs.

The paper is structured as follows. Section 2 provides the methodological foundations by calculating material-specific carbon benchmark reference values. Section 3 assesses carbon leakage risks under an incomplete BCA for downstream domestic manufacturing sales, as well as in export markets. Section 4 evaluates the distributional consequences of consistent carbon pricing for basic material production. In Section 5, we approximate potential fiscal revenues, taking into account a stylised demand response to increased carbon prices. Section 6 concludes.

2. Product-level price increases along the value chain

In this section, we calculate product-level price increases due to consistent carbon pricing of cement, steel, aluminium, plastics, pulp and paper, with a focus on manufactured products. To do so, we first calculate product-level carbon intensities for about 4400 PRODCOM⁴ commodity groups, based on EU-ETS benchmarks and assuming full cost

⁴ PRODCOM is a database that provides statistics on the production and sale of about 4400 industrial goods and services. PRODCOM mainly covers materials, material products, and manufactured goods, but also including some industrial services (mining, quarrying and manufacturing). Annual PRODCOM statistics include both the physical volume (kg, m², number of items, etc.) and the monetary value of production sold, imports, and exports. Products are detailed at an eight-digit level: The first four digits refer to the equivalent class within the Statistical classification of economic activities in the European Community (NACE), and the next two digits refer to subcategories within the Statistical classification of products by activity (CPA). The last two digits are used to indicate the different sub-divisions within a CPA 6 digit subcategory.

pass-through along the value chain, to obtain an upper boundary estimate of carbon costs at different levels of manufacturing⁵ (Sections 2.1 and 2.2). We then calculate price increases for these products, which we report at an aggregate level of four different product categories, namely, basic materials, basic material products, components, and final goods (Section 2.3).

2.1. Construction of product-level carbon intensity benchmarks

Greenhouse gases (GHGs) are generally accounted for at the process level, like GHG emissions in the blast furnace (steelmaking), aluminium smelting, electricity generation, or operation of vehicles with internal combustion engine. Matching these emissions, a list of process-based emissions benchmarks was developed for the EU-ETS to form the basis of (free) allocation of emissions allowances to address carbon leakage risks (Direct emissions benchmarks for industrial processes, EU-ETS 2019/331/EU). This process-based list was complemented by electricity intensity benchmarks (EU-ETS 2012/C 387/06) and emissions intensity benchmarks for electricity (EU-ETS 2012/C 158/04) to derive indirect emission benchmarks.

Consumers, importers, and exporters deal with commodities and not with processes and therefore need product-level GHG benchmarks to work with. Embodied emissions or resources are the most common product-level supply chain indicators, they are defined as the sum of all emissions that occur in the supply chain of a commodity. We can apply this definition to calculate EU-ETS-compatible material-specific carbon intensities, using simplified supply chains of commodities, EU-ETS process and electricity benchmarks, and data from life cycle databases such as ecoinvent (Wernet et al., 2016). We assign the EU-ETS

⁵ Firms do not necessarily need to fully pass on carbon costs along the value chain. For example, as Sijm et al. (2012) demonstrate for the power market, the rate of cost pass-through of the cost of CO₂ emissions to electricity prices depends on a number of factors, including the number of firms in the market, the shape of the demand curve and the shape of the marginal cost (supply) curve.

Table 1

Total EU material production in 2019, related CO₂ benchmarks, and carbon liability per tonne (t) created upon material production.

Material	Total production, EU27, 2019, Mt	EU-ETS benchmark t CO ₂ -eq/t	Liability per tonne (EUR)
Steel (all)	152	1.780**	53.4
Al (all)	6.2	12.82	384.6
Plastics	116	0.902*	27.1
Pulp	20.4	0.09	2.7
Paper	82	0.308	9.24
Cement	141	0.69	20.7
Carbon price: EUR/t of CO₂	30		

Production volumes include primary and secondary production except for pulp (only pulp from virgin resources was counted) and cement (virtually no recycling). Sources: World Steel Association (2020), PRODCOM industrial production statistics (Eurostat).

* For PVC, a benchmark of 1.5 t CO₂-eq/t is applied.

** The steel benchmark decreases to 1.4 t CO₂-eq/t for a share of 20% scrap in primary (BOF) steelmaking (cf. Fig. 1).

benchmarks to the relevant processes to calculate and sum up the different emissions contributions (Fig. 1).

2.2. Implications for carbon intensity of products

The resulting EU-ETS-based product benchmarks for the basic material commodities (Table 1) are in general smaller than full carbon product footprints calculated by life cycle assessment. This has two reasons. First, the supply chain scope of the simplified product-level benchmarks (Fig. 1) is reduced compared to the supply chain depth of databases like ecoinvent. Second, the EU ETS GHG benchmarks do not represent industrial averages, but well-above-the-average technology.⁶

Table 1 shows a high benchmark for aluminium, which is due to the large electricity-related contribution (scope 2) that can be seen in Fig. 1. The benchmark for pulp is rather low, which is a direct consequence of the low process-level benchmark as most of the energy for the pulp extraction is sourced from the lignin component of the wood.

The product level benchmarks approximate how much GHG is covered by the EU ETS in the supply chain of each material, assuming that all production steps happen in the EU. If there are no free allocations of emission allowances in the EU ETS, the total material-specific carbon costs can be calculated as GHG benchmark multiplied by the market price of a ton of CO₂ emitted. If the materials are imported and subject to either a full border carbon adjustment or an excise duty (Ismer et al., 2020), a mass-based liability that corresponds to full domestic supply chain carbon costs would be levied.

The indicator liability per tonne is calculated as the product of the product-level benchmark and the carbon price (here: 30 EUR/t), so that plastics, with a benchmark of 0.9 t have a per-tonne-liability of 0.9*30 = 27 EUR/t. Total liability volumes are calculated as production volume * liability per tonne, and here, the large-quantity materials steel, plastics, and cement dominate the results, accounting for around 75% of all material-related carbon liabilities created at the point of production in the EU.

2.3. Product-level price increases and definition of product categories

2.3.1. Calculation of product-level price increases

Above, the material-related liabilities were calculated in EUR/t of material. These results can be used to calculate the maximum price change of products that contain these materials in a first order

⁶ EU ETS benchmarks are based on the average emission intensity of the 10% most efficient installations.

Table 2

Maximum percentage price change from carbon charges at a carbon price of 30 EUR/t for selected basic material commodities.

ProdCom/ NACEv2.2 code	ProdCom/ NACEv2.2 name	Price change [%]	Material
23511100	Cement clinker	49.3	Cement
23511210	Portland cement	28.2	Cement
24101100	Pig iron and spiegeleisen in primary forms	25.8	Steel
24102110	Flat semi-finished products (of non-alloy steel)	21.2	Steel
24421130	Unwrought non-alloy aluminium	17.6	Aluminium
20162090	Polymers of styrene, in primary forms	4.0	Plastics
20163010	Polyvinyl chloride in primary forms	6.4	Plastics
20165230	Polymers of vinyl acetate, in primary forms	3.8	Plastics
20161050	Polyethylene in primary forms	3.3	Plastics
17111400	Mechanical wood pulp	0.7	Pulp
17111200	Chemical wood pulp, soda or sulphate	0.5	Pulp

approximation, assuming that their composition and weight per price does not change under full carbon cost pass-through. Here, the following calculations are performed for each commodity group *c* and all basic materials *m* considered:

$$\begin{aligned} \Delta p/p(c) &= \text{Carbon charge per kg}(c) / \text{price per kg}(c) \\ &= \text{Carbon price} * \text{Benchmark}(m) * \text{MatContent}(mc) / \text{price per kg}(c) \\ &= \text{Carbon price} * \text{Benchmark}(m) * \text{MatContent}(mc) * \text{Flow weight}(c) / \text{Flow Value}(c) \end{aligned} \tag{1}$$

Where $\Delta p/p(c)$ is the relative price change (first order, in 1 or %) and the carbon-charge per kg of *c* is calculated as above as carbon price (*C-price*) times the material-specific *Benchmark(m)* times the material content of material *m* in commodity group *c* (*MatContent(m,c)*). The commodity group-specific material composition was taken from previous work (Pauliuk et al., 2016) and updated to the full list of 4476 commodity groups. Unit prices (*price per kg of c*) can be obtained by dividing the production flow weight by the production flow value as reported for the commodity groups as part of the PRODCOM production statistics (Eurostat, 2020).

