Potential carbon leakage risk: A cross-sector cross-country assessment in the OECD area

By: J.G. Fournier Gabela and F. Freund

08.03.2022

Abstract: Achieving climate targets requires more stringent mitigation policies, including the participation of economic sectors beyond energy-intensive industries. However, what this implies for carbon leakage risks remains largely an open question. This paper aims to fill this gap by assessing potential carbon leakage risk for all sectors under varying climate policy scopes covering GHG emissions along global supply chains. To measure this risk, we use the emission-intensity and trade-exposure metric and emission data including CO_2 and non-CO_2 gasses. Under a uniform carbon price and assuming full carbon cost pass-through, we find that carbon leakage risk in downstream sectors can be as high as in sectors whose direct GHG emissions are subject to carbon pricing. We also find that agri-food and transport sectors have, on average, a higher potential risk than energy-intensive industries. Our results highlight the importance of developing sound anti-leakage mechanisms tailored to each sector's characteristics.

Keywords: unilateral climate policy, multi-regional input-output (MRIO) analysis, embodied GHG emissions, global supply chain

1. Introduction

Accordingly, most governments have already recognized the relevance of including additional sectors in their national climate policies. For instance, 148 (157) nations included the agricultural (LULUCF) sector in their Intended National Determined Contributions (INDCs) prior to the Paris Agreement (FAO, 2016). Some have taken the lead, such as the European Union with its Farm-to-Fork strategy or New Zealand with its plan to include agriculture its carbon pricing program in 2025 (Henderson *et al.*, 2020).

As governments broaden the scope of climate policies, the concern is growing about carbon leakage risk (Sugino *et al.*, 2013; Dray & Doyme, 2019; Dumortier & Elobeid, 2021; Frank *et al.*, 2021). Domestic sectors fear that the costs caused by domestic climate policy are higher than those in foreign countries, putting them at a competitive disadvantage in global markets. This disadvantage could cause their products to be replaced by cheaper products from countries whose production bears lower carbon costs. In addition to entailing economic losses for the sectors, little would be gained in terms of GHG emissions, as they would simply be displaced to countries with less stringent climate policies (Frankel & Aldy, 2008; Elliott *et al.*, 2013).

Carbon leakage is not only a concern in sectors directly targeted by climate policy, for example, those whose direct GHG emissions are subject to a carbon pricing system, but also for downstream sectors (Bushnell & Humber, 2017; Stede *et al.*, 2021). Given that indirect GHG emissions, i.e., GHG emission associated with a sector's inputs, often make up the largest share of organizations' GHG footprint, downstream sectors might face significant impacts due to carbon costs passed through higher input prices (Li *et al.*, 2020). In Germany, for example, the agricultural sector is asking for government protection due to the potential effect that implementing a carbon border adjustment mechanism (CBAM) could generate on this sector (Lehmann, 2021). While the EU's Emission Trading System (EU-ETS) already imposes carbon costs to downstream agricultural sectors via higher prices of domestic fertilizers, a CBAM would impose higher carbon costs on fertilizer imports.

There is extensive literature on identifying the most vulnerable sectors to carbon leakage (Juergens et al., 2013; Sugino et al., 2013; Sato et al., 2015; Wang et al., 2017; Santos et al., 2019; Stede et al., 2021). This literature focuses on carbon leakage risk due to specific climate policies, such as the EU-ETS or hypothetical climate policies in specific countries. Therefore, these analyses focus on some sectors, in certain countries, and on certain types of GHG. However, although they provide relevant information, this type of study is not informative for sectors and countries outside the scope of the analyzed policy. A more general analysis would allow knowing and comparing climate policy challenges in all sectors, including downstream sectors and sectors hitherto excluded from current or planned mitigation efforts. Such an analysis could, for example, help identify the most vulnerable sectors in a scenario in which a government subjects all domestic sectors to a national carbon tax. Similarly, such an analysis would allow comparing the risk of a particular sector across countries.

To fill this gap in the literature, this article assesses potential carbon leakage risk in all economic sectors and OECD countries, which generally have a higher climate ambition (World Bank, 2021). To make our results comparable and representative of different policy constellations, we assume a uniform carbon price and analyze three hypothetical climate policies of varying scope: one covering all GHG emissions, one covering only direct GHG emissions, and one covering only indirect GHG emissions. We assess potential carbon leakage risk with the help of the EITE metric, which remains an operational method used by most carbon jurisdictions worldwide. This metric is based on two simple quantitative indicators: emission intensity (EI), reflecting the potential carbon cost burden faced by sectors; and trade exposure (TE), reflecting the potential risk that imports replace domestic products.

To estimate the EITE metric, we use a global environmentally-extended (EE) multi-regional input-output (MRIO) model, which is a popular attribution model used to estimate upstream (indirect) emissions along global value chains (Hertwich & Wood, 2018; Li *et al.*, 2020). We use economic data from the GTAP-MRIO database (based on GTAP 10A), which contains harmonized economic data for 141 countries and 65 economic sectors in 2014. Compared to the usual GTAP database, the GTAP-MRIO database provides a higher resolution of international trade flows (Carrico *et al.*, 2020). Direct GHG emissions data comes from the CO_2 and non-CO_2 GTAP databases, including all GHG emissions except for land-use and land-use change (LULUC) emissions.

Our results show that, under a uniform carbon price and assuming full carbon cost pass-through, carbon leakage risk in downstream sectors could be comparable in magnitude to that of sectors directly subject to carbon pricing. Moreover, we find that that agriculture and transport sectors, usually excluded from climate policy in most countries, could have a considerable carbon leakage risk under either policy scenario. This risk is, on average, even greater than that in energy-intensive industrial sectors. We find that these sectors also have a comparatively higher cross-country variation in the OECD area.

Our article contributes to the literature in several ways. First, it provides the first cross-country cross-sector carbon leakage risk analysis based on the EITE metric. As such, it complements other more specific analyses, such as Sato et al. (2015), Wang et al. (2017), or Santos et al. (2019). Second, our results can help increase sectors' acceptance of more stringent climate policies by generating additional information on this subject, which is essential for designing sound anti-leakage policies. Third, our results are highly relevant for policy-makers. While the inter-sectoral differences suggest which sectors should receive special attention, the cross-country differences in some sectors highlight the importance of measuring risk on a country-by-country basis. Fourth, our results are also relevant for other researchers. Given that the GTAP database is often employed to analyze climate policies, researchers can compare our results towards alternative approaches to estimate sectoral carbon leakage risk. Fifth, due to the popularity of the EITE criterion in the major carbon jurisdictions, our results are relevant in an international climate policy context. In the absence of alternative operational criteria, governments will likely continue to use this criterion in the future.

2. Background

2.1. Carbon leakage & consequences

A characteristic feature of contemporary international climate policy is its high level of fragmentation. On the one hand, climate policy vastly differs from country to country. The main differences include the degree of ambition and mechanisms used to achieve mitigation targets (World Bank, 2021). On the other hand, there are differences between economic sectors. For example, in the European Union, while the EU-ETS covers manufacturing and energy sectors, the Effort-Sharing Regulation targets GHG emissions of the remaining sectors (Peeters & Athanasiadou, 2020). Also, except for British Columbia's carbon tax from 2008 to 2011, carbon pricing mechanisms have systematically excluded the agricultural sector (Murray & Rivers, 2015). From an economic point of view, this set of different mitigation policies implies the existence of divergent carbon prices across countries and sectors (OECD, 2013).

In a highly integrated world through international trade and foreign direct investments, asymmetric carbon prices can seriously undermine the effectiveness of unilateral climate mitigation policies (Frankel & Aldy, 2008; Elliott *et al.*, 2013; Frank *et al.*, 2021). This phenomenon, known as policy-induced carbon leakage, happens when GHG emissions increase unintendedly in countries with less stringent climate policies due to GHG emission reductions in countries with more ambitious climate policies (Peters, 2010; Lanzi *et al.*, 2013). These GHG emission increases can neutralize or, even worse, exceed any GHG emission savings, leading to a net increase in global GHG emission, sometimes known as carbon misallocation (Blandford, 2018).

Carbon leakage mainly happens via two channels (Frankel & Aldy, 2008; Elliott *et al.*, 2013).[1] Under the "competitiveness" channel, domestic climate policy raises production costs of regulated domestic firms resulting in a loss of competitiveness in the domestic and export markets. As a result, the unregulated foreign product replaces the more expensive domestic variety in domestic and export markets, increasing emissions in other jurisdictions. Under the "world energy price" channel, if the regulating country is large enough, policy-induced domestic demand reductions of fossil fuels cause world prices of these to fall. This, in turn, increases fossil fuel demand and GHG emissions in other countries.

Carbon leakage can bring several negative consequences. On the one hand, when economic agents expect future carbon leakage, they oppose mitigation measures. For instance, the United States used carbon leakage as an excuse for delaying mitigation action (Elliott *et al.*, 2013). Similarly, the agricultural sector has used it to justify its exclusion from carbon pricing policies (Murray & Rivers, 2015; Grosjean *et al.*, 2018). On the other hand, if carbon leakage were to materialize, besides reducing firms' competitiveness and the effectiveness of unilateral mitigation policies, carbon leakage could bring about additional costs, including reductions in production, employment, and tax revenue (Martin *et al.*, 2014b).

2.2. Sectoral carbon leakage risk assessment

Evaluating carbon leakage *ex-ante* is essential to counteract the possible consequences discussed above. On the one hand, generating information on how severe carbon leakage risk could be across economic agents helps reduce opposition to stricter climate policies by less affected agents. On the other hand, designing anti-leakage countermeasures requires carbon jurisdictions to assess carbon leakage risk *ex-ante* (Fischer & Fox, 2018; Fowlie & Reguant, 2018). For example, although anti-leakage programs could include all economic sectors, a focus on the most vulnerable sectors could significantly facilitate implementation feasibility and legality (Cosbey *et al.*, 2019).

Unfortunately, carbon leakage risk assessment is a complex task. On the one hand, there is still a severe data shortage problem, particularly concerning GHG emissions. This has forced many studies to focus on specific sectors or countries, often ignoring GHG emissions other than CO_2 from fossil-fuel combustion (Aichele & Felbermayr, 2015; Aldy & Pizer, 2015; Sato *et al.*, 2015). On the other hand, countries' limited experience in mitigation policy hinders the *ex-post* analysis of carbon leakage.[2] While the exclusion of some sectors from mitigation policies prevents any *ex-post* assessment on these sectors, anti-leakage compensation programs mask carbon leakage happening in regulated sectors (Joltreau & Sommerfeld, 2019). This is aggravated by historically low GHG emission prices and their short duration (Fischer & Fox, 2018). Because of this, ex-post studies assess potential carbon leakage risk with the help of energy or transportation cost differentials instead of carbon cost differences (Aldy & Pizer, 2015; Fowlie *et al.*, 2016; Fischer & Fox, 2018).

[1] These two channels are alternatively known as direct and indirect carbon leakage.

[2] To the best of our knowledge, Aichele and Felbermayr (2015) is the only econometric analysis of carbon leakage. However, this analysis is limited to the Kyoto protocol, only considers CO_2 emissions, and offers a rough sectoral detail (15 industries).

Given the above limitations, there are two main quantitative approaches for evaluating sectoral carbon leakage risk *ex-ante*. The first is based on economic simulation models, ranging from single-sector partial equilibrium (Monjon & Quirion, 2011; Santamaría *et al.*, 2014) to multi-sector computable general equilibrium (CGE) models (Kuik & Hofkes, 2010; Böhringer *et al.*, 2012). Despite their ability to capture an industry's technological characteristics more accurately, the main drawbacks of the former include their focus on a specific sector and the exclusion of market mechanisms potentially affecting carbon leakage. While CGE models capture complex market mechanisms, estimating carbon leakage with this type of model also faces several problems, including high data requirements. Unfortunately, many economic models on the market lack transparency, and their estimates depend on many exogenous parameters and theoretical assumptions, both crucial factors affecting carbon leakage magnitudes (Burniaux & Martins, 2012; Branger & Quirion, 2014).

The second approach refers to the EITE metric, the official approach to identify vulnerable sectors used by the largest carbon jurisdictions worldwide. These include the EU-ETS (phases 3 and 4), the South Korean ETS, the California Cap-and-Trade System (CA C&T), and New Zealand's ETS (Santos *et al.*, 2019; Sun *et al.*, 2019). This metric is based on two simple and transparent quantitative indicators: emission intensity (EI), reflecting the potential carbon cost burden faced by sectors; and trade exposure (TE), reflecting the potential trade responsiveness to the carbon cost burden.[3] [4] To identify vulnerable sectors, carbon jurisdictions usually define cut-off thresholds for each component independently and consider those sectors that exceed the threshold values of one or both components to be vulnerable. For example, according to the ETS Directive 2009/29/EC, a sector was deemed vulnerable if either its EI or TE component exceeds 30% (separated approach), or if EI exceeds 5% and its TE 10% (integrated approach) (Clò, 2010; Juergens *et al.*, 2013). Differences across jurisdictions mainly vary along the components used in for the EITE formulas and the thresholds used to define sectors' exceptions (Wang *et al.*, 2017; Santos *et al.*, 2019).

2.3. A closer look at the EITE metric

To the best of our knowledge, the EITE metric was used for the first time by a series of studies aiming to assess sectors' potential competitiveness impacts from the EU-ETS at the country level (Hourcade *et al.*, 2007; Sato *et al.*, 2007; Graichen *et al.*, 2008). That is, these authors used the EITE metric as a proxy for the potential international competitiveness losses faced by domestic sectors in particular countries. While the authors used the EI component to estimate the maximum value at stake, they introduced the TE component to measure the ability of a sector to pass through EU-ETS costs to downstream prices, which also depends on a sector's exposure to international trade. Recognizing that the EITE components ignore information on additional factors also affecting competitiveness, the authors justify its use due to the scarcity and unreliability of alternatives such as trade and demand elasticities (Graichen *et al.*, 2008).

---

[3] We prefer this definition over the one according to which the TE component is a proxy for the ability of firms to pass through carbon costs downstream. Since this ability depends only partly on international trade, we think that the last definition is closer to the analysis of competitiveness than carbon leakage.

[4] The former is usually calculated as the sum of a sector's potential direct and indirect carbon costs in relation to its gross value-added. The latter is calculated as the value of a sector's imports plus exports in relation to the value of the sector's total domestic market supply.

As a proxy for potential competitiveness losses, the EITE metric also offers a risk measure for carbon leakage through the competitiveness channel. However, as captured by the EITE metric, competitiveness losses are necessary but not sufficient for carbon leakage to happen (Clò, 2010). That is, even if subject to carbon costs and absent any support, a sector could not experience carbon leakage. This could be the case if, for example, transport costs are so high that they hinder substituting domestic output by imports (Næss-Schmidt *et al.*, 2019), or if emission intensities in third countries are lower than those domestically. Furthermore, notice that competitiveness losses say nothing about carbon leakage happening through channels other than competitiveness, for example, that which occurs in third countries due to energy prices (Aldy & Pizer, 2015). Given that known anti-leakage mechanisms only address the competitiveness channel (Monjon & Quirion, 2011; Martin *et al.*, 2014b), identifying vulnerable sectors based on a metric of carbon leakage risk through the competitive channel seems a justified practice.

The limitations of the EITE metric have led several authors to criticize its robustness for estimating carbon leakage, especially the ability of the TE component as an appropriate indicator of trade responsiveness to domestic climate policy (Fowlie *et al.*, 2016; Bushnell & Humber, 2017; Fischer & Fox, 2018; Fowlie & Reguant, 2018). However, to the best of our knowledge, only two studies formally evaluate the EITE metric's robustness. The first is Martin et al. (2014b), who compare the EITE metric against a carbon leakage risk measure based on interviews with regulated firms' managers. Because the authors find that the TE component does not correlate with carbon leakage risk, they recommend excluding developed countries when calculating it. The intuition is that, because a developed country is likely to have a more ambitious climate policy than the average country, it would be unlikely that this country serves as the source of carbon leakage of climate policy implemented in another developed country. The second study is Fowlie et al. (2016), who, by comparing econometric estimates of carbon leakage with EITE components, find that leakage risk only increases when both components increase together.

Beyond the EITE components, a further critic of the EITE metric focuses on how carbon jurisdictions use these components to decide upon a sector's vulnerability: the cut-off thresholds and whether to use the components individually or simultaneously. Regarding the former, it has been criticized that the process for setting thresholds lacks an economic rationale (Clò, 2010). Due to this, there is a high probability that the decision is subject to political influence, which would undermine the impartiality of the EITE metric. Regarding the latter, several authors note that most of the sectors that enter the list of vulnerable sectors do so through the TE component alone (Clò, 2010; De Bruyn *et al.*, 2013; Martin *et al.*, 2014b; Creason *et al.*, 2021). Due to this, several studies suggest using the two EITE components simultaneously, that is, using the so-called "integrated approach" (Clò, 2010; Droege & Cooper, 2010; Martin *et al.*, 2014b).

Finally, several studies assessing carbon leakage risk with the help of the EITE metric offer us important insights. For instance, Sato et al. (2015) highlight the importance of assessing carbon leakage risk at the country level after comparison results obtained using the EU-ETS EITE metric with data for Germany, the UK, and the EU. The authors argue that these inter-country differences depend on several factors, including differences in production processes, technologies, fuel mix, and process emissions. Sugino et al. (2013) apply two versions of the EITE metric (Waxman–Markey Bill and EU-ETS) to data on Japanese industries. The authors find considerable differences in eligibility: 23 industries under the former vs. 122 industries under the latter. In a similar paper, Santos et al. (2019) apply three versions of the EITE metric (EU-ETS, California C&T, and the

Australian Carbon Pricing Mechanism) to Brazilian data. Again, the authors find that results are susceptible to different EITE definitions. Unfortunately, neither of the two previous papers specify if the differences are due to varying definitions of the EITE components or the thresholds. De Bruyn et al. (2013) show that the number of vulnerable sectors would be considerably reduced from 60% to 33% if the EITE metric used by the EU-ETS would be applied using more realistic data, particularly concerning carbon prices, benchmarks, and geographical coverage. Creason et al. (2021) conducted a retrospective analysis of the Waxman–Markey Bill's EITE metric. Under a static EITE metric, the authors find that the number of eligible industries decreases over time, highlighting the importance of frequent updates of the list of vulnerable sectors.

3. Methodology

3.1. EE-MRIO model

To calculate sectors' EITE metric, we use an environmentally-extended (EE) multi-regional input-output (MRIO) model. On the one hand, the input-output (IO) framework has been extended since the late 1960s to account for environmental pollution generation from interindustry activity (Miller & Blair, 2009). On the other hand, many-region IO models improve single-region IO analysis by explicitly recognizing the interconnections between regions. EE-MRIO models combine these two features. Particularly because they relax the usual assumption of single-region models that the carbon content of imports equals that of domestic production, they are a helpful attribution model to estimate GHG emissions along global supply chains (Arto *et al.*, 2014; Hertwich & Wood, 2018; Li *et al.*, 2020).

Let the global economy be composed of $o, d = \{1, \dots, P\}$ countries, where o are origin and d destination countries, and $i, j = \{1, \dots, N\}$ sectors, where i denotes rows and j columns. A MRIO system of this economy can be defined by a (NP x 1) vector of output $\mathbf{x} = [x_j^d]$, a (NP x NP) matrix of intermediate demand $\mathbf{Z} = [z_{ij}^{od}]$, a (NP x P) matrix of final demand $\mathbf{Y} = [y_i^{od}]$, and a (1 x NP) vector of value added $\mathbf{v} = [v_j^d]$. For the sake of simplicity, we assume an MRIO model with exogenous international transport services, that is, we assume that the latter are part of the $\mathbf{Y}$ matrix (Peters *et al.*, 2011). This assumption implies that the calculation of indirect emissions ignores emissions due to international transport services.

Note that in the $\mathbf{Z}$ matrix, reproduced in equation 1, while the block-diagonals contain domestic inter-sectoral intermediate demand flows (from producing sector i to consuming sector i within the same country), the block-off-diagonals contain international inter-sectoral intermediate demand flows (from sector i in country o to sector j in country d). Note also that, given that a survey-based version of the $\mathbf{Z}$ table does not exist, it must be estimated. Estimation approaches typically combine national IOTs with trade data of different nature (Andrew & Peters, 2013; Tukker & Dietzenbacher, 2013). In the present study we use the $\mathbf{Z}$ table offered by the Global Trade Analysis Project (GTAP). Section 4 offers additional details.

$$\mathbf{Z} = \begin{pmatrix} \mathbf{Z}^{11} & \mathbf{Z}^{12} & \cdots & \mathbf{Z}^{1P} \\ \mathbf{Z}^{21} & \mathbf{Z}^{22} & \cdots & \mathbf{Z}^{2P} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{Z}^{P1} & \mathbf{Z}^{P2} & \cdots & \mathbf{Z}^{PP} \end{pmatrix} \qquad (1)$$

By definition, a sector's total production GHG emissions, $\mathbf{t} = [t_j^d]$, equal the sum of its direct, $\mathbf{d} = [d_j^d]$, and indirect GHG emissions, $\mathbf{i} = [i_j^d]$. This is represented by the LHS of the equivalence in equation 2. In an EE-MRIO system, this balance of sectors' embodied GHG emissions can be equivalently represented by the RHS of equation 2. According to it, total production GHG emissions ($\mathbf{t} = \mathbf{rx}$) equal those GHG emissions occurring directly inside of a sector due to the production process ($\mathbf{d} = \mathbf{cx}$) plus GHG emissions embodied in the sector's production inputs ($\mathbf{i} = \mathbf{mZ}$). Given the nature of the $\mathbf{Z}$ matrix, the latter can be either of domestic or foreign origin (imports). $\boldsymbol{r} = [r_j^d]$ is a vector of total GHG emissions coefficients (total GHG emissions per dollar's worth of sector j's output in country d), $\boldsymbol{c} = [c_j^d]$ a vector of direct GHG emission coefficients (direct GHG emissions per dollar's worth of sector j's output in country d), and $\boldsymbol{m} = [m_i^o]$ a vector of indirect GHG emission coefficients (indirect GHG emissions per dollars' worth of input i from country o). Note that, since one sector's direct GHG emissions are another sector's indirect GHG emissions, counting emissions with the help of equation 2 implies double-counting. Similar to the objective of identifying abatement opportunities for sectors, on our case double-counting is intentional due to our interest in estimating sector's potential carbon cost impact.[5]

$$\mathbf{t} \equiv \mathbf{d} + \mathbf{i} \;\leftrightarrow\; \mathbf{rx} \equiv \mathbf{cx} + \mathbf{mZ} \qquad (2)$$

Assuming one has data on direct GHG emissions, it is possible to use the EE-MRIO model to estimate indirect GHG emissions. Similarly to Hertwich & Wood (2018), we do so by assuming that $m_i^o = r_j^d$ for all $i = j$ and $o = d$ in equation 2. This assumption means that each sector in each country in the MRIO system produces a good with the same cradle-to-gate GHG emissions regardless of whether it enters intermediate or final demand. Thus, replacing **r** and **m** by $\widehat{\mathbf{m}}$ in equation 3, post-multiplying it with $\boldsymbol{x}^{-1}$, and re-arranging yields the vector $\widehat{\mathbf{m}} = \mathbf{c}(\mathbf{I} - \mathbf{A})^{-1}$, where $\mathbf{A} = \boldsymbol{Z}\boldsymbol{x}^{-1}$ is the (NP x NP) global coefficient matrix and **I** a (NP x NP) identity matrix. Post-multiplying $\widehat{\mathbf{m}}$ by the matrix of intermediate demand $\mathbf{Z}$ yields the vector of estimated indirect GHG emissions, $\hat{\mathbf{i}}$, as shown in equation 3. Due to the nature of the EE-MRIO system, we can break down the latter according to GHG emissions' origin. The final term in equation 3 considers three different origins: domestic (dom), OECD, and non-OECD. Note that this approach, according to which multipliers are applied to intermediate instead of final demand, is popular in the IO literature to estimate upstream emissions along supply chains (Huang *et al.*, 2009; Hertwich & Wood, 2018; Li *et al.*, 2020).