Cement has the highest carbon charge level per product price and here, price signals of up to 50% are possible at a carbon price of 30 EUR/t. Price signals for steel (primary production) are between 20 and 25%, those for aluminium around 17% (Table 2). For plastics, price changes between 5 and 7% can be expected and even lower values for pulp and paper. Relatively high price changes for basic material products are plausible, since these are composed of 100% of a certain material and have not accumulated any additional value added through subsequent fabrication and manufacturing.

2.3.2. From commodities to product categories

In the previous section, we showed price increases for selected goods at the level of single PRODCOM commodity groups. To understand how price changes evolve as the degree of manufacturing becomes higher, we group the commodities containing basic materials into four groups.⁷

(Basic) materials. A material is either a (technically pure) substance or a mixture of substances in a physical form that can be sold and transported, such as gaseous (hydrogen, ethylene, etc.), liquid (nitric acid, gasoline) or

⁷ This classification builds on input from Hubert Fallmann.

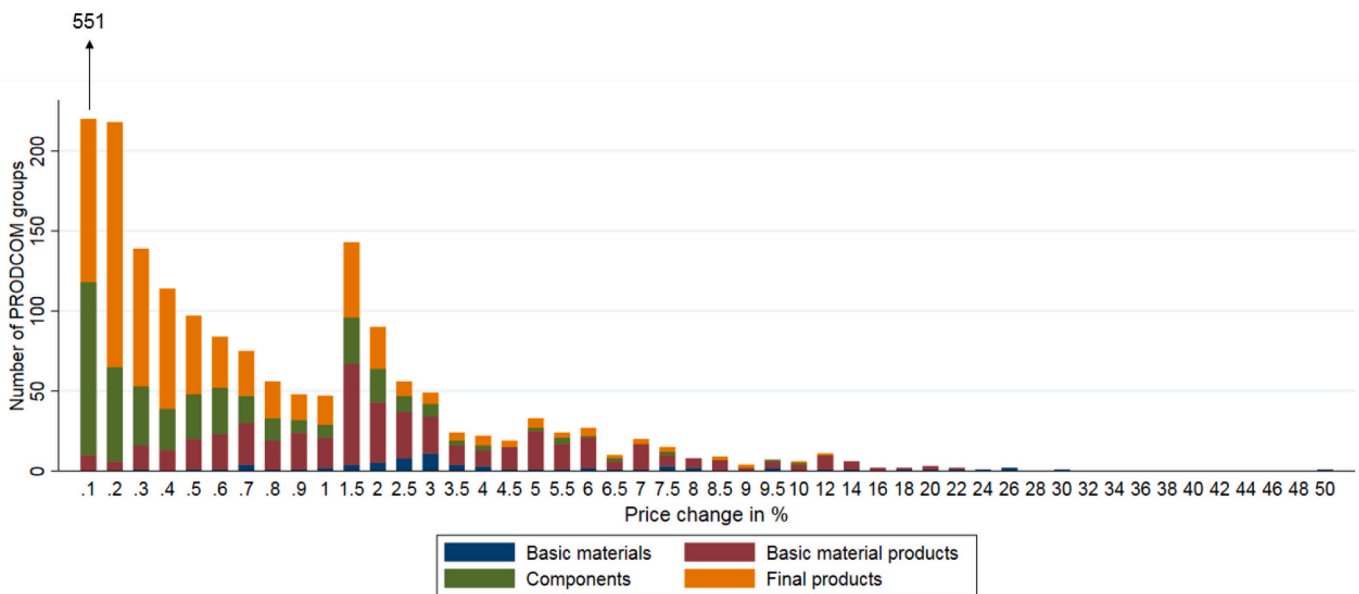


Fig. 2. Distribution of PRODCOM trade groups by price increase at a carbon price of 30 EUR/t. Commodities are grouped into the following four categories, according to their level of manufacturing 1: basic material; 2: (pure) basic material product; 3: component; 4: final product. 2026 commodities exhibit price increases larger than zero. 1061 commodities have zero price increases, since these do not contain any of the basic materials we study. The y axis is trimmed at 220.

solid (cement clinker, polyethylene granules, metal ingots etc.). Materials are either produced from raw materials (i.e., natural resources, in which case they are called primary materials) or from waste or scrap (in which case they are called secondary materials) in an industrial process during which their chemical composition is modified.⁸

Basic material products. Products which consist of one single basic material (barring additives such as alloying elements), and which are often produced in a (sometimes energy intensive) process closely coupled and performed in the same installation as the basic material production. Examples are bricks and ceramic tiles, glass bottles, steel or aluminium sheets, rods, bars, coils, profiles, etc. There are often high energy saving potentials in the process chain if the forming step is integrated with the material production, e.g., if the still hot steel can move from continuous casting directly to the hot rolling plant. Therefore, there is little incentive to perform the forming in a separate plant, and the basic material is seldom traded without a subsequent forming step.

Components (also referred to as semi-finished products). This term would refer to products made of more than one basic material or basic material product, which thus require more complex manufacturing steps. Steel sheets after surface treatment and coating, cutting and further forming (e.g. into sheets that have already the form of a car door) belong to this category. Car tyres, electrical components, or processed wood products like fibreboards are further examples. Components are usually not intended for end consumers, but are manufactured into final products.

Final products. By this term, we mean every product which is made out of components and/or further basic materials/products. In contrast to the other products in the value chain, final products are not part of other final products. This category comprises a wide range of products, including cars, mobile phones and television sets, but also simpler things such as carton-packaged aluminium foil on a roll ready for sales to end consumers.

⁸ For example, cement clinker is result of burning, iron ores are reduced to metallic iron (pig iron), crude oil is split into its constituents by distillation, which are further refined into a wide range of basic organic chemicals, etc..

Some products can plausibly be assigned to several groups, e.g., tissue paper or metal casting applications or metal furniture, which are both a basic material product and a final product. For the purpose of material production-based carbon liabilities, pure material products are classified as more “upstream” (i.e., basic material products) in order to reflect that such goods (with high cost increases due to carbon pricing) can easily and would likely be included in the scope of a border carbon adjustment.

2.3.3. Price increases for product categories

Fig. 2 shows the number of PRODCOM commodity groups by relative price change (resulting from a carbon price of 30 EUR/t), sorted into the four categories basic material, basic material product, component and final product as defined above. Here, each group’s price change is counted irrespective of the group’s economic significance (total value or volume). In Section 3, we extend the analysis to consider the value of commodity groups and link price changes to value added, in order to assess carbon leakage risks for European manufacturers.

The relative price changes of commodities of a higher degree of manufacturing tend to be smaller than the ones of basic materials. This is due to the increasing relevance of cumulative value added with a higher degree of manufacturing and – for some supply chains – a decline of the share of the six materials studied in products along the supply chain, as other materials, like wood or copper, are added. For the basic materials, price changes range from 0.1 to 50%, with the highest value (around 50%) for cement clinker and many groups ranging between one and 7%. For the basic material products, the typical price changes also range from ca. 0.5 to 7%. For component and final products, most groups show a price change of below 0.5%, with many even below 0.1%. This illustrates the dominance of value added over material-related costs in the price of these commodities.

3. Carbon cost differences as indicator for carbon leakage risks

In this section, we quantify carbon leakage risks under an import-only BCA combined with full auctioning. Such an import-only BCA may have a limited coverage of the value chain, in order to limit administrative costs and avoid more than single charging of products in the case of value chains that are integrated across borders (Ismer et al., 2020). Moreover,

an import-only BCA has an impact on relative costs of domestic producers in external markets (Evans et al., 2020). This may trigger two potential sources of increased carbon leakage risk for European manufacturers with a high ratio of carbon cost increases relative to GVA.

First, under any border carbon adjustment with a limited coverage of the value chain (both an import-only BCA and a symmetric BCA with a reimbursement for exports), European producers selling products not included in the BCA in the European market would face higher carbon costs on their inputs than their international competitors. Hence they may reduce domestic production and emissions at the expense of foreign production and emissions.

Second, in many cases manufacturers export parts of their domestically produced goods, while facing price competition on international markets. In an import-only BCA without rebate for exports, higher carbon costs might therefore trigger a reduction of exports of domestic production and corresponding emissions at the expense of an increase in non-EU production and emissions.

3.1. Definition: Carbon cost increase relative to value added

To identify which industrial activities may be exposed to a risk of carbon leakage through the two channels mentioned above, we compute the ratio of carbon costs relative to gross value added (GVA) for 4400 product categories along the value chain. In principle, carbon cost increases of products can be depicted relative to a variety of reference values. Product prices are commonly applied as reference values. However, for a comparison across different firms and sectors, the results will also reflect the large variations in the share of input costs not under the control of firms. Hence, we use gross value added as a reference value for carbon cost increases. This follows the approach of most assessments of carbon leakage risks, and corresponds to the indicator used to assess carbon leakage risk under the EU ETS until 2020 for primary material producers (Directive 2003/87/EC, Sato et al., 2015).⁹

In line with the threshold defined in the EU ETS Directive, we consider product categories to be potentially at risk of carbon leakage, where carbon costs relative to GVA exceeds 5%.¹⁰ We also include the second criteria under the EU ETS Directive in our analysis, namely a trade intensity¹¹ of at least 10%.

To compute the values, we calculate first carbon cost increases relative to sales value due to consistent carbon pricing of basic materials at a carbon price of 30 EUR/t for all PRODCOM commodity groups, as described in Section 2.3.1. We divide this price increase by a NACE-specific ratio of gross value added (GVA) to turnover.¹² The cost increases relative to GVA linearly scale to higher carbon prices, such that an increase of the indicator by 2% at a carbon price of 30 euros translates into an increase of costs relative to GVA by 5% at a carbon price of 75 euros.

The results vary largely across the four product categories. The highest increases of carbon costs relative to GVA occur for basic materials and basic material products, but there are also components and final products with high increases of costs relative to GVA (Table 3).

⁹ While carbon leakage can theoretically be defined as the increase in foreign emissions caused by the introduction of a domestic regulation, for practical reasons policymakers have focused on indicators measuring leakage risks based on domestic emissions intensity and trade exposure (Fowlie and Reguant, 2018).

¹⁰ The 5% threshold for the assessment of carbon leakage risks in Art 10a(15) of Directive 2003/87/EC has been replaced for the period post-2020 by a new indicator based on the product of trade intensity and emissions intensity (emissions divided by gross value added).

¹¹ Trade intensity is defined as the sum of the value of imports and exports, divided by the EU market size (domestic sales plus imports).

¹² Gross value added is not available at the PRODCOM level. We therefore calculate the average GVA to turnover ratio at the NACE 4 level, assuming that this is constant for all PRODCOM commodity groups that belong to the same 4-digit NACE sector.

Table 3

Carbon cost increase (in %) relative to GVA in different product categories.

	Mean	Median	Max	Min	Standard deviation
1: Basic materials	23.0	11.2	155.8	0	33.9
2: Basic material product	8.8	2.4	108.9	0	15.1
3: Components	1.5	0.7	32.5	0	3.7
4: Final products	1.3	0.2	45.0	0	3.6

The statistics (in percent) are calculated for a carbon price of 30 EUR/t under the assumption of full carbon cost pass-through (i.e. without free allocation of allowances).

Our analysis provides only an indicator for the upper bound of potential carbon leakage risks for a number of reasons. First, we assume full carbon cost pass-through. However, the extent of carbon cost pass-through depends on many factors, in particular the level of international trade and free allowance allocation provisions. Under the current EU ETS, there is evidence that for basic materials there is only limited carbon cost pass-through (Branger et al., 2015; de Bruyn et al., 2015; Martin et al., 2016; Neuhoff and Ritz, 2019). Second, our assessment of carbon leakage risks assumes that EU producers incur full carbon costs for their inputs, while competitors in other regions do not face similar carbon costs. Third, while this work analyses sales price increases under the assumption of full carbon cost pass-through to quantify maximum impacts on consumers, the actual desired response of companies to higher carbon costs is to pursue further efforts to enhance material efficiency, switch to low-carbon energy carriers, and enhance energy efficient. Only where this is not possible or not economic, reduced profit margins or higher sales prices may be needed, and future sector-specific studies can help identify optimal strategies for different material producers.

3.2. Potential carbon leakage risks linked to domestic sales

In combination with full auctioning of emission allowances, border carbon adjustment mechanisms covering only some product categories will increase input costs for domestic producers of components and final products. For a BCA covering only basic materials and basic material products, Fig. 3 depicts that 240 billion euros worth of domestic sales of internationally traded components and final goods would be subject to cost increases relative to GVA of more than 5% at a carbon price of 30 EUR/t.¹³ For a carbon price of 75 euros, this sales volume would increase to 760 billion euros (or 15% of overall manufacturing). This sales volume is at risk of carbon leakage, since higher input costs for domestic producers could result in a relocation of production and thus emissions to other countries. Table 4 depicts the corresponding values also for other product categories.

Considering only the carbon cost increase and not the trade intensity, sales of components and final products with a cost increase relative to GVA of more than 5% increase by 10%, to 266 billion euros and 817 billion euros for a carbon price of 30 and 75 EUR/t.

3.3. Potential carbon leakage risks linked to exports

Under an import-only BCA in combination with full auctioning, European exporters would face full carbon costs and might thus lose

¹³ Our calculations are based on 2019 EU27 PRODCOM data, downloaded from Eurostat. In case the value of sales or the value of exports are missing in the 2019 data, we use 2018 values, where available. Moreover, for 2% of the commodity groups, we calculate the trade intensity indicator with 2018 data due to missing values in the 2019 statistics. We also include 48 commodity groups, for which the costs relative to GVA indicator is available, but the trade intensity indicator cannot be calculated due to missing values for imports or exports.

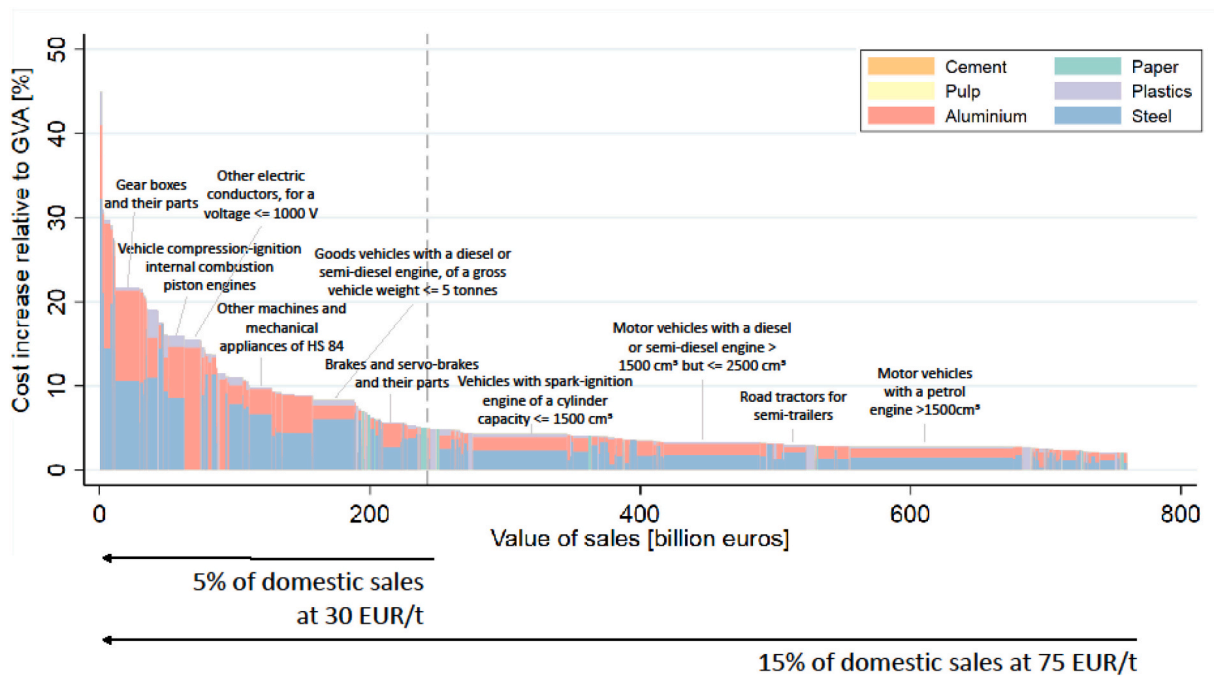


Fig. 3. Components and final products in domestic markets potentially at risk of carbon leakage under a BCA that covers only basic materials and basic material products. Based on EU27 PRODCOM manufacturing data (NACE codes 10–33) from 2019. Cost increases relative to GVA are based on a carbon cost of 30 EUR/t, under the assumption of full carbon cost pass-through. The figure graphs all goods that meet both carbon leakage criteria, i.e. a cost increase relative to GVA of at least 5% (at different CO₂ prices) and trade intensity of at least 10%.