[5] Cases in which double-counting would become problematic include estimating total GHG emissions in the economy or assigning responsibilities to sectors (Hertwich & Wood (2018)).

$$\hat{\mathbf{i}} = \widehat{\mathbf{m}}\mathbf{Z} = \mathbf{c}(\mathbf{I} - \mathbf{A})^{-1}\mathbf{Z} = \hat{\mathbf{i}}^{(\mathbf{dom})} + \hat{\mathbf{i}}^{(\mathbf{OECD})} + \hat{\mathbf{i}}^{(\boldsymbol{non-OECD})} \qquad (3)$$

3.2. EITE metric

Equation 4 shows the emission intensity (EI) component for sector j in country d, which serves to assess a sector's relative potential carbon cost increase due to climate policy. The nominator gives the potential carbon cost increase, which equals the volume of each sector's GHG emissions multiplied by a domestic economy-wide carbon price p. Equation 4 considers all sector's GHG emissions, that is, direct and indirect GHG emissions, irrespective of origin. The denominator contains sectoral gross value added (GVA), represented by v_j^d. Besides being a popular option, Sato et al. (2015) recommend using GVA over other alternatives due to its temporal stability and sectors' direct control over it. Hence, other things equal, the larger a sector's absolute GHG emissions or the smaller sector's GVA, the larger the EI component.

$$ei_j^{d\,(TOT)} = \frac{\left(d_j^d + \hat{\iota}_j^{d\,(dom)} + \hat{\iota}_j^{d\,(OECD)} + \hat{\iota}_j^{d\,(non-OECD)}\right) \cdot p}{v_j^d} \qquad (4)$$

Note that equation 4 is based on two main assumptions. The first is that climate policy's stringency and scope are the same across countries. That is, we assume a uniform carbon price covering the same GHG emissions in each country. This assumption lets us compare sectors across countries on an equal policy "footing." Hence, different values of the EI component are only caused by differences between sectors in terms of their economic emissions intensities, that is, their volume of GHG emissions divided by GVA. Note that the magnitude of p does not matter for our comparative analysis since it scales ei_j^ds linearly. The second is that equation 4 assumes a full carbon cost pass-through rate. As long as sectors do not directly pay for their indirect GHG emissions, the additional carbon costs come through inputs due to carbon prices paid by other sectors. Departures from this assumption would lead to an overestimation of the actual carbon costs increase (Stede *et al.*, 2021).

Equation 5 shows the trade exposure (TE) component, which provides a proxy for the trade responsiveness due to domestic climate policy. This proxy is based on the weight of a country's "current" international trade volume relative to its domestic market size. More specifically, the nominator gives the value of international trade, that is, the value of exports plus imports. The denominator gives total domestic market value, which equals the value of domestic production plus imports. Similarly to Graichen et al. (2008) and in line with the suggestion by Martin et al. (2014b), we only consider export and imports to/from less developed countries, in our case, countries outside of the OECD area. Hence, the larger this indicator, the higher the risk that domestically produced goods get substituted by goods from countries with laxer climate policies.

$$te_j^d = \frac{exp_j^{d\,(non-OECD)} + imp_j^{d\,(non-OECD)}}{x_j^d + imp_j^{d\,(non-OECD)}} \qquad (5)$$

There are several alternatives on how to use the previous components for assessing carbon leakage risk. As already said in section 2, a usual identification strategy has been to deem a sector as vulnerable if one or both of its EITE components exceed pre-defined thresholds defined for each component independently (Santos *et al.*, 2019). However, given that the literature suggests using both EITE components together (Clò, 2010; Martin *et al.*, 2014b; Fowlie *et al.*, 2016), we follow the approach adopted by phase 4 of the EU-ETS. According to it, carbon leakage risk is assessed by multiplying the two EITE components to construct a carbon leakage indicator, as shown in equation 6 (European Commission, 2019). Finally, note that in the forthcoming analysis, we refrain from using thresholds due to three reasons: 1) threshold levels have been criticized for being politically motivated instead of having an economic base (Clò, 2010); 2) they depend on the choice of the carbon price; 3) due to the objective of this work of providing a comparative analysis and not presenting a definitive list of vulnerable sectors.

$$eite_j^{d\,(TOT)} = ei_j^{d\,(TOT)} \cdot te_j^d \qquad (6)$$

3.3. Scenarios

Which sector's GHG emissions to include in the EI component depends on the scope of the climate policy. Equation 4 considers the extreme situation in which a sector has carbon costs due to all its GHG emissions. However, given that the scope of climate policies differs between sectors, it is helpful to consider two additional scenarios: one in which a sector has carbon costs due to its direct GHG emissions only. In such case, the EI component is $ei_j^{d\,(DIR)}$, which only includes direct GHG emissions; and another in which a sector has carbon costs due to its indirect GHG emissions only. Similarly, the corresponding EI component is $ei_j^{d\,(IND)}$, which only includes indirect GHG emissions. The different EI components introduced above lead to different versions of equation 6: $eite_j^{d\,(DIR)} = ei_j^{d\,(DIR)} \cdot te_j^d$, and $eite_j^{d\,(IND)} = ei_j^{d\,(IND)} \cdot te_j^d$. Table 1 summarizes these scenarios.

Scenario name	GHG emissions covered (policy scope)	EI component	EITE metric
Total	All	$ei_j^{d\,(TOT)}$	$eite_j^{d\,(TOT)}$
Direct	Direct	$ei_j^{d\,(DIR)}$	$eite_j^{d\,(DIR)}$
Indirect	Indirect	$ei_j^{d\,(IND)}$	$eite_j^{d\,(IND)}$

Figure 1 Description of the climate policy scenarios.

Note that considering different climate policy scenarios makes this work's results relevant for a larger number of sectors. Because, in practice, climate policy affects sectors heterogeneously, not all sectors have the same interest in the results of each scenario. For example, looking at the case discussed in the introduction, the agricultural sector in Germany is probably more interested in knowing its potential risk of carbon leakage under the "indirect" scenario. Finally, note that the scenarios considered here do not represent climate policies with additional scopes, such as one under which a sector has carbon costs due to a subset of the inputs it uses in production. However, our results provide an upper limit of carbon leakage risk under such policies.

4. Data

Our analysis uses economic data from the GTAP-MRIO database (Carrico *et al.*, 2020). This database is based on GTAP 10A, which contains harmonized economic data for 141 global regions and 65 economic sectors in 2014. Compared to the standard GTAP database, the GTAP-MRIO database provides a higher resolution of international trade flows (Carrico *et al.*, 2020). As such, it provides a fully compatible dataset with the information requirements of a global MRIO model. More specifically, we construct the $\mathbf{Z}$ table in equation 1 by combining the *VDFM* and VIFM tables.[6] [7] The $\mathbf{x}$ vector is, as usual, the column-wise addition of the *VDFM*, *VXMD*, *VDPM*, *VDGM*, and *VST* tables. The $\mathbf{v}$ vector corresponds to the *VFM* table. Finally, we calculate exports with the help of the *VXMD* table and imports by adding up the *VIFM*, *VIPM*, and *VIGM* tables. The upper part of table B1 in appendix B contains a short description of these economic tables. For additional details on these tables, the reader is referred to the GTAP documentation.

Direct GHG emissions data comes from the CO_2 and non-CO_2 GTAP databases (Lee, 2008; Chepeliev, 2020). These databases provide sector and country-level GHG emissions except for land-use and land-use change (LULUC) emissions. More specifically, we construct our vector of direct GHG emissions, $\mathbf{d}$, by summing over CO_2 emissions (*MDF* and *MIF* tables), and non-CO_2 emissions (*NCQO*, *NCQE*, and *NCQF* tables). The lower part of table B1 in appendix B contains a short description of these environmental tables. Note that, since we are interested in cradle-to-gate emissions only, we ignore GHG emissions data related to final consumption. The volume of direct GHG emissions globally adds up to 38,41 billion tCO_2eq, of which 67.5% and 32.5% correspond to CO_2 and non- CO_2 emissions, respectively. The volume of indirect GHG emissions globally, as estimated by the EE-MRIO model, adds up to 71,42 billion tCO2eq. These totals are higher than those in Hertwich & Wood (2018) for 2015 because we include non-CO2 emissions in our analysis.

Although we used all the regions available in the GTAP datasets to calculate the EITE components, we only present results for the OECD countries in this work. Column four of table B3 in Appendix B indicates which GTAP regions are OECD countries. There is a one-to-one relationship for 37 out of 38 OECD countries. The exception refers to Iceland, which GTAP includes in the Rest of European Free Trade Association (XEF) region together with other countries. Due to this, we only consider 37

[6] To achieve a symmetric sector-by-sector matrix, we consider investment to be part of the final demand.

[7] Market prices are prices paid by purchasers, including domestic margins, less commodity taxes.

OECD countries in the analysis. Column five of the same table indicates which GTAP regions are carbon-pricing countries, according to the World Bank report (World Bank, 2021). We see that all but four OECD countries belong to the latter list.

To make our results comparable to other studies (Clò, 2010; Juergens *et al.*, 2013; Stede *et al.*, 2021), we use a benchmark carbon price of $30/tCO2e for calculating the EI component. After calculating the EITE component for each of the 2405 observations (37 OECD countries x 65 sectors), we noticed several observations with extremely high values for the EI component. Although we think that very high values of the EI component for certain sector-country combinations can be legitimate, we removed these observations to avoid our results depending on extreme values. To remove these observations, we used the inter-quartile range (IQR) method at the sector level, according to which observations above (below) the third (first) quartile of the data plus (minus) 1.5 times the IQR are removed. That leaves us with a total of 2237 observations.

Finally, table B2 in Appendix B contains GTAP sectors and concordances. Columns three and four contain Central Product Classification (version 2.1) and UN ISIC (revision 4) concordances, respectively.[8] Column five contains concordances with the seven sector groups used by Hertwich & Wood (2018) and Li et al. (2020): AFOLU+, buildings, energy, industry, materials, transport, and services. The AFOLU+ group includes all agri-food products plus forestry-related GTAP sectors. GTAP's traditional manufacturing sectors are split between the industry and materials groups. The materials group includes all the traditional energy-intensive manufacturing sectors identified by the energy literature (Fischer & Fox, 2018). These are paper products & printing (ppp*), chemical products (chm*), rubber and plastic products (rpp*), basic pharmaceutical products (bph*), mineral products n.e.c. (nmm*), ferrous metals (i_s*), and metals n.e.c. (nfm*). Since these sectors serve as a natural reference for the other sectors, we flag them with an asterisk to improve visibility through the analysis.

5. Results

5.1. GTAP sectors

Figure 1 plots sector averages for the EI and TE components in OECD countries under the "total" scenario, i.e., each sector bears carbon costs due to all its GHG emissions. The different colors indicate membership to one of the seven sector groups, and the size of the circles indicates cross-country variation (standard deviation) in the OECD area. Besides the unsurprising high emission intensity of the petroleum & coal products (p_c) sector, we see notable differences between the sector groups. For example, we see that the sectors belonging to AFOLU+ are generally more emission-intensive than those belonging to industry. Likewise, we see that the sectors belonging to services and construction have a much lower variation across OECD countries than those belonging to energy. The left panel of table A1 in appendix A shows the ten sectors with the highest risk of carbon leakage under this scenario. There are four sectors belonging to energy: petroleum & coal products (p_c), coal (coa), gas manufacture & distribution (gdt), and gas; three to AFOLU+: processed rice (pcr), paddy rice (pdr), and plant-based fibers (pfb); two to materials: ferrous metals

[8] GTAP provides concordances of agricultural and food processing sectors with respect to CPC to have additional details.

(i_s*), and chemical products (chm*); and one to transport: air transport (atp). Although it is not surprising that energy sectors rank very high, it is surprising to see that several non-energy and non-manufacturing sectors make this list.

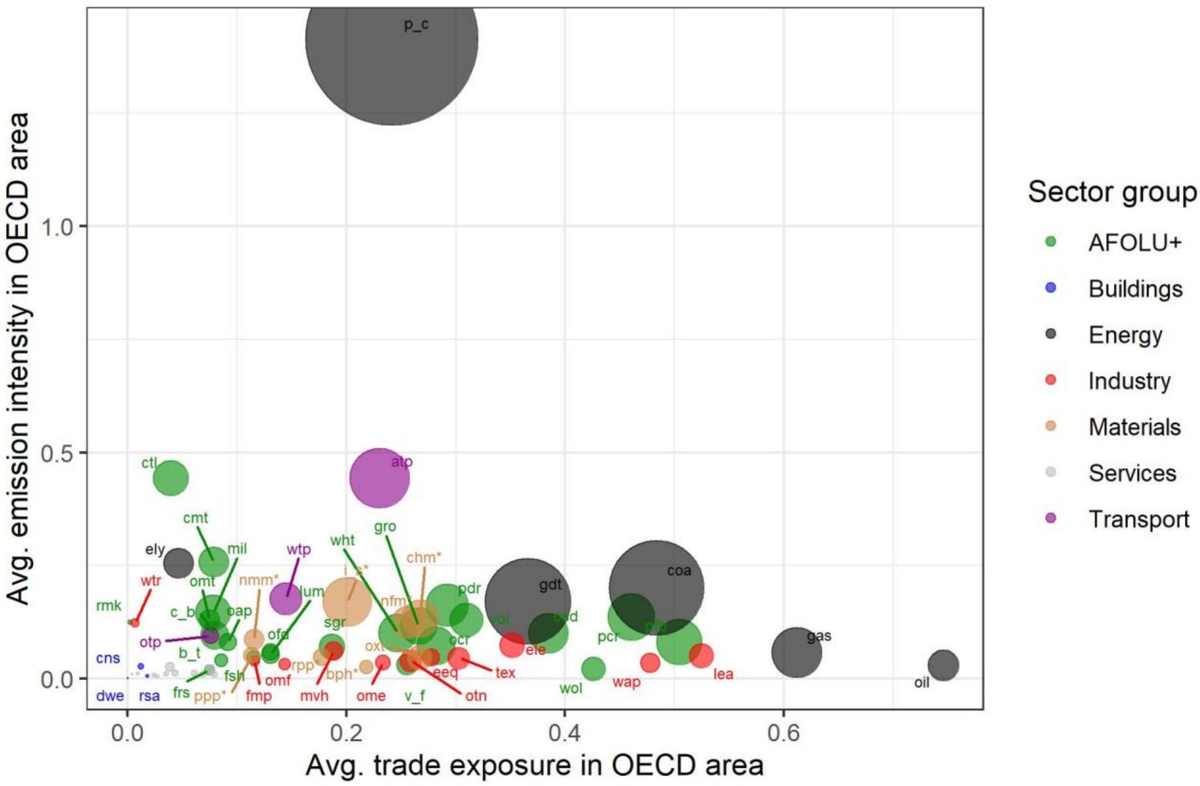

Figure 1 Emission intensity vs. trade exposure under the "total" scenario, OECD country averages by sector. Note: The circles' area is proportional to the cross-country variation (standard deviation) of the EITE metric in the OECD area.

Now we analyze how the results change as we consider the two alternative climate policy scenarios. The larger the difference between the EI components, the more variation in carbon leakage risk under different climate policies. Although we know that the EI component in these two scenarios must be lower for every sector, figure 3 shows that potential carbon cost differences can be highly heterogeneous across sectors. The sectors with the highest absolute difference are petroleum & coal products (p_c), bovine animals, horses & other equines (ctl), and air transport (atp). We also see differences between sector groups: sectors belonging to AFOLU+ have a higher absolute span between the different EI components compared to industry sectors.

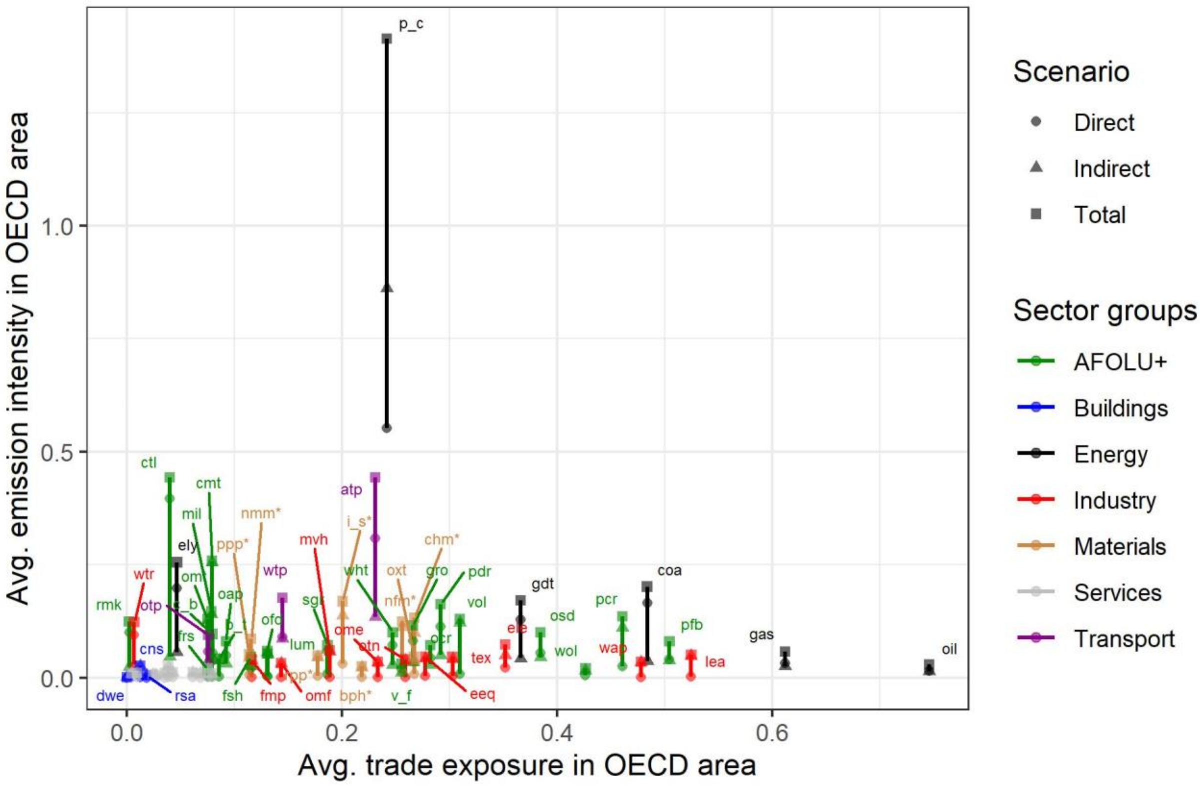

Figure 2 Emission intensity vs. trade exposure under different scenarios, OECD country averages by sector.

Naturally, these alternative scenarios lead to different sectoral rankings, given by the middle and right panels of table A1 in appendix A, respectively. For example, under the second scenario, there is a larger number of sectors belonging to AFOLU+: plant-based fibers (pfb), cereal grains (gro), paddy rice (pdr), wheat (wht), and bovine animals, horses & other equines (ctl). Importantly, the EITE values under the direct and indirect scenarios are comparable in magnitude. Considering only the top 10 ranking, they rank from 0.017 to 0.262 and from 0.021 to 0.161 under the direct and indirect scenarios, respectively. Finally, figures A1 and A2 in appendix A give the counterparts of figure 1 for the direct and indirect scenarios, respectively.

5.2. Sector groups

Figure 3 shows the average value of the EITE components in the OECD area by sector group. Table A2 in appendix A contains the corresponding values. Beginning with EI components, we see that the share of potential carbon cost due to indirect GHG emissions is substantial for all sectors. It exceeds that due to direct GHG emissions for all sector groups besides energy and transport, and accounts for about ninety percent of total EI in services and buildings. We also see that most carbon costs due to indirect GHG emissions are domestic. An exception is energy, whose GHG emissions originating in non-OECD countries make the greatest share of potential indirect carbon costs. Considering total EIs, we see that, due to their nature, the services and buildings sectors are very low emission-intensive sectors. In contrast, the energy sector has the highest EI (0.38), followed by transport (0.24), AFOLU+ (0.11), materials (0.085), and industry (0.053). Notably, the transport and AFOLU+ sectors have a higher emission intensity than the materials sector. Turning to the TE component, Figure 3 shows that energy is again the most trade-exposed sector (0.404), followed by industry (0.262), materials (0.202), AFOLU+ (0.200), and transport (0.151). The services and buildings sectors have a shallow trade exposure. By comparing total EI and TE across sectors, we see that buildings and services have the lowest values while the energy sector is by far both the most trade-exposed and emission-intensive sector. We see a negative correlation between the EI and TE components for the four remaining sectors.

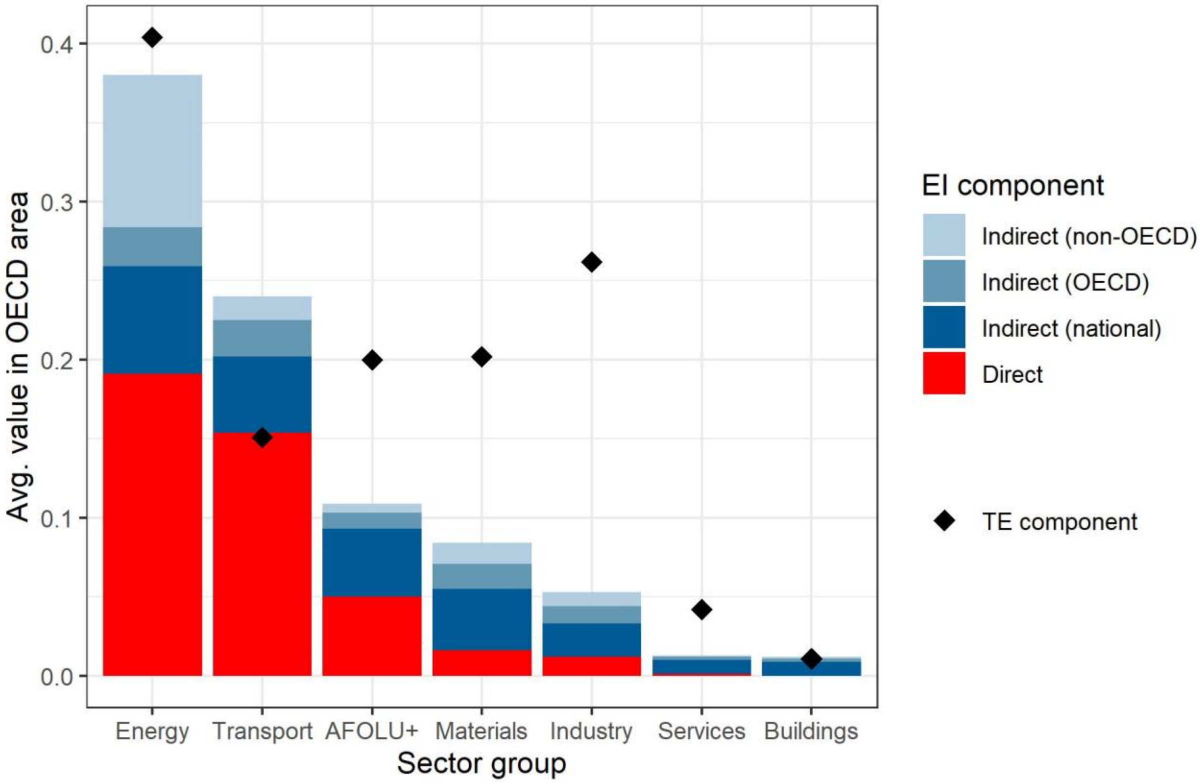

Figure 3 Average value of EITE components in OECD countries, by sector group. Note: averages are calculated by taking the mean of the EITE component value over sectors belonging to the sector group in OECD countries.

Figure 4 shows values for the EITE metric, i.e., the product of EI and TE, under each of three different scenarios. We can see that, while energy and transport have the highest potential carbon leakage risk among all scenarios, buildings and services have almost negligible risk. We can also see that due to the relatively large weight of direct GHG emission in carbon costs in the energy and transport sectors, carbon leakage risk under the “direct” scenario is higher than in the other two scenarios for these sectors. We see that carbon leakage risk is relatively similar among AFOLU+, materials, and industry under all scenarios. This is a crucial finding since materials contain traditional energy-intensive manufacturing sectors usually considered vulnerable to carbon leakage in the energy literature. Focusing only on these three sectors groups, we see that, while the materials group has slightly higher carbon leakage risk than AFOLU+ and industry under the total and indirect scenarios, AFOLU+ has a higher carbon leakage risk under the direct scenario. This is due to the relatively larger weight of direct GHG emissions in the AFOLU+ sector.