Table 4
Potential carbon leakage risks in manufacturing – domestic sales.

	Number of PRODCOM categories	Value of sales [mEUR]	Value of sales with potential carbon leakage risks at 75 EUR/t [mEUR]	Value of sales with potential carbon leakage risks at 30 EUR/t [mEUR]
Not relevant	1313	1,681,325	–	–
Basic material	90	148,105	110,691	100,269
Basic material product	768	882,421	472,879	317,721
Component of product	743	1,076,112	209,598	94,868
Final product	1480	1,364,615	550,256	147,647
Total manufacturing	4394	5,152,578	1,343,424	660,506

Carbon leakage risks are defined as those commodity groups with cost increases relative to gross value added of more than 5% and a trade intensity of at least 10%, using the benchmarks from Section 2.2 and assuming full carbon cost pass-through. Calculations based on PRODCOM statistics from Eurostat, using EU27 data for manufacturing (NACE codes 10–33) in 2019.

market share to other producers not exposed to carbon costs, potentially contributing to relocation of production and emissions. Almost 190 billion euros worth of exports, or 10% of the total value of exports in manufacturing, would face an increase of costs relative to GVA of at least 5% at a carbon price of 30 euros (Table 5 and Fig. 4). This share would increase to 23% (almost 450 billion euros) at 75 EUR/t.

Since product groups that are exported typically classify as trade-intensive, the second carbon leakage criterion of trade intensity has little effect on the overall volume of exports at risk of carbon leakage. Without an application of this criterion, the exports with a cost increase relative to GVA of more than 5% alone would increase by 2.5%.

While the EU is a net importer of many basic material and basic material products, it also exports 89 billion euros of basic material and basic material products, for which an import only BCA would result in cost increases of more than 5% relative to GVA at a carbon price of 30 EUR/t. The sectors with the highest share of production at risk from carbon leakage for exported materials are aluminium (almost half of the

production is exported, cf. Table 6), pulp and paper (31 and 23% export share, respectively) and steel (19% exports).

4. Distributional impacts on final consumers

If carbon prices are passed on to product manufacturers and the construction sector and, ultimately, from there to the final consumers or purchasers of products, buildings, and infrastructure, then this will impact consumers and may have distributional implications. While the accurate estimation of price changes of final consumption with high commodity resolution is impossible given the interference of the carbon charge with profit margins, demand changes, material substitution and reduction, and technological change, a first order estimate can be given. For this estimate, we compute the ‘price signal’, which is the maximum carbon charge per disposable income due to price changes of commodities along the value chain. The estimate assumes that quantities do not change, meaning that industries do not improve the efficiency of

Table 5
Potential carbon leakage risks in manufacturing – exports.

	Number of PRODCOM categories	Value of sales [mEUR]	Value of sales with potential carbon leakage risks at 75 EUR/t [mEUR]	Value of sales with potential carbon leakage risks at 30 EUR/t [mEUR]
Not relevant	1313	519,187	–	–
Basic material	90	36,662	29,145	24,857
Basic material product	768	186,577	106,889	63,880
Component of product	743	407,802	71,004	33,145
Final product	1480	771,958	241,886	66,617
Total manufacturing	4394	1,922,186	448,925	188,499

Carbon leakage risks are defined as those commodity groups with cost increases relative to gross value added of more than 5% and a trade intensity of at least 10%, using the benchmarks from Section 2.2 and assuming full carbon cost pass-through. Calculations based on PRODCOM statistics from Eurostat, using EU27 data for manufacturing (NACE codes 10–33) in 2019.

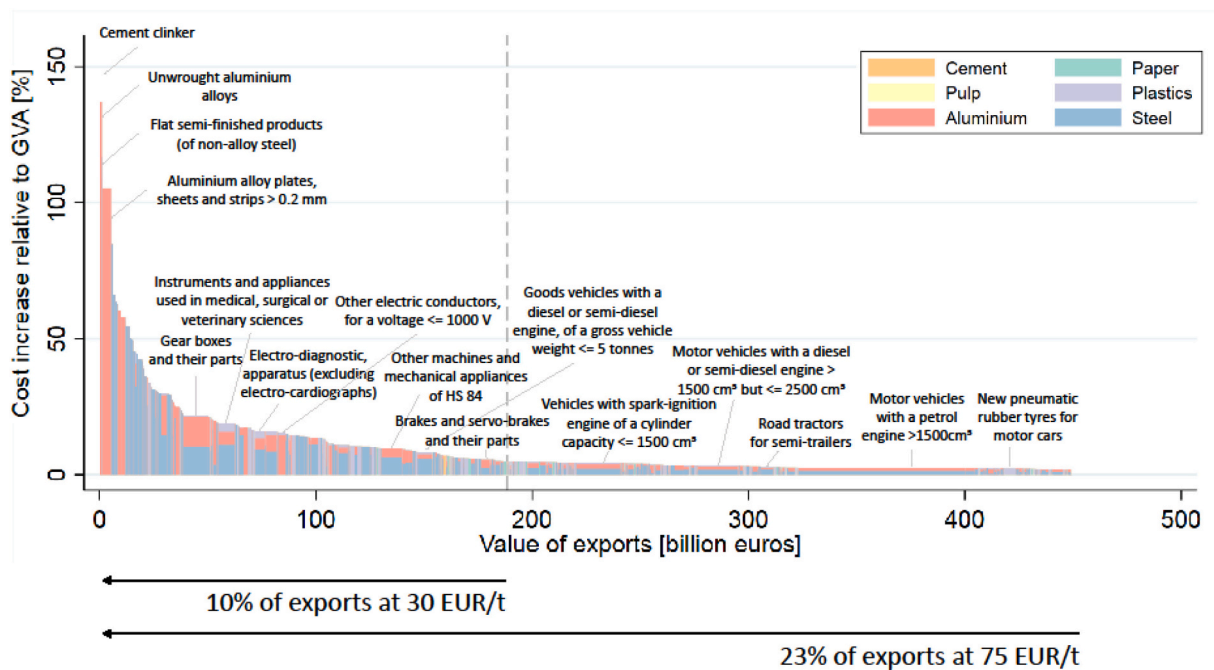


Fig. 4. Products in export markets potentially at risk of carbon leakage under a BCA without reimbursement for exports. Based on EU27 PRODCOM manufacturing data (NACE codes 10–33) from 2019. Cost increases relative to GVA are based on a carbon cost of 30 EUR/t, under the assumption of full carbon cost pass-through. The figure graphs all goods that meet both carbon leakage criteria, i.e. a cost increase relative to GVA of at least 5% (at different CO₂ prices) and trade intensity of at least 10%.

Table 6
Production, imports and exports of selected basic materials.

	Total production [Mt]	Imports [Mt]	Exports [Mt]	Export share [%]
Cement	152	5,4	11,9	8
Steel	159	47,0	29,7	19
Aluminium	7	8,2	3,3	49
Plastics	119	24,2	21,4	18
Pulp	21	8,1	6,3	31
Paper	88	7,6	20,3	23

EU27 data for 2019. Production volumes for steel and aluminium include primary and secondary production. Imports and exports include basic materials and basic material products. The export share is calculated as export/production. Calculations based on PRODCOM statistics from Eurostat, as well as data from World Steel Association (2020), Brown et al. (2019), U.S. Geological Survey (2018).

their choice of materials in products and consumers do not shift demand. Due to this simplification, this calculation leads to an upper boundary of the expected price changes.

With consumer expenditure data by income decile, we compute price signals for different income groups (Fig. 5). We compute these price signals for a case study for Germany by constructing the global supply chains of a detailed inventory of consumer expenditure (DESTATIS, 2015) with the EXIOBASE multi-regional global input-output model (Stadler et al., 2018), using the readily available refinement and matching done by Hardadi et al. (2020). We first estimate the EU27 average price changes of seven EXIOBASE basic commodity groups (one for each of the different materials studied), using the methodology from Section 2, and then apply EXIOBASE to propagate these price signals through the supply chains that contain these materials until the point of final consumption.