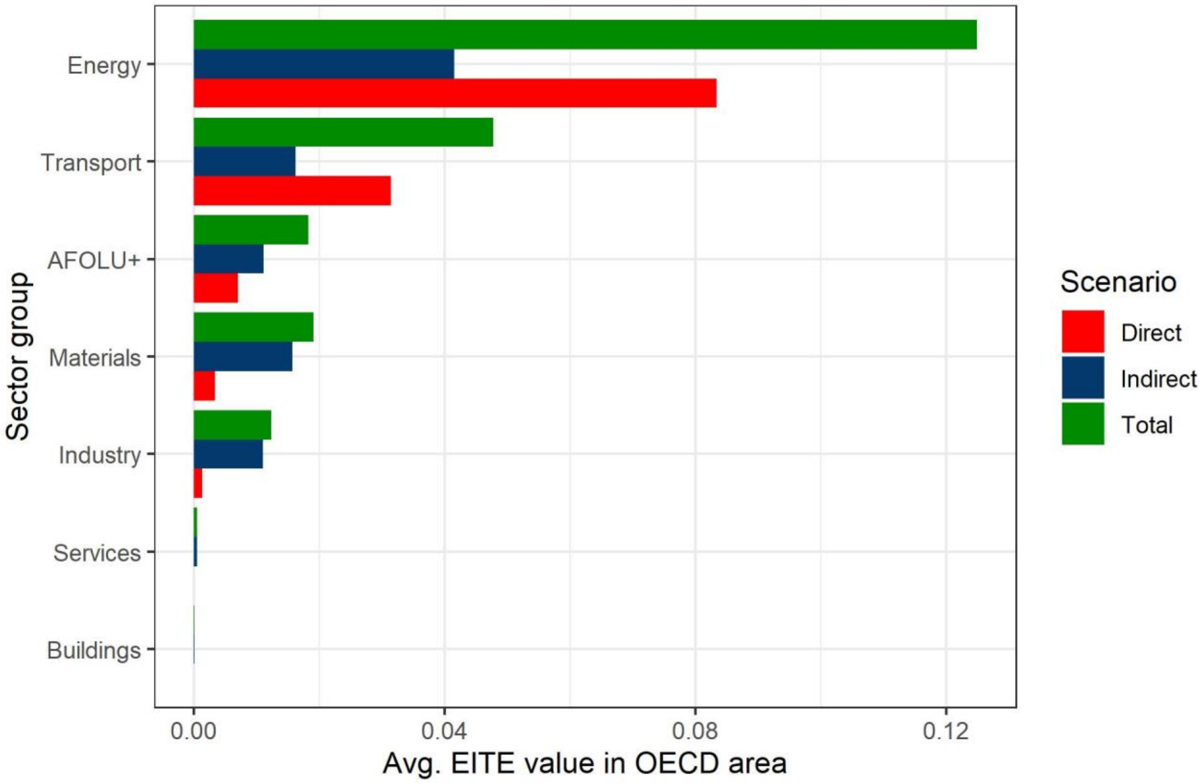

Figure 4 Average EITE value in OECD countries for different scenarios, by sector group. Note: averages are calculated by taking the mean of the EITE value over sectors belonging to the sector group in OECD countries.

Finally, Figure 5 shows how the EITE value under the "total" scenario varies across countries. It is immediately visible that, while energy and transport have the higher cross-country variation than other sector groups, services and buildings have the lowest variation. This plot is particularly interesting for country-sector comparisons. For instance, while carbon leakage risk in the AFOLU+ sector is similar in the USA (0.013) and Japan (0.009), in Estonia (0.055) is about five to six times larger than in the USA and Japan.

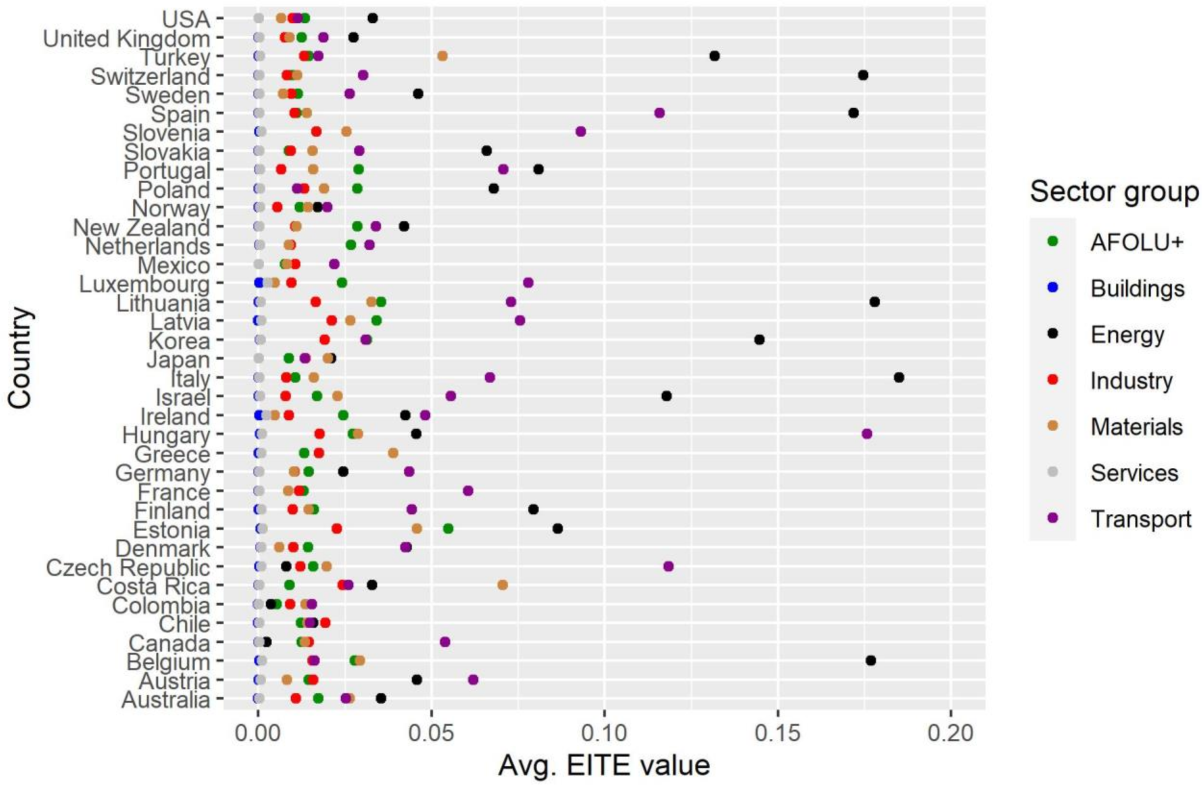

Figure 5 Average EITE value under the "total" scenario, by OECD country. Notes: to improve visualization, this figure does not show the following EITE values belonging energy: Slovenia (1.454), Luxemburg (0.726), Latvia (0.556), France (0.302), Netherlands (0.264), and Greece (0.232). Averages are calculated by taking the mean of the EITE value over sectors belonging to the sector group in OECD countries.

6. Discussion and limitations

We believe that there are two key findings in our results. The first is that carbon leakage risk under the direct and indirect scenarios is comparable in magnitude. The second is that sectors belonging to AFOLU+ and transport, usually excluded from climate policy in most countries, could have a considerable carbon leakage risk. This risk is, on average, even greater than that in energy-intensive industrial sectors. Both findings underscore the importance of developing anti-leakage mechanisms also for downstream and non-traditional sectors. Ideally, this type of mechanism should be part of climate policy design from the very beginning to improve political support for more stringent climate policy (Metcalf & Weisbach, 2009).

As stated in section 3, the hypothetical climate policy that we assume in this work, including the scenarios and the carbon price, are not representative of all cases. Even so, our results are informative from a comparative point of view. For example, a country can see how different the risk of leakage is between sectors under a carbon pricing scheme that includes all sectors. Likewise, a sector can know its potential carbon leakage risk under a climate policy that makes its indirect emissions more expensive. Obviously, if the carbon price is higher in a particular country, the EITE value needs to be adjusted accordingly. The different sectors and countries interested in more detailed results can read the complete results in the supplementary material that we offer together with this paper.

A limitation of the data used in this analysis is its high level of sectoral aggregation. As is already known, the higher the within-sector heterogeneity, the stronger the confounding effect risk of analyses using aggregated data (Juergens *et al.*, 2013; Steen-Olsen *et al.*, 2014). In other words, the fact that a sector has low carbon leakage risk neither means that all of its subsectors must have the same low risk. This problem motivates several authors to work with more disaggregated data. Unfortunately, a comprehensive comparison using all economic sectors and countries, such as the one presented in this paper, would not have been possible using more disaggregated data. The latter is usually not available for all countries, not comparable between sectors, and often based on unreliable sources, such as self-reported data (Sato *et al.*, 2015).

It is important to remind the reader that the GHG emissions data we have used excludes land use (LU) and land-use change (LUC) emissions. While a typical example of a LU emission source is the burning of biomass (forest fires and agricultural burning), an example of LUC emissions is deforestation. LULUC emissions are not to underestimate, as they make a significant part of global total GHG emissions. For example, Chepeliev (2020) estimates net global LU GHG emissions for 2014 in 3.58 billion tCO2eq, or equivalently 9.3% of the global GHG emissions considered in this study. Consequently, the emission intensities of several sectors, mainly land-based sectors such as several belonging to the AFOLU+ group, are likely to be underestimated in this study.

Finally, we think that due to the limitations of the EITE metric mentioned in section 2, a formal carbon leakage risk analysis on specific climate policies should combine the EITE metric with additional criteria. An accurate carbon leakage risk assessment is necessary to guarantee the efficiency and legality of anti-leakage mechanisms (Cosbey *et al.*, 2019). Taking the EU-ETS as an example again, studies find that free allocation under the EU's strategy to assess carbon leakage risk has led to overcompensation (Martin *et al.*, 2014a). Overcompensation reduces the credibility of carbon pricing, reduces economic efficiency, and lessens the incentives of mitigating emissions (Martin *et al.*, 2014b; Sato *et al.*, 2015).

7. Conclusions

Stopping global warming in time requires the contribution of more and more economic sectors beyond the energy and energy-intensive sectors. However, due to the high degree of fragmentation of global climate policy, there is concern about the effects that increasing the scope of these climate policies could have on these sectors. Carbon leakage implies reducing the competitiveness of sectors without achieving the full mitigation objectives. The evidence presented in this article suggests that sectors traditionally excluded from climate policy, such as transport and agriculture, would have an even higher risk of carbon leakage than energy-intensive industries, traditionally considered vulnerable to carbon leakage. Furthermore, we find that in some sectors, carbon leakage risk can be quite variable between OECD countries. Our results highlight the importance of assessing carbon leakage risks and developing anti-leakage mechanisms for each sector and country. Given that carbon leakage risk is regarded as one of the main obstacles to accepting more stringent climate policies, developing a broad set of anti-leakage mechanisms is crucial. If optimally designed, these mechanisms could become legal, prevent competitiveness losses, and avoid situations of overcompensation.

1 Supplementary material

Supplementary material for this paper includes a table containing values for the EITE components and metrics at the sector level, and a table containing EITE values for each sector group at the country level. Furthermore, the full dataset used for this paper is available under request.

References

Aguiar, A., Chepeliev, M., Corong, E.L., McDougall, R. & van der Mensbrugghe, D. (2019) The GTAP Data Base: Version 10. *Journal of Global Economic Analysis*, 4(1), 1–27. Available from: https://doi.org/10.21642/JGEA.040101AF.

Aichele, R. & Felbermayr, G. (2015) Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade. *Review of Economics and Statistics*, 97(1), 104–115. Available from: https://doi.org/10.1162/REST_a_00438.

Aldy, J.E. & Pizer, W.A. (2015) The competitiveness impacts of climate change mitigation policies. *Journal of the Association of Environmental and Resource Economists*, 2(4), 565–595. Available from: https://doi.org/10.1086/683305.

Andrew, R.M. & Peters, G.P. (2013) A multi-regional input-output table based in the Gobal Trade Analysis Project database (GTAP-MRIO). *Economic Systems Research*, 25(1), 99–121. Available from: https://doi.org/10.1080/09535314.2012.761953.

Arto, I., Rueda-Cantuche, J.M. & Peters, G.P. (2014) Comparing the GTAP-MRIO and WIOD databases for carbon foorprint analysis. *Economic Systems Research*, 26(3), 327–353. Available from: https://doi.org/10.1080/09535314.2014.939949.