The total price signal for households by income decile due to full carbon charging of basic material production is small and progressive: Fig. 5 shows that the price signal due to the carbon charge levied on basic material production both in the EU27 and the supply chain of imported material commodities is below 0.2% and increases by about

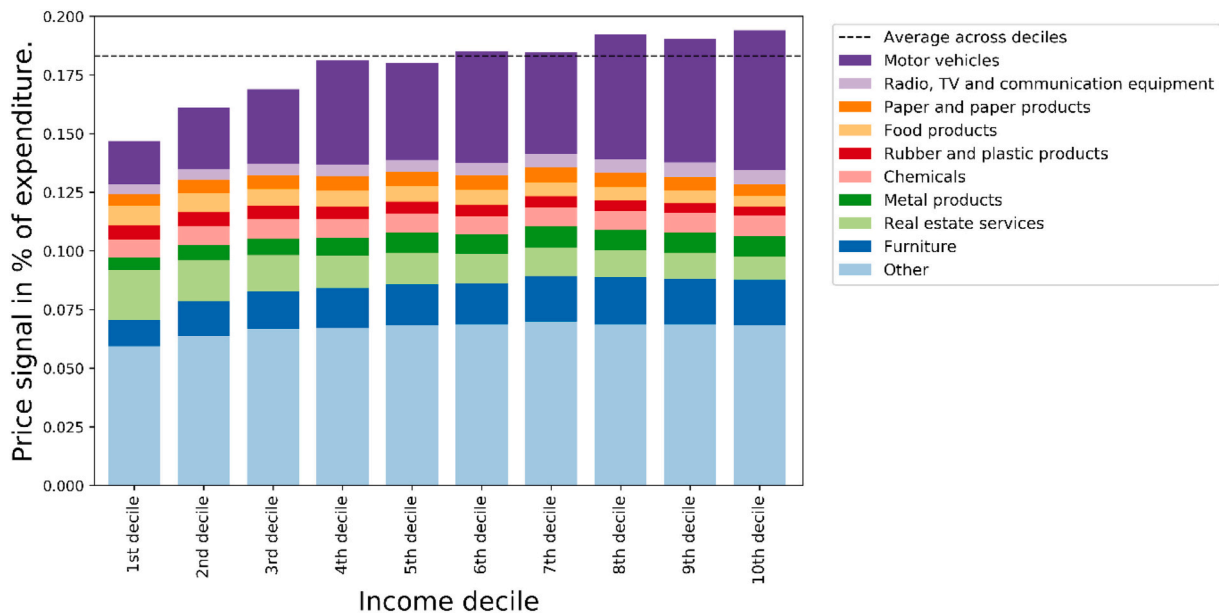


Fig. 5. Carbon cost related price increase for German households by income decile. Price increase assuming carbon costs of 30 EUR/t are reflected in basic material prices and all products comprising basic materials. Total expenditures are divided into 163 subgroups, of which the nine with the largest price signals are shown.

one third with disposable income across all income groups. That means that high income households would receive a carbon charge signal corresponding to relatively larger share of their disposable income than low income households. Consistent carbon pricing of materials therefore does not exhibit the regressive behaviour common to electricity charges and gasoline taxes (Wier et al., 2005; Bureau, 2011). Instead, it would contribute to a reduction of income-related inequality, resulting in a small but positive potential synergy with the societal and policy goal of inequality reduction.

The price change signal trend across income deciles varies with the consumption groups. Due to the homogeneity of the 163 expenditure groups in the supply chain model, the carbon footprint and related price signal per unit of expenditure on a certain income group is the same across income deciles. Hence, the distributional changes seen here are a direct consequence of the variations across income deciles in the share of disposable income spent on each group. Most remarkably, increases in expenditure on motor vehicles vary substantially across income deciles, i.e., richer households spend relatively more on cars. Moreover, motor vehicles show a relatively high price change (0.93% on average), which results in that most of the progressive trend of the price change can be attributed to motor vehicle purchases (Fig. 5). Furniture, metal products, and all other consumption categories together also show a slightly progressive trend, whereas the trend for real estate services is clearly regressive, but not enough to dominate the overall result.

The price signal in the largest expenditure groups is well below 2%: It is highest for metal products (1.4%), followed by paper and paper products (1.2%), while the other major expenditure categories displayed in Fig. 5 have price changes of less than 1% on average. We therefore expect that the direct impact of consistent carbon pricing of materials on household consumption choice would not be large. From a material efficiency point of view, this is not a major issue, as most material choice decisions are not made by final consumers, but by component manufacturers, where price signals are stronger, as the ratio of the carbon price increase to the total value added is larger for products with a high degree of manufacturing (see Sections 2 and 3).

5. Fiscal revenues

Following Ismer et al. (2020), we estimate additional public revenues available to the EU27 and its member states to purse climate action

that would result from the implementation of the following BCA designs, namely (i) a shift to full auctioning in combination with an import only BCA on basic materials and basic material products (import-only BCA, Option I); (ii) a shift to full auctioning in combination with a BCA on imports and exports of basic materials included in basic material products, components and final products (BCA on imports and exports, Option II); and (iii) a climate contribution (excise duty, Option III) levied on all domestic production not exported and imports of basic materials imported, including basic material products, components and final products with significant shares of the relevant basic materials.¹⁴

5.1. Assumptions

We include revenues from the inclusion of cement, steel, aluminium, pulp and paper and plastics in our revenue estimates. For each material, the charge is set at the same reference values as described in Section 2.3.1 for all three options. For the estimation of additional auction revenue in Options I and II, we assume that allowances needed for the production of materials beyond the reference value were already auctioned in the past. The additional auction revenues thus equal the volume of (primary) production multiplied with the material-specific reference value and the EU ETS price.

For steel and aluminium, we calculate additional auction revenues based on the share of primary production only.¹⁵ Additionally, in the

¹⁴ Potential revenues for two additional options are shown in appendix A.1, namely an import-only BCA with full coverage of the value chain, and a BCA with export reimbursement and limited coverage of the value chain.

¹⁵ Around 60% of the total EU27 production of 152 million tonnes of steel is production from basic oxygen furnaces (World Steel Association, 2020), which is mostly primary steel but also contains around 20% re-melted scrap. For aluminium, 1.6 m tonnes (26% of EU aluminium production) is primary aluminium. We do not differentiate between primary and secondary production for plastics and paper. This leads to an overestimation of auction revenues under the import-only BCA (i) and the BCA on imports and exports (ii). For pulp (only wood-based pulp was included here) and cement (virtually no recycling), there is no recycled content.

Table 7
Excise charge created based on EU production.

Material	Total production, EU27, 2019, Mt	EU-ETS benchmark t CO ₂ -eq/t	Liability per tonne (EUR)	Total charge created within EU27 (MEUR)
Steel (all)	152	1.780	53.4	8117
Al (all)	6.2	12.82	384.6	2385
Plastics	116	0.902*	27.1	3139
Pulp	20.4	0.09	2.7	55
Paper	82	0.308	9.2	758
Cement	141	0.69	20.7	2919
Carbon	30		Sum	17,373
price: EUR/t of CO ₂				

Production volumes include primary and secondary production except for pulp (only pulp from virgin resources was counted) and cement (virtually no recycling). Sources: World Steel Association (2020), PRODCOM industrial production statistics (Eurostat).

* For PVC, a benchmark of 1.5 t CO₂-eq/t is applied.

case of steel, we assume that 20% of scrap is used in primary steelmaking (basic oxygen furnace, BOF).¹⁶ Since the allocation volume is today already adjusted for the share of scrap and hence scrap does not benefit from free allowance allocation, additional auction revenues are reduced in line with the scrap share.

For Options I and II (import-only and symmetric BCA), we assume that all imported products contain only primary materials and are thus fully liable to the border charge.¹⁷ However, imported steel from the BOF route also contains scrap, which we account for by lowering the benchmark by about 20% (mirroring the assumption on domestic primary steelmaking). For the calculation of the export rebate in Option II, we assume that exports only comprise primary production of steel and aluminium.¹⁸

For the excise (Option III), the liability for the climate contribution is created at the benchmark reference level both for imports of primary and secondary produced material, i.e. the use of the materials is charged for, independently of the specific production process. Globally, any additional tonne of material demand will trigger an additional tonne of primary production, since in aggregate no surplus scrap capacity is available. Consequently, we do not apply any discount to the excise charge for the scrap share used in primary production processes.

Some EU member states offer power price compensation up to a certain maximum allowed under EU state aid guidelines for EU ETS indirect cost compensation. This support would probably be abandoned in Options I and II, but the scale of savings is difficult to estimate as approaches differ across EU member states on whether and at what level to offer such an indirect cost compensation. Our estimates thus do not reflect potential reduced expenditures under Options I and II for electricity-intensive processes, such as primary aluminium production (26% of the total EU27 aluminium production) and secondary steel production in electric arc furnaces within the EU (around 40% of total steel production).

For a BCA, a significant share of imports could be subject to risks of resource shuffling, i.e., the less emissions-intensive materials produced abroad may be directed or merely re-labelled and allocated on paper

¹⁶ We thank Hubert Fallmann for pointing this out. The assumption on the use of scrap reduces the benchmark from 1.78 to 1.4 t CO₂-eq/t (cf. Table 1). See also Broadbent (2016) on the use of scrap as iron input in the BOF route.

¹⁷ However, if non-European producers can demonstrate that they do export secondary production to Europe, actual revenues would be lower. Our estimates for the revenues from imports under Options I and II are therefore an upper bound.

¹⁸ Exported steel consists of more higher-value (primary) steel. Moreover, if incurred carbon costs are refunded for exports, EU producers have an incentive to export steel from more carbon intensive primary production.

towards the European market to reduce carbon costs. The scale of potential risks from resource shuffling under Options I and II are approximated for aluminium and steel. For the lower bound of revenues for aluminium, we assume that only 80% of the embodied emissions in basic materials, basic material products, components and final goods are liable to an import charge, because of the opportunity to source or attribute the production of aluminium to clean electricity.¹⁹ For the lower bound of the revenue estimates for steel, we assume that the corresponding import liability may be reduced by up to 50%.²⁰ The upper bound of the revenue estimate assumes no resource shuffling takes place at all.

5.2. Results

We estimate revenues for two demand scenarios. First, in Section 5.2.1, we estimate revenues assuming zero demand elasticity. Second, in Section 5.2.2, we assume a demand elasticity of -0.5 , which leads to a reduction of demand for basic materials in response to price increases due to consistent carbon pricing (see Table 10 in Appendix A.2).

The revenues for the excise on domestic production, as well as additional auction revenues for a perfectly inelastic demand are shown in Table 7, which is a simple extension of Table 1 in Section 2.2. Table 8 and Table 9 depict the charges created for imports and exports of basic materials and basic material products, as well as components and final goods (for Options I and II, which include a full coverage of the value chain).

5.2.1. Revenues assuming no demand response

Fig. 6 graphs potential revenues of different forms of border carbon adjustments, as well as an excise duty, under the assumption of no demand response (a perfectly inelastic demand) for the EU27.

The excise duty (Option III) would generate the highest revenue total of around 20.4 billion euros for the EU27. Revenues are roughly split in half between an excise on domestic production and imports from outside of the EU. Since free allocation is continued, there are no additional revenues from additional auctioning.

The import-only BCA on basic materials and basic material products (Option I) generates the second-highest revenue (up to 18.4 billion Euros). More than 60% of this revenue comes from additional auctioning at the level of the EU member states. Additional revenues mainly come from aluminium, steel and plastics. However, a significant part of this revenue is at risk of resource shuffling, so total revenues may also be much lower. Considering this risk of resource shuffling, additional revenues may decline to 14.4 billion euros (striped columns in Fig. 6).

The BCA with export reimbursement (Option II) results in the lowest revenue (up to 14.2 billion), due to the existence of export rebates. Resource shuffling of imports could further reduce the expected revenue to 8.6 billion euros. Although revenues partially increase due to an

¹⁹ Electricity plays a major role in the production of aluminium. According to EU ETS benchmarks for free allocation and power price compensation, direct emissions of aluminium production are 1.5 t CO₂/t material, and indirect emissions from electricity use are 14.3 MWh/t * 0.465 t CO₂/MWh. This means that 81.6% of total emissions are electricity-related, which can be avoided by fully attributing zero carbon electricity to aluminium production.

²⁰ Resource shuffling opportunities for steel depend on the production process. Long products are typically produced by electric arc furnaces (EAFs), where a major share of the carbon costs charged by a BCA can be avoided by attributing renewable electricity to the production of EAF steel. More high-value and high quality flat products, on the other hand, are typically produced by the basic oxygen furnace (BOF) route. Even for this production process, there are some opportunities for resource shuffling due to greening electricity use. Additional opportunities for resource shuffling exist, for example by increasing the scrap share in BOF production. This would lower the carbon intensity charged by a border carbon adjustment, but not necessarily lower global emissions, since a global scarcity of scrap implies this increased demand for scrap would have to be met by additional primary production.

Table 8
Import-related charge, by group.

Product category	Steel	Aluminium	Plastics	Pulp	Paper	Cement	Sum
0: not relevant	0	0	0	0	0	0	0
1: Basic material	856	2113	385	21	0	109	3484
2: Basic material product	2991	1142	375	0	50	5	4563
3: Components of products	470	538	64	0	0	0	1072
4: Final good	1254	664	338	0	18	0	2274
Sum 1–4	5571	4457	1162	21	68	114	11,393

In million euros.

Table 9
Export-related charge, by group.

Product category	Steel	Aluminium	Plastics	Pulp	Paper	Cement	Sum
0: not relevant	0	0	0	0	0	0	0
1: Basic material	122	133	463	18	0	310	1046
2: Basic material product	2927	1009	303	0	127	17	4383
3: Components of products	384	427	100	0	0	0	911
4: Final good	1084	538	182	0	104	0	1908
Sum 1–4	4517	2107	1048	18	231	327	8248

In million euros.

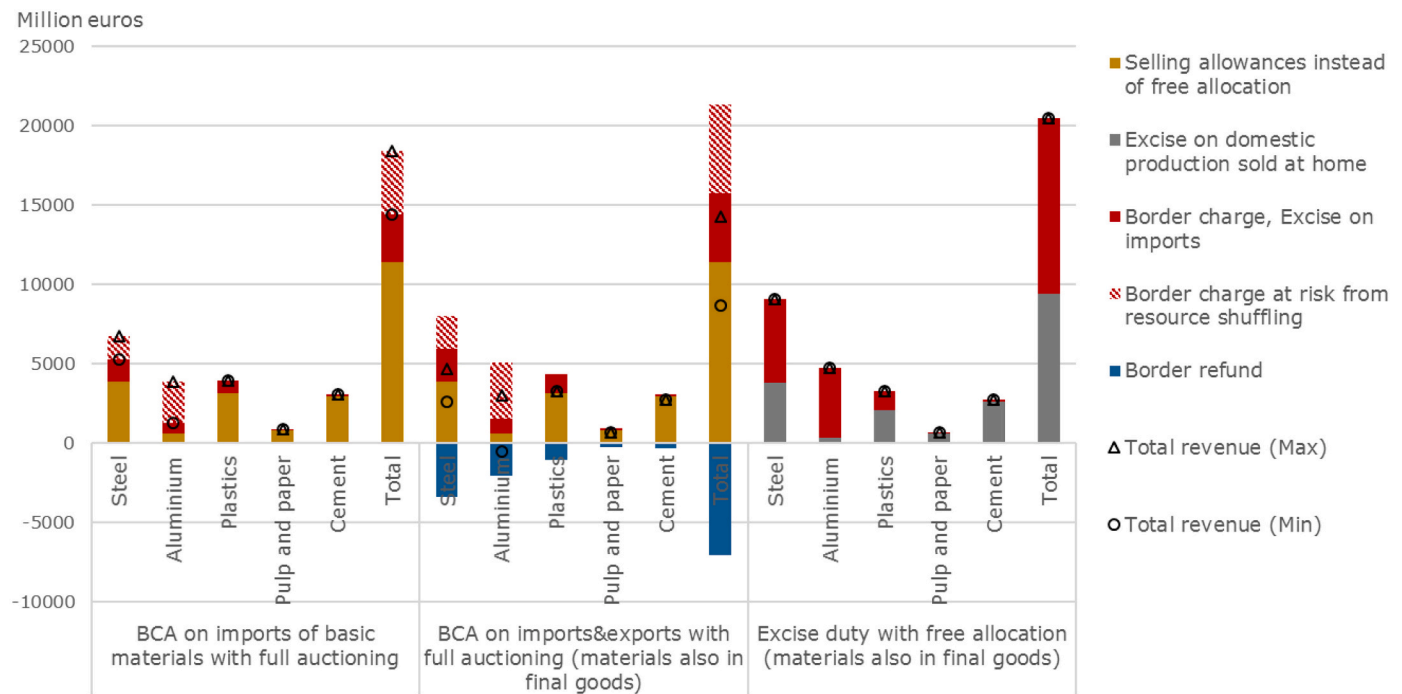


Fig. 6. Potential annual revenues under different types of border carbon adjustments assuming no demand response. Calculations are based on EU27 2019 trade flow data, assuming a CO₂ price of 30 EUR/t. Export reimbursements (blue column) decrease the net revenue in the BCA on imports and exports.

increased coverage of the value chain, the export reimbursement decreases overall revenues by more than this increase relative to the import-only BCA. As for the import-only BCA, additional auction revenues make up the majority of revenues. Overall revenues are lower than for the excise even in the case of no resource shuffling primarily because the excise charge is independent of the production process, whereas additional auction revenues accrue only for the share of primary production for steel and aluminium. Increased revenue from sales of recycled steel or aluminium results either in windfall profits or higher prices paid for steel and aluminium scrap.