Blandford, D. (2018) *Border and related measures in the context of adaptation and mitigation to climate change*, Rome. The State of Agricultural Commodity Markets (SOCO): Background paper.

Böhringer, C., Carbone, J.C. & Rutherford, T.F. (2012) Unilateral climate policy design: Efficiency and equity implications of alternative instruments to reduce carbon leakage. *Energy Economics*, 34, S208-S217. Available from: https://doi.org/10.1016/j.eneco.2012.09.011.

Branger, F. & Quirion, P. (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. Available from: https://doi.org/10.1016/j.ecolecon.2013.12.010.

Burniaux, J.-M. & Martins, J.O. (2012) Carbon leakages: A general equilibrium view. *Economic Theory*, 49(2), 473–495. Available from: https://doi.org/10.1007/s00199-010-0598-y.

Bushnell, J. & Humber, J. (2017) Rethinking trade exposure: The incidence of environmental charges in the nitrogenous fertilizer Industry. *Journal of the Association of Environmental and Resource Economists*, 4(3), 857–894. Available from: https://doi.org/10.1086/692506.

Carrico, C., Corong, E. & van der Mensbrugghe, D. (2020) *The GTAP 10A multi-region input output (MRIO) data base*. Research Memorandum: 34.

Chepeliev, M. (2020) *Development of the non-CO2 GHG emissions database for the GTAP data base version 10A*. Research Memorandum: 32.

Clò, S. (2010) Grandfathering, auctioning and Carbon Leakage: Assessing the inconsistencies of the new ETS Directive. *Energy Policy*, 38(5), 2420–2430. Available from: https://doi.org/10.1016/j.enpol.2009.12.035.

Cosbey, A., Droege, S., Fischer, C. & Munnings, C. (2019) Developing Guidance for Implementing Border Carbon Adjustments: Lessons, Cautions, and Research Needs from the Literature. *Review of Environmental Economics and Policy*, 13(1), 3–22. Available from: https://doi.org/10.1093/reep/rey020.

Creason, J., Alsalam, J., Chiu, K. & Fawcett, A.A. (2021) Energy intensive manufacturing industries and GHG emissions. *Climate Change Economics*, 12(3). Available from: https://doi.org/10.1142/s201000782150010x.

De Bruyn, S., Nelissen, D. & Koopman, M. (2013) *Carbon leakage and the future of the EU ETS market: Carbon leakage and the future of the EU ETS market Impact of recent developments in the EU ETS on the list of sectors deemed to be exposed to carbon leakage*, Delft. Report.

Dray, L. & Doyme, K. (2019) Carbon leakage in aviation policy. *Climate Policy*, 19(10), 1284–1296. Available from: https://doi.org/10.1080/14693062.2019.1668745.

Droege, S. & Cooper, S. (2010) *Tackling Leakage in a World of Unequal Carbon Prices – A study for the Greens/EFA Group*.

Dumortier, J. & Elobeid, A. (2021) Effects of a carbon tax in the United States on agricultural markets and carbon emissions from land-use change. *Land Use Policy*, 103, 105320. Available from: https://doi.org/10.1016/j.landusepol.2021.105320.

Elliott, J., Foster, I., Kortum, S., Khun Jush, G., Munson, T. & Weisbach, D. (2013) Unilateral Carbon Taxes, Border Tax Adjustments and Carbon Leakage. *Theoretical Inquiries in Law*, 14(1). Available from: https://doi.org/10.1515/til-2013-012.

European Commission (2019) Commission delegated decision (EU) 2019/708 of 15 February 2019: supplementing Directive 2003/87/EC of the European Parliament and of the Council concerning the determination of sectors and subsectors deemed at risk of carbon leakage for the period 2021 to 2030. *Official Journal of the European Union*, L 120.

FAO (2016) *The agriculture sectors in the Intended Nationally Determined Contributions: Analysis*, Rome. Environment and Natural Resources Management working paper: 62.

Fischer, C. & Fox, A.K. (2018) How Trade Sensitive Are Energy-Intensive Sectors? *AEA Papers and Proceedings*, 108, 130–135. Available from: https://doi.org/10.1257/pandp.20181088.

Fowlie, M. & Reguant, M. (2018) Challenges in the Measurement of Leakage Risk. *AEA Papers and Proceedings*, 108, 124–129. Available from: https://doi.org/10.1257/pandp.20181087.

Fowlie, M.L., Reguant, M. & Ryan, S.P. (2016) *Measuring leakage risk*.

Frank, S., Havlík, P., Tabeau, A., Witzke, P., Boere, E. & Bogonos, M. et al. (2021) How much multilateralism do we need? Effectiveness of unilateral agricultural mitigation efforts in the global context. *Environmental Research Letters*, 16(10), 104038. Available from: https://doi.org/10.1088/1748-9326/ac2967.

Frankel, J.A. & Aldy, J.E. (2008) Addressing the Leakage/Competitiveness Issue in Climate Change Policy Proposals [with Comment]. *Brookings Trade Forum*, 69–91.

Graichen, V., Schumacher, K., Matthes, F.C., Mohr, L., Duscha, V. & Schleich, J. et al. (2008) *Impacts of the EU Emissions Trading Scheme on the industrial competitiveness in Germany*, Dessau-Roßlau. Research Report: 3707 41 501.

Grosjean, G., Fuss, S., Koch, N., Bodirsky, B.L., Cara, S. de & Acworth, W. (2018) Options to overcome the barriers to pricing European agricultural emissions. *Climate Policy*, 18(2), 151–169. Available from: https://doi.org/10.1080/14693062.2016.1258630.

Henderson, B., Frezal, C. & Flynn, E. (2020) *A survey of GHG mitigation policies for the agriculture, forestry and other land use sector*, Paris. OECD food, agriculture and fisheries papers: 145. Available from: https://doi.org/10.1787/59ff2738-en.

Hertwich, E.G. & Wood, R. (2018) The growing importance of scope 3 greenhouse gas emissions from industry. *Environmental Research Letters*, 13(10), 104013. Available from: https://doi.org/10.1088/1748-9326/aae19a.

Höhne, N., Gidden, M.J., Elzen, M. den, Hans, F., Fyson, C. & Geiges, A. et al. (2021) Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nature Climate Change*, 11(10), 820–822. Available from: https://doi.org/10.1038/s41558-021-01142-2.

Hourcade, J.-C., Demailly, D., Neuhoff, K. & Sato, M. (2007) *Climate Strategies Report: Differentiation and Dynamics of EU ETS Industrial*. Report.

Huang, Y.A., Weber, C.L. & Matthews, H.S. (2009) Categorization of Scope 3 emissions for streamlined enterprise carbon footprinting. *Environmental Science & Technology*, 43(22), 8509–8515. Available from: https://doi.org/10.1021/es901643a.

Joltreau, E. & Sommerfeld, K. (2019) Why does emissions trading under the EU Emissions Trading System (ETS) not affect firms' competitiveness? Empirical findings from the literature. *Climate Policy*, 19(4), 453–471. Available from: https://doi.org/10.1080/14693062.2018.1502145.

Juergens, I., Barreiro-Hurlé, J. & Vasa, A. (2013) Identifying carbon leakage sectors in the EU ETS and implications of results. *Climate Policy*, 13(1), 89–109. Available from: https://doi.org/10.1080/14693062.2011.649590.

Kuik, O. & Hofkes, M. (2010) Border adjustment for European emissions trading: Competitiveness and carbon leakage. *Energy Policy*, 38(4), 1741–1748. Available from: https://doi.org/10.1016/j.enpol.2009.11.048.

Lanzi, E., Mullaly, D., Château, J. & Dellink, R. (2013) *Addressing competitiveness and carbon leakage impacts arising from multiple carbon markets: A modelling assessment*. OECD environment working papers. 58.

Lee, H.-L. (2008) *The combustion-based CO2 emissions data for GTAP Version 7 data base*. GTAP Resource: 1143.

Lehmann, N. (2021) Land- und Forstwirtschaft in der EU sollen Klimaneutral werden [Agriculture and forestry in the EU should become climate-neutral]. *agrarheute,* 14 July. Available from: https://www.agrarheute.com/politik/land-forstwirtschaft-eu-klimaneutral-583358 [Accessed 21 February 2022].

Li, M., Wiedmann, T. & Hadjikakou, M. (2020) Enabling Full Supply Chain Corporate Responsibility: Scope 3 Emissions Targets for Ambitious Climate Change Mitigation. *Environmental Science & Technology*, 54(1), 400–411. Available from: https://doi.org/10.1021/acs.est.9b05245.

Martin, R., Muûls, M., Preux, L.B. de & Wagner, U.J. (2014a) Industry Compensation under Relocation Risk: A Firm-Level Analysis of the EU Emissions Trading Scheme. *American Economic Review*, 104(8), 2482–2508. Available from: https://doi.org/10.1257/aer.104.8.2482.

Martin, R., Muûls, M., Preux, L.B. de & Wagner, U.J. (2014b) On the empirical content of carbon leakage criteria in the EU Emissions Trading Scheme. *Ecological Economics*, 105, 78–88. Available from: https://doi.org/10.1016/j.ecolecon.2014.05.010.

Metcalf, G.E. & Weisbach, D. (2009) The design of a carbon tax. *Harvard Environmental Law Review*, 33, 499.

Miller, R.E. & Blair, P.D. (2009) *Input–Output Analysis*. Cambridge University Press: Cambridge.

Monjon, S. & Quirion, P. (2011) Addressing leakage in the EU ETS: Border adjustment or output-based allocation? *Ecological Economics*, 70(11), 1957–1971. Available from: https://doi.org/10.1016/j.ecolecon.2011.04.020.

Murray, B. & Rivers, N. (2015) British Columbia's revenue-neutral carbon tax: A review of the latest "grand experiment" in environmental policy. *Energy Policy*, 86, 674–683. Available from: https://doi.org/10.1016/j.enpol.2015.08.011.

Næss-Schmidt, H.S., Hansen, M.B.W., Holm, S.R., Lumby, B.M., Rygner Holm, S. & Modvig Lumby, B. (2019) *Carbon leakage in the Nordic countries: What are the risks and how to design effective preventive policies*. Nordic Council of Ministers: Copenhagen.

OECD (2013) *Effective Carbon Prices*. OECD Publishing: Paris.

Peeters, M. & Athanasiadou, N. (2020) The continued effort sharing approach in EU climate law: Binding targets, challenging enforcement? *Review of European, Comparative & International Environmental Law*, 29(2), 201–211. Available from: https://doi.org/10.1111/reel.12356.

Peters, G.P. (2010) Policy Update: Managing carbon leakage. *Carbon Management*, 1(1), 35–37. Available from: https://doi.org/10.4155/cmt.10.1.

Peters, G.P., Andrew, R. & Lennox, J. (2011) Constructing an environmentally-extended multi-regional input-output table using the GTAP database. *Economic Systems Research*, 23(2), 131–152. Available from: https://doi.org/10.1080/09535314.2011.563234.

Rogelj, J., Popp, A., Calvin, K.V., Luderer, G., Emmerling, J. & Gernaat, D. et al. (2018) Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change*, 8(4), 325–332. Available from: https://doi.org/10.1038/s41558-018-0091-3.

Santamaría, A., Linares, P. & Pintos, P. (2014) The effects of carbon prices and anti-leakage policies on selected industrial sectors in Spain – Cement, steel and oil refining. *Energy Policy*, 65, 708–717. Available from: https://doi.org/10.1016/j.enpol.2013.10.031.

Santos, L., Lucena, A.F.P. & Garaffa, R. (2019) Would different methodologies for assessing carbon leakage exposure lead to different risk levels? A case study of the Brazilian industry. *Climate Policy*, 19(9), 1102–1116. Available from: https://doi.org/10.1080/14693062.2019.1627180.

Sato, M., Grubb, M., Cust, J., Chan, K., Korppoo, A. & Ceppi, P. (2007) *Differentiation and dynamics of competitiveness impacts from the EU ETS*. Cambridge Working Papers in Economics: CWPE0712. Available from: https://doi.org/10.17863/CAM.5176.