5.2.2. Revenues with demand response

For the calculation of revenues with a demand elasticity of -0.5 , we assume that the reduction of demand applies equally for domestically produced materials and imports. We also assume there are no effects of reduced demand for EU allowances on the ETS price, which remains at 30 EUR/t.

Fig. 7 graphs the results. The revenue from the excise (Option III) decreases by around one billion euros, to 19.5 billion euros. The excise continues to generate the highest overall revenue. Some of the decrease of excise revenue is offset by an increase in auctioning revenues, since a reduction in material production leads to a decrease in

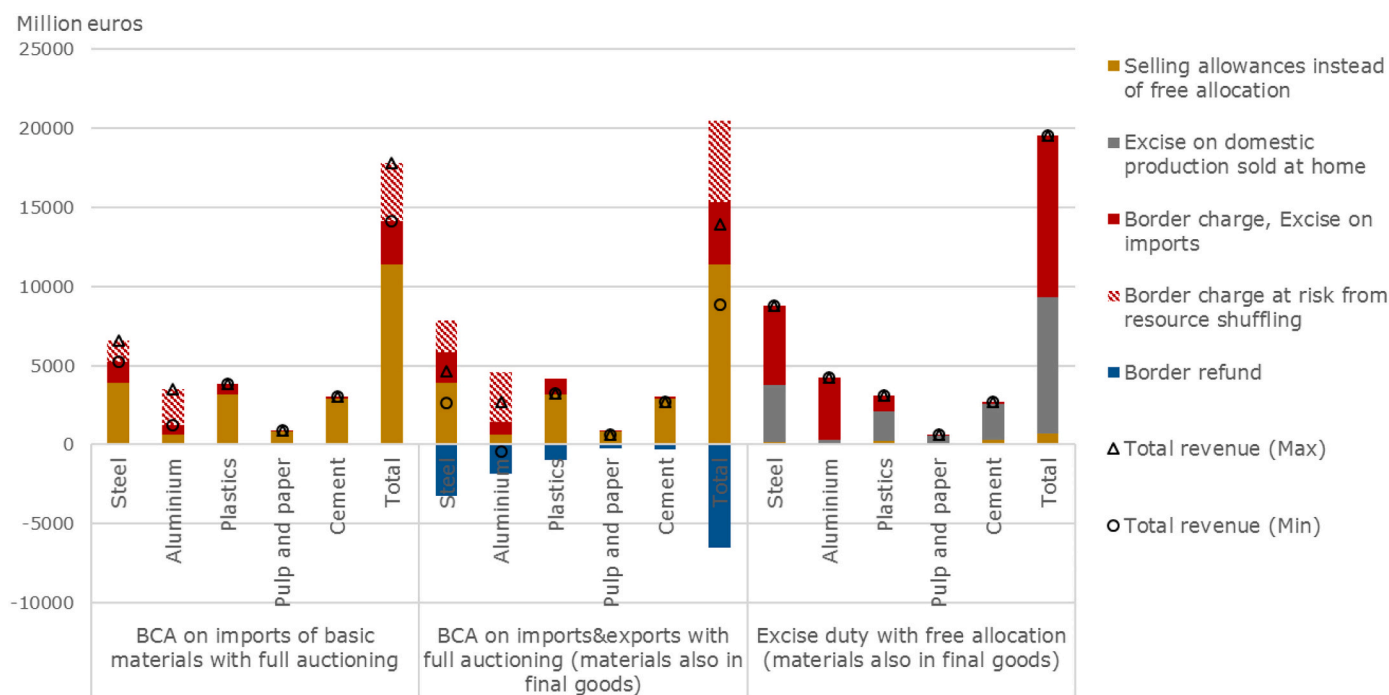


Fig. 7. Potential annual revenues under different types of border carbon adjustments with demand response. Calculations are based on EU27 2019 trade flow data, assuming a CO₂ price of 30 EUR/t. Export reimbursements (blue column) decrease the net revenue in the BCA on imports and exports. We assume a demand elasticity of -0.5.

free allowance allocation and thus triggers an increase in allowances available for auctioning.²¹

The BCA revenues decrease relatively less, since auction revenues are not directly affected by a decrease of primary production resulting from a demand response, as long as the allowance price remains unchanged.²² Since the auction revenues make up the bulk of revenues for the import-only BCA (Option I), overall revenues decrease only slightly as a result of lower import demand: Revenues are estimated in the range of 14.1 to 17.8 billion euros, depending on the scale of resource shuffling. For the BCA on imports and exports (Option II), the border refund for European exporters of roughly 6.5 billion euros means that total revenues of a maximum of 14 billion euros are lowest.

6. Conclusion and outlook

As countries across the globe are committing to climate neutrality, they can no longer ignore the so-called hard to abate emissions from basic material production. This requires policy designs for a shift to climate neutral production processes, enhanced material efficiency and recycling and climate friendly material choices. In Europe, the carbon price from the EU ETS could in principle play an important role in such a policy mix. In practice, the expected absence of a comparable level of carbon prices in major trading partners implies that European basic material producers cannot pass the full carbon costs to international traded material and product prices, thus rendering the EU ETS carbon price ineffective for supporting the transition to climate neutrality. While the free provision of EU ETS allowances to material producers

addresses the risk that increased carbon costs trigger a relocation of production and emissions (carbon leakage), it further reduces the effectiveness of the carbon pricing signal.

Reform options for EU ETS are currently being discussed for the basic materials sector with the aim of reinstating the full carbon price signal, while avoiding carbon leakage risks. We assess some of the features of these reform options using product-level price increases at a highly disaggregated analysis of the value chain.

One reform strategy involves abandoning free allowance allocation and instead providing carbon leakage protection by making the import of basic materials and basic material products liable to surrender allowances corresponding to their incurred carbon emissions. We demonstrate that if products further down the value chain are not covered, for example to limit complexity of monitoring and verification of incurred carbon emissions, increased prices for basic material and basic material products could imply significant cost increases for domestic producers of intermediary and final products competing in domestic markets with international imports not subject to a border adjustment. 242 billion euros of domestic sales of components and final products are subject to a carbon cost increase relative to GVA of more than 5% at a carbon price of 30 EUR/t, increasing to 760 billion euros (or 15% of manufacturing) for a carbon price of 75 EUR/t.

If exports are not refunded for their carbon costs, which could be difficult to implement in a WTO compatible manner, then domestic producers may face higher costs and lose market share to foreign producers in export markets, resulting in a relocation of production and emissions. We show that for 10% of the total value of exports in manufacturing (almost 190 billion euros), the cost increase relative to GVA would be above 5% at a carbon price of 30 EUR/t. This share would increase to almost a quarter of all exports (450 billion euros) for a carbon price of 75 EUR/t. It is important to point out that the estimated scale of activities at risk of carbon leakage is only a rough estimate and ignores other factors that may limit carbon leakage risks. These include the ability of manufacturers to accommodate lower profit margins or strong customer relationships that allow for carbon cost pass-through.

²¹ We assume that the overall ETS cap is (at least in the short term) not affected by the decrease in production.

²² The EU ETS price might decrease as a result of reduced demand for primary materials from higher carbon prices, which would result in a proportional decrease of auction revenues in line with the reduction of the ETS price. For example, if the allowance price decreased by 10%, the auction revenue under the import-only BCA would also decrease by 10%, or 1.1 billion euros.

Our results show two disadvantages of implementing border carbon adjustment if administrative and WTO constraints put limitations on their scope. These disadvantages can be avoided, if instead the reform of EU ETS involves three elements. Firstly, an excise charge (climate contribution) levied on the production of basic materials at the level of EU ETS carbon price and carbon intensity of material based on the benchmark of conventional material production. It would include adjustments for imports and exports along the value chain using established and WTO-aligned adjustment mechanisms at the border. Secondly, to avoid double charging from the excise and EU ETS, free allowances would be granted to conventional installations during the transition to climate neutrality. Thirdly, incremental costs of clean production processes could be covered with carbon contracts for difference (Climate Strategies, 2021).

An EU ETS reform that aims to ensure an effective carbon price for all actors along the value chain ultimately also implies product prices increases for final consumers. By combining our analysis with data from consumer expenditure survey, we assess the distributional consequences and find that price signals for final consumers are progressive. This contrasts with experience of climate policies in other sectors like electricity, where distributional effects are typically regressive. Moreover, at a price of 30 EUR/t, distributional consequences are limited: Household expenditures (assuming no demand response) would increase only marginally, namely below 0.2% of disposable income on average. This implies that the corresponding incentive to reduce or substitute consumption is small for final consumers. The main impact of a consistent carbon pricing is therefore expected in the value chain, where the share of material content is higher and manufacturers and construction industry therefore have an incentive to use carbon-intensive materials or

products more efficiently, or substitute to lower-carbon alternatives.

Finally, we estimate carbon pricing revenues for different EU ETS reform for materials steel, cement, aluminium, plastics, pulp and paper. For a carbon price of 30 Euro/t we find ranges of 14.4–18.4 billion euros (import-only BCA) and 8.6–14.2 billion euros (symmetric BCA). The amount depends strongly on the degree of resource shuffling, which would likely reduce the overall revenues significantly, as indicated by the lower bound estimates. The majority of BCA revenues stems from additional auctioning revenues. For the design involving an excise charge combined with continued free allowance allocation, we estimate additional 20.4 billion euros for the EU27.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A.1. Revenues for an import-only BCA with full coverage of the value chain and a BCA with export reimbursement and limited coverage of the value chain

Fig. 8 graphs revenues of two types of carbon border adjustment mechanism that are less prominent in the political discourse. Under a hypothetical import-only BCA with full coverage of the value chain (including components and final goods), potential revenues would be between 15.8 and 21.6 billion euros, depending on the degree of resource shuffling (left panel). A BCA with reimbursement for exports, but a limited coverage of the value chain, on the other hand, would lead to revenues between 9.7 and 13.8 billion euros (right panel). In both instances, we do not consider changes in trade patterns that may be induced.

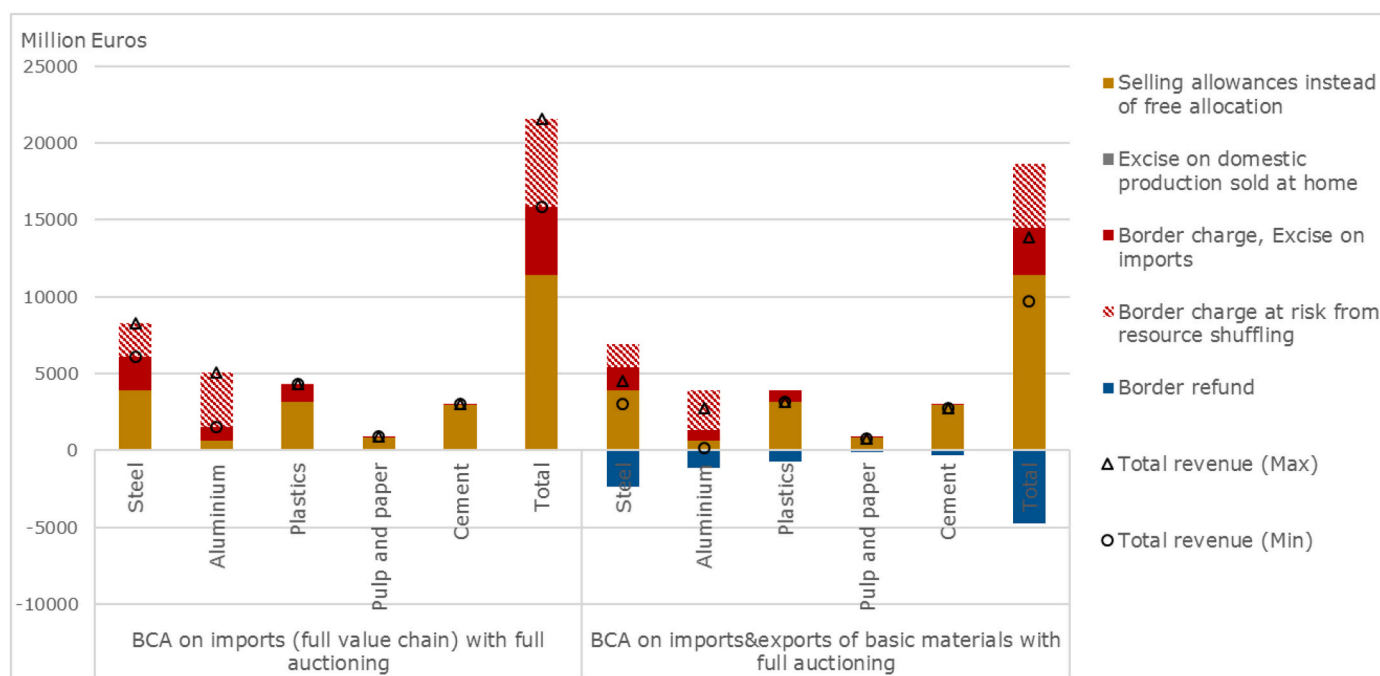


Fig. 8. Potential annual revenues for an import-only BCA with full coverage of the value chain and a BCA with export reimbursement and limited coverage of the value chain. Calculations are based on EU27 2019 trade flow data, assuming a CO₂ price of 30 EUR/t. Export reimbursements (blue column) decrease the net revenue in the BCA on imports and exports. Demand is assumed to be perfectly inelastic.

A.2. Estimation of potential demand response

In this section, we estimate a simplified demand response to consistent carbon pricing for the estimation of revenues from consistent carbon pricing in Section 5.2.2, using price elasticities of demand. Price increases of basic materials due to a consistent carbon pricing will likely have an effect on material demand, for example due to a more efficient use of material in production. Economic theory and empirical estimates suggest that the demand for commodities is price responsive. While estimated price elasticities vary by sector and over time (e.g. Röller and Steen, 2006; Smale et al., 2006; Demilly and Quirion, 2008; Pollitt et al., 2020), the assumption of a completely inelastic demand is not realistic. Following Pollitt et al. (2020), we therefore assume a demand elasticity of -0.5 as the basis for our estimates for medium-term demand responses for the different materials.

We find that demand reductions of 5% for steel, 11% for aluminium, and 12% for cement are triggered by a carbon price of 30 EUR/t over the medium term (Table 10). To allow for a comparison, we also depict the price and demand impact an additional carbon price would have on gasoline in Table 10. The coverage of refining emissions alone would have a negligible impact. Only if end-of-life emissions from incineration of gasoline are covered, a demand impact of 7% would be observed. This illustrates the importance of also considering embodied emissions. In the case of gasoline, these emissions are covered through national excises on fuels.

For plastics, the majority of emissions are not process related, but linked to an end-of life incineration, as is the case for gasoline. In the case of plastic, the carbon costs from incineration are usually exempt from EU ETS charges. Even where incineration plants are not exempt from the EU ETS, the costs incurred at the end of a product lifetime are not reflected in purchasing prices. Thus, carbon costs do not trigger material efficiency and do not allow for a fair inter-material competition. If end of life emissions were fully priced, and if the corresponding carbon costs would be translated to purchase decisions (for example through advanced disposal fees), then a demand impact of 10% could be anticipated at a demand elasticity of -0.5 .

Table 10
Demand response for basic materials.

	Price of material EUR/t	Emissions/t production	Emissions/t incineration	% cost increase prod.	% cost increase full	% demand response medium-term
Steel	500	1.78		11		-5%
Cement	70	0.69		30		-12%
Aluminium	1500	12.82		26		-11%
Pulp	750	0.09		0.4		-0.2
Plastics	500	1.5	2.5	9	24	-10%
Gasoline	1500	0.0295	3.1	0.6	7	-3%

The calculations are based on a CO₂ price of 30 EUR/t, as well as a medium-term demand elasticity of -0.5 . Emissions per tonne of production are equivalent to the benchmarks developed in Table 1. The low demand response for pulp reflects that emissions from burning biomass (the bulk of emissions) are not covered under the EU ETS. The gasoline emissions intensity of 0.0295 equals the EU-ETS refining benchmark, the price assumes a weight of 0.75 kg/l. Full cost increases and the demand elasticities include end-of-life emissions from incineration.

Appendix B. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2021.107168>.

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