Sato, M., Neuhoff, K., Graichen, V., Schumacher, K. & Matthes, F. (2015) Sectors Under Scrutiny: Evaluation of Indicators to Assess the Risk of Carbon Leakage in the UK and Germany. *Environmental and Resource Economics*, 60(1), 99–124. Available from: https://doi.org/10.1007/s10640-014-9759-y.

Stede, J., Pauliuk, S., Hardadi, G. & Neuhoff, K. (2021) Carbon pricing of basic materials: Incentives and risks for the value chain and consumers. *Ecological Economics*, 189, 107168. Available from: https://doi.org/10.1016/j.ecolecon.2021.107168.

Steen-Olsen, K., Owen, A., Hertwich, E.G. & Lenzen, M. (2014) Effects of sector aggregation on CO2 multipliers in multiregional input-output analysis. *Economic Systems Research*, 26(3), 284–302. Available from: https://doi.org/10.1080/09535314.2014.934325.

Sugino, M., Arimura, T.H. & Morgenstern, R.D. (2013) The effects of alternative carbon mitigation policies on Japanese industries. *Energy Policy*, 62, 1254–1267. Available from: https://doi.org/10.1016/j.enpol.2013.06.074.

Sun, Y., Xue, J., Shi, X., Wang, K., Qi, S. & Wang, L. et al. (2019) A dynamic and continuous allowances allocation methodology for the prevention of carbon leakage: Emission control coefficients. *Applied energy*, 236, 220–230. Available from: https://doi.org/10.1016/j.apenergy.2018.11.095.

Tukker, A. & Dietzenbacher, E. (2013) Global multiregional input-output frameworks: An introduction and outlook. *Economic Systems Research*, 25(1), 1–19. Available from: https://doi.org/10.1080/09535314.2012.761179.

Wang, X., Teng, F., Zhou, S. & Cai, B. (2017) Identifying the industrial sectors at risk of carbon leakage in China. *Climate Policy*, 17(4), 443–457. Available from: https://doi.org/10.1080/14693062.2015.1104497.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M. & Tubiello, F.N. et al. (2016) Reducing emissions from agriculture to meet the 2 °C target. *Global Change Biology*, 22(12), 3859–3864. Available from: https://doi.org/10.1111/gcb.13340.

World Bank (2021) *State and trends of carbon pricing 2021*, Washington, DC.

2Appendix A

	Scenario								
	Total			Direct			Indirect		
No.	Sector	Sector group	EITE	Sector	Sector group	EITE	Sector	Sector group	EITE
1	Petroleum & coal products	Energy	0.424 (0.771)	Petroleum & coal products	Energy	0.262 (0.772)	Petroleum & coal products	Energy	0.161 (0.174)
2	Coal	Energy	0.125 (0.232)	Coal	Energy	0.106 (0.222)	Processed rice	AFOLU+	0.042 (0.034)
3	Air transport	Transport	0.106 (0.089)	Gas manufacture & distribution	Energy	0.076 (0.162)	Vegetable oils & fats	AFOLU+	0.035 (0.026)
4	Gas manufacture & distribution	Energy	0.095 (0.190)	Air transport	Transport	0.073 (0.062)	Ferrous metals	Materials	0.033 (0.047)
5	Processed rice	AFOLU+	0.055 (0.055)	Gas	Energy	0.023 (0.035)	Air transport	Transport	0.032 (0.028)
6	Gas	Energy	0.044 (0.063)	Plant-based fibers	AFOLU+	0.019 (0.025)	Chemical products	Materials	0.029 (0.028)
7	Ferrous metals	Materials	0.040 (0.060)	Cereal grains not elsewhere classified (n.e.c.)	AFOLU+	0.019 (0.022)	Metals n.e.c.	Materials	0.029 (0.021)
8	Paddy rice	AFOLU+	0.039 (0.044)	Paddy rice	AFOLU+	0.019 (0.018)	Leather products	Industry	0.025 (0.013)
9	Plant-based fibers	AFOLU+	0.039 (0.051)	Wheat	AFOLU+	0.018 (0.025)	Bovine meat products	AFOLU+	0.021 (0.022)
10	Chemical products	Materials	0.038 (0.034)	Bovine animals, horses & other equines	AFOLU+	0.017 (0.028)	Paddy rice	AFOLU+	0.021 (0.033)

Table A1 Top 10 sectors according to average EITE value in OECD countries under different scenarios. Note: values in parenthesis give standard deviations in the OECD area.

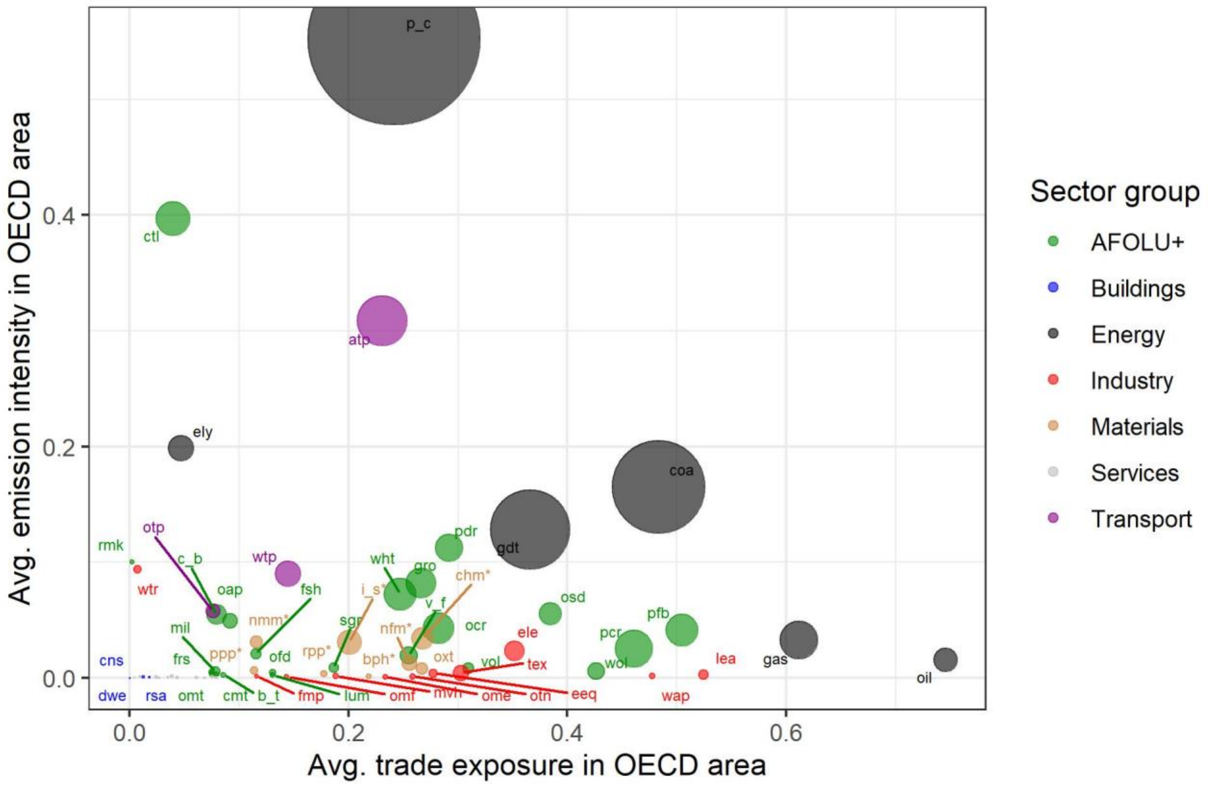

Figure A1 Emission intensity vs. trade exposure under the "direct" scenario, OECD country averages by sector. Note: The circles' area is proportional to the cross-country variation (standard deviation) of the EITE metric in the OECD area.

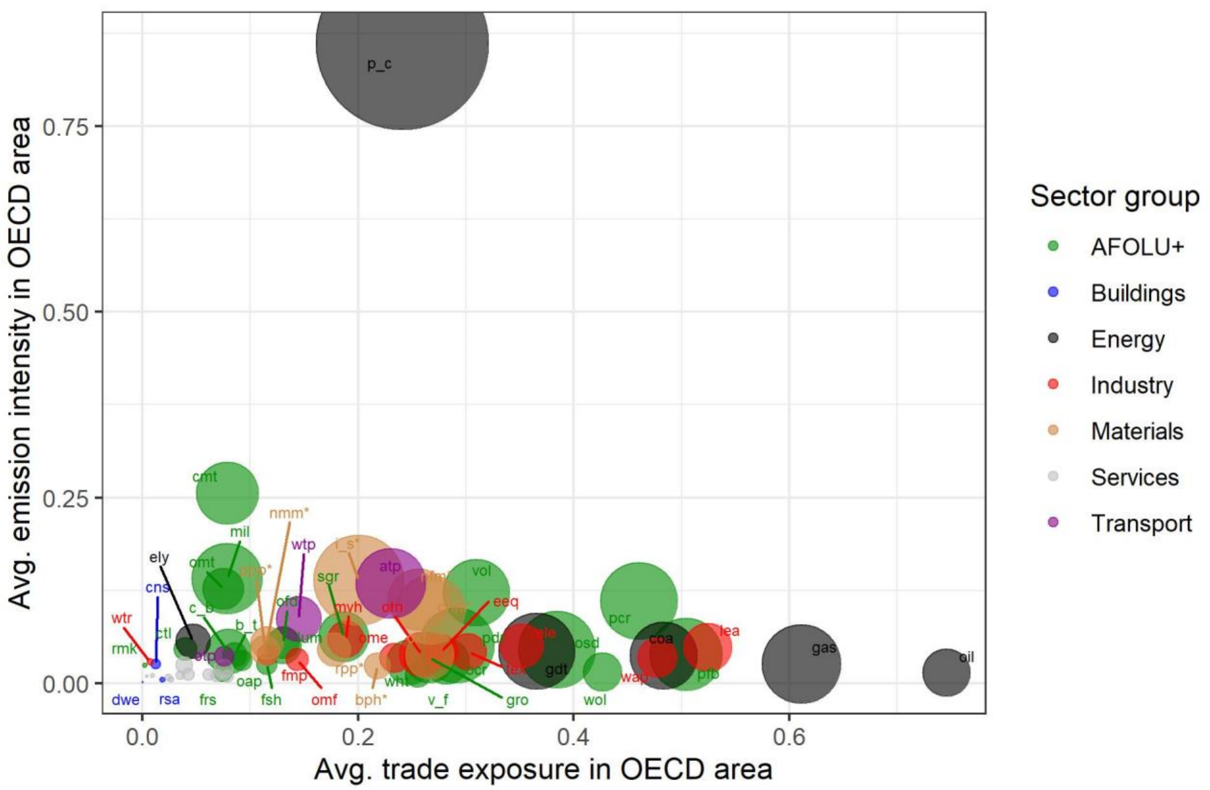

Figure A2 Emission intensity vs. trade exposure under the "indirect" scenario, OECD country averages by sector. Note: The circles' area is proportional to the cross-country variation (standard deviation) of the EITE metric in the OECD area.

No.	Sector group	EI component						EITE		
		Total	Direct	Indirect domestic	Indirect OECD	Indirect non-OECD	TE component	Direct ($eite^{DIR}$)	Indirect ($eite^{IND}$)	Total ($eite^{TOT}$)
1	AFOLU+	0.110 (0.121)	0.050 (0.105)	0.043 (0.055)	0.010 (0.018)	0.006 (0.010)	0.200 (0.215)	0.007 (0.016)	0.011 (0.020)	0.018 (0.030)
2	Buildings	0.012 (0.013)	0.000 (0.001)	0.009 (0.009)	0.002 (0.002)	0.001 (0.002)	0.011 (0.015)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)
3	Energy	0.380 (0.693)	0.191 (0.396)	0.068 (0.136)	0.025 (0.059)	0.096 (0.298)	0.404 (0.401)	0.083 (0.358)	0.042 (0.096)	0.125 (0.379)
4	Industry	0.053 (0.043)	0.012 (0.038)	0.021 (0.012)	0.011 (0.010)	0.009 (0.007)	0.262 (0.187)	0.001 (0.004)	0.011 (0.010)	0.012 (0.012)
5	Materials	0.085 (0.069)	0.016 (0.021)	0.039 (0.035)	0.016 (0.017)	0.013 (0.017)	0.202 (0.148)	0.003 (0.007)	0.016 (0.024)	0.019 (0.030)
6	Services	0.012 (0.008)	0.001 (0.001)	0.009 (0.006)	0.002 (0.002)	0.001 (0.001)	0.042 (0.046)	0.000 (0.000)	0.001 (0.001)	0.001 (0.001)
7	Transport	0.240 (0.236)	0.154 (0.169)	0.048 (0.049)	0.023 (0.029)	0.015 (0.023)	0.151 (0.089)	0.031 (0.048)	0.016 (0.021)	0.048 (0.069)

Table A2 Average value of EITE components in OECD countries, by sector group. Notes: averages are calculated by taking the mean of th EITE component value over sectors belonging to the sector group in OECD countries. Values in parenthesis give standard deviations.

3Appendix B

Data type	Variable name	Description
Economic	*VDFM*	Intermediates - Firms' domestic purchases at market prices
	VIFM	Intermediates - Firms' import purchases at market prices
	VXMD	Trade - Bilateral exports at market prices
	VDPM	Household domestic purchases at market prices
	VDGM	Government domestic purchases at market prices
	VST	Trade - Exports for international transportation at market prices
	VFM	Endowments - Firms' purchases at market prices
	VIPM	Household import purchases at market prices
	VIGM	Government import purchases at market prices
Environmental	*MDF*	Emissions from domestic product in current production, MtCO2
	MIF	Emissions from imports in current production, MtCO2

	NCQO	Emissions associated with output in 2014, mil tCO2.eq
	NCQE	Emissions associated with endowment in 2014, mil tCO2.eq
	NCQF	Emissions associated with intermediate use in 2014, mil tCO2.eq

Table B1 Names and description of the GTAP variables used in the EE-MRIO model

No.	Abb.	Description	CPC version 2.1	ISIC revision 4	7 sectors (Hertwich & Wood, 2018)
1	pdr	Paddy rice	0113	-	AFOLU+
2	wht	Wheat	0111	-	AFOLU+
3	gro	Cereal grains not elsewhere classified (n.e.c.)	0112, 0114-0119	-	AFOLU+
4	v_f	Vegetables, fruit, nuts	012, 013, 015, 017	-	AFOLU+
5	osd	Oilseeds and oleaginous fruits	014	-	AFOLU+
6	c_b	Sugar crops (cane, beet)	018	-	AFOLU+
7	pfb	Plant-based fibers	0192	-	AFOLU+
8	ocr	Crops nec	016, 0191, 0193-0197, 0199	-	AFOLU+
9	ctl	Bovine animals, horses and other equines	0211-0213, 0299	-	AFOLU+
10	oap	Other animals and animal products nec	0214, 0215, 0219, 023, 024, 0291-0293, 0295, 0296	-	AFOLU+
11	rmk	Raw milk	022	-	AFOLU+
12	wol	Wool, silk-worm cocoons	0294	-	AFOLU+
13	frs	Forestry and logging products	03	-	AFOLU+
14	cmt	Bovine meat products	21111, 21112, 21115-21119, 2113, 2115	-	AFOLU+
15	omt	Meat products nec	21113, 21114, 2112, 2114, 2116-2119	-	AFOLU+
16	vol	Vegetable oils and fats	215-219	-	AFOLU+
17	mil	Dairy products and egg products	22	-	AFOLU+
18	pcr	Processed rice	2316	-	AFOLU+
19	sgr	Sugar and molasses	235	-	AFOLU+
20	ofd	Food products nec	212-214, 2311-2314, 2317, 2318, 232-234, 236-239	-	AFOLU+
21	b_t	Beverages and tobacco products	24, 25	-	AFOLU+
22	cns	Construction	-	41-43	Buildings
23	coa	Coal	-	05	Energy
24	oil	Oil	-	061, 091 (part)	Energy
25	gas	Gas	-	062, 091 (part)	Energy

26	oxt	Other extraction (formerly omn minerals n.e.c.)	-	07, 08, 099	Materials
27	ely	Electricity; steam and air conditioning supply	-	351, 353	Energy
28	gdt	Gas manufacture, distribution	-	352	Energy
29	wtr	Water supply; sewerage, waste management and remediation activities	-	36-39	Industry
30	fsh	Fishing	-	03, 017	AFOLU+
31	tex	Textiles	-	13	Industry
32	wap	Wearing apparel	-	14	Industry
33	lea	Leather products	-	15	Industry
34	lum	Wood products	-	16	AFOLU+
35	ppp*	Paper products, printing	-	17, 18	Materials
36	p_c	Petroleum, coal products	-	19	Energy
37	chm*	Chemical products	-	20	Materials
38	bph*	Basic pharmaceutical products	-	21	Materials
39	rpp*	Rubber and plastic products	-	22	Materials
40	nmm*	Mineral products n.e.c.	-	23	Materials
41	i_s*	Ferrous metals	-	241, 2431	Materials
42	nfm*	Metals n.e.c.	-	242, 2432	Materials
43	fmp	Metal products	-	25	Industry
44	ele	Computer, electronic and optical products	-	26	Industry
45	eeq	Electrical equipment	-	27	Industry
46	ome	Machinery and equipment n.e.c.	-	28	Industry
47	mvh	Motor vehicles and parts	-	29	Industry
48	otn	Transport equipment n.e.c.	-	30	Industry
49	omf	Manufactures n.e.c.	-	31, 32, 33	Industry
50	otp	Land transport and transport via pipelines	-	49	Transport
51	wtp	Water transport	-	50	Transport
52	atp	Air transport	-	51	Transport
53	trd	Wholesale and retail trade; repair of motor vehicles and motorcycles	-	45-47	Services
54	afs	Accommodation and food service activities	-	55, 56	Services
55	whs	Warehousing and support activities	-	52	Services
56	cmn	Information and communication	-	53, 58-63	Services
57	ofi	Financial services nec	-	64, 661, 663	Services
58	ins	Insurance (formerly isr)	-	65, 662	Services
59	rsa	Real estate activities	-	68	Buildings
60	obs	Other business services	-	69-82 (M and N)	Services
61	ros	Recreational and other services	-	90-98 (R, S, and T)	Services
62	osg	Public administration and defense; compulsory social security; and activities of extraterritorial organizations and bodies	-	84, 99	Services
63	edu	Education	-	85	Services
64	hht	Human health and social work activities	-	86-88 (Q)	Services

65	dwe	Dwellings	-	not available	Buildings

Table B2 GTAP 10 sectors' concordances. Source: Aguiar et al. (2019). Notes: * indicates traditional energy-intensive manufacturing sectors.

No.	Abb.	Name	OECD countries	Carbon pricing countries (World Bank, 2021)*
1	AUT	Austria	x	x
2	BEL	Belgium	x	x
3	CZE	Czech Republic	x	x
4	DNK	Denmark	x	x
5	EST	Estonia	x	x
6	FIN	Finland	x	x
7	FRA	France	x	x
8	DEU	Germany	x	x
9	GRC	Greece	x	x
10	HUN	Hungary	x	x
11	IRL	Ireland	x	x
12	ITA	Italy	x	x
13	LVA	Latvia	x	x
14	LTU	Lithuania	x	x
15	LUX	Luxembourg	x	x
16	NLD	Netherlands	x	x
17	POL	Poland	x	x
18	PRT	Portugal	x	x
19	SVK	Slovakia	x	x
20	SVN	Slovenia	x	x
21	ESP	Spain	x	x
22	SWE	Sweden	x	x
23	GBR	United Kingdom	x	x
24	CHE	Switzerland	x	x
25	NOR	Norway	x	x
26	NZL	New Zealand	x	x
27	JPN	Japan	x	x
28	KOR	Korea, Republic of	x	x
29	CAN	Canada	x	x
30	USA	United States of America	x	x
31	MEX	Mexico	x	x
32	CHL	Chile	x	x
33	COL	Colombia	x	x
34	TUR	Turkey	x	-
35	ISR	Israel	x	-
36	AUS	Australia	x	-

37	CRI	Costa Rica	x	-
38	BGR	Bulgaria	-	x
39	HRV	Croatia	-	x
40	CYP	Cyprus	-	x
41	MLT	Malta	-	x
42	ROU	Romania	-	x
43	ZAF	South Africa	-	x
44	CHN	China	-	x
45	ARG	Argentina	-	x
46	IDN	Indonesia	-	x
47	UKR	Ukraine	-	x
48	KAZ	Kazakhstan	-	x
49	XEF	Rest of European Free Trade Association	-	-
50	ALB	Albania	-	-
51	BLR	Belarus	-	-
52	RUS	Russian Federation	-	-
53	XEE	Rest of Eastern Europe	-	-
54	XER	Rest of Europe	-	-
55	XOC	Rest of Oceania	-	-
56	HKG	Hong Kong, Special Administrative Region of China	-	-
57	MNG	Mongolia	-	-
58	TWN	Taiwan	-	-
59	XEA	Rest of East Asia	-	-
60	BRN	Brunei Darussalam	-	-
61	KHM	Cambodia	-	-
62	LAO	Lao PDR	-	-
63	MYS	Malaysia	-	-
64	PHL	Philippines	-	-
65	SGP	Singapore	-	-
66	THA	Thailand	-	-
67	VNM	Viet Nam	-	-
68	XSE	Rest of Southeast Asia	-	-
69	BGD	Bangladesh	-	-
70	IND	India	-	-
71	NPL	Nepal	-	-
72	PAK	Pakistan	-	-
73	LKA	Sri Lanka	-	-
74	XSA	Rest of South Asia	-	-
75	XNA	Rest of North America	-	-
76	BOL	Bolivia	-	-
77	BRA	Brazil	-	-
78	ECU	Ecuador	-	-
79	PRY	Paraguay	-	-
80	PER	Peru	-	-
81	URY	Uruguay	-	-

82	VEN	Venezuela (Bolivarian Republic of)	-	-
83	XSM	Rest of South America	-	-
84	GTM	Guatemala	-	-
85	HND	Honduras	-	-
86	NIC	Nicaragua	-	-
87	PAN	Panama	-	-
88	SLV	El Salvador	-	-
89	XCA	Rest of Central America	-	-
90	DOM	Dominican Republic	-	-
91	JAM	Jamaica	-	-
92	PRI	Puerto Rico	-	-
93	TTO	Trinidad and Tobago	-	-
94	XCB	Rest of Caribbean	-	-
95	KGZ	Kyrgyzstan	-	-
96	TJK	Tajikistan	-	-
97	XSU	Rest of Former Soviet Union	-	-
98	ARM	Armenia	-	-
99	AZE	Azerbaijan	-	-
100	GEO	Georgia	-	-
101	BHR	Bahrain	-	-
102	IRN	Iran, Islamic Republic of	-	-
103	JOR	Jordan	-	-
104	KWT	Kuwait	-	-
105	OMN	Oman	-	-
106	QAT	Qatar	-	-
107	SAU	Saudi Arabia	-	-
108	ARE	United Arab Emirates	-	-
109	XWS	Rest of Western Asia	-	-
110	EGY	Egypt	-	-
111	MAR	Morocco	-	-
112	TUN	Tunisia	-	-
113	XNF	Rest of North Africa	-	-
114	BEN	Benin	-	-
115	BFA	Burkina Faso	-	-
116	CMR	Cameroon	-	-
117	CIV	Côte d'Ivoire	-	-
118	GHA	Ghana	-	-
119	GIN	Guinea	-	-
120	NGA	Nigeria	-	-
121	SEN	Senegal	-	-
122	TGO	Togo	-	-
123	XWF	Rest of Western Africa	-	-
124	XCF	Rest of Central Africa	-	-
125	XAC	South Central Africa	-	-
126	ETH	Ethiopia	-	-

127	KEN	Kenya	-	-
128	MDG	Madagascar	-	-
129	MWI	Malawi	-	-
130	MUS	Mauritius	-	-
131	MOZ	Mozambique	-	-
132	RWA	Rwanda	-	-
133	TZA	Tanzania, United Republic of	-	-
134	UGA	Uganda	-	-
135	ZMB	Zambia	-	-
136	ZWE	Zimbabwe	-	-
137	XEC	Rest of Eastern Africa	-	-
138	BWA	Botswana	-	-
139	NAM	Namibia	-	-
140	XSC	Rest of South African Customs Union	-	-
141	XTW	Rest of the World	-	-

Table B3 GTAP regions. Notes: *Carbon pricing countries are those that implemented or scheduled a carbon pricing scheme (World Bank, 2021)