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Revisiting Carbon Leakage

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Abstract

This paper estimates the carbon leakage rate across countries, arguably a key parameter in the international climate policy discussion including on border carbon adjustment, but which remains subject to significant uncertainty. We propose innovations along two lines. First, we exploit recently published data on sector-country-specific changes in energy prices to identify changes in domestic carbon emissions and other flows (rather than the historically limited variation in carbon prices or adherence to international climate agreements). Second, we present a simple accounting framework to derive carbon leakage rates from reduced-form regressions in contrast to existing papers, thereby making our results directly comparable to model-based estimates of carbon leakage. We show that carbon leakage rates differ across countries and could be larger than what existing estimates suggest.

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Contents Page

I. INTRODUCTION

As effective global cooperation to mitigate climate change has proven difficult to achieve, several countries are unilaterally abating carbon emission; one example is the emission trading system of the EU (EU ETS). However, unilateral climate policies can in principle lead to carbon leakage, whereby domestic emission reductions are offset by increases in other countries.[1] The objective of this paper is to revisit carbon leakage econometrically.

Carbon leakage is potentially of significant concern for policymakers and a key parameter for the international climate policy discussion. First, carbon leakage undermines the effectiveness of unilateral environmental policies. Second, carbon leakage can reflect a loss of domestic economic competitiveness and global market share if production costs increase, thereby inducing production to shift to other countries alongside emissions. If domestically produced goods and services become relatively more expensive as a result of say an increase in the carbon price, consumers, both domestically and abroad, can switch to foreign goods and services. Third, carbon leakage provides the rationale for border carbon adjustment mechanisms which continue to be debated (see for instance Keen et al., 2021).

However, there remains significant uncertainty with respect to carbon leakage as the existing literature provides at best little guidance for policy. The large body of the existing theoretical literature (which we review in the Appendix) has not reached consensus on the approximate magnitude or even the sign of carbon leakage. These model-based estimates of carbon leakage appear to be sensitive to underlying model and scenario assumptions. Earlier theoretical papers have found generally positive leakage rates of widely differing magnitudes, whereas some recent papers identify a number of channels that could lead to negative carbon leakage.

The empirical literature is smaller, and the results mostly imply that carbon leakage is limited. However, many papers are subject to data-related and methodological limitations, some of which are widely recognized. In particular, many papers examine the effects of domestic carbon pricing policies including the EU ETS, but the limited historical variation (and hard-to-measure loopholes or compensation mechanisms in some cases) is often seen as the reason why they do not find much evidence in support of leakage (see Appendix). There is a much smaller literature that finds evidence of carbon leakage as a result of abiding to the Kyoto Protocol, but the results of the most prominent paper by Aichele and Felbermayr (2015) remain controversial in the literature.[2] We summarize the empirical literature in the Appendix; see also Felbermayr and Peterson (2020) and Zachmann and McWilliams (2020) for recent summaries of the literature.

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[1] Dating back to Sinn (2012), the literature has also discussed the possibility of intertemporal leakage, referred to as a the 'green paradox'. The green paradox refers to the possibility that announcing a future climate policy may increase carbon emissions today as fossil fuel producers increase their extraction today in response to a reduction in future resource rents (Jensen et al., 2015).

[2] Naegele and Zaklan (2019) suggest that the channel through which the Kyoto protocol has induced carbon leakage is unclear, and Branger and Quirion (2014) and Sato and Dechezleprêtre (2015) suggest that the absence of sectoral variation in the policy variable makes it difficult to control for other confounding macroeconomic shocks.

In this paper, we revisit carbon leakage rates empirically and innovate along two fronts, thereby overcoming some of the obvious limitations of existing empirical papers. First, in contrast to most of the related literature, we exploit policy-induced changes in country-sector-specific energy prices to estimate plausibly exogenous variation in carbon emissions and flows at the country-sector level making use of recently published data by Sato et al. (2019).[3] While the underlying policy changes may not aim at reducing carbon emissions per se, their economic and environmental effects are similar to changes in the price of carbon. However, energy prices show more variation than the historically small changes in carbon prices and are available for many more countries and sectors compared to carbon pricing schemes. This, in turn, allows us to control for a richer set of unobserved effects and address omitted variable bias in a more compelling way. We combine these data with country-sector level information on carbon embodied in final demand and trade flows compiled by Wiebe and Yamano (2016).

Second, we calculate carbon leakage rates from our estimated coefficients that measure the effects of energy prices on cross-border carbon flows and domestic emissions. To this end, we develop a simple accounting framework for emissions, which enables us to derive an expression for carbon leakage that is akin to the theoretical modeling literature. This allows us to retrieve precise estimates of country-level carbon leakage rates from our country-sector level regressions.

We show that carbon leakage can be significant, but that there are differences across countries, depending on country size and openness to trade. Our results are statistically robust and significant. As a plausibility test of our regression framework and the underlying data, we also document some (although limited) evidence of the underlying loss in competitiveness and changes in energy usage patterns. Finally, we also examine differences in energy price elasticities of emissions and carbon flows between different country and sector groupings.

The paper is organized as follows. Section 2 presents the data used in the empirical analysis. Section 3 presents our regression estimates on the energy price elasticity of carbon trade flows and domestic carbon production. Section 4 presents a simple accounting framework to obtain carbon leakage rates from our coefficient estimates. Section 5 concludes.

II. Data

Domestic carbon emissions can differ from carbon embodied in goods and services consumed domestically. The latter includes the carbon emitted throughout the supply chains of final goods and services consumed domestically. Importantly, it includes the carbon that was emitted abroad in the production of intermediate inputs used for domestic final consumption. For instance, using electronics generates little emissions by itself, but the

[3] One exception is Sato and Dechezleprêtre (2015) who find small, but significant effects of country-sector-specific changes in energy prices on imports of goods and services.

production of such goods extends over global supply chains. As an example, Apple reports that producing an iPhone 12 generates 60 kg of carbon emissions (Apple, 2020).[4]

We use the OECD's Trade in Embodied CO2 Database (TECO2) to measure carbon embodied in goods and services trade and final demand.[5] These data are multi-dimensional: they measure the ultimate origin of carbon consumed in a given country by the country and sector through the use of inter-country input-output tables (see Wiebe and Yamano, 2016, for details).

For sectoral energy prices, we use a new dataset compiled by Sato et al. (2019) that covers 21 production sectors in 48 countries for the period from 1995 to 2015.[6] Prices are constructed as weighted averages of tax-inclusive fuel-specific prices, where the weights are held constant and derived from fuel input use by country and sector. This dataset provides the largest coverage of energy prices in a cross-country setting and is therefore ideal to empirically estimate carbon leakage that can arise from changes in domestic policies.

As de Sato et al. (2019) note, sectoral energy prices depend on a range of factors, including generation and distribution costs, taxes and levies among other factors. However, they find that taxes and levies contribute to most of the cross-country variation in energy prices, ranging from 80 percent to 90 percent for coal, 30 percent to 70 percent for electricity and 40 percent to 80 percent for oil prices. Taxes and levies explain less of the variation of gas prices. Since we include country-year and sector-year fixed effects in all regressions, the residual variation in energy prices at the sector-country level over time can reasonably be attributed to changes in effective taxes in combination with differences in the energy mix within sectors and across countries. Other relevant factors, such as changes in global commodity prices, sector-level technologies, country-wide changes in energy prices or macroeconomic conditions, are differenced out from energy prices.

Merging the two datasets results in an unbalanced panel data that covers 38 countries and 21 sectors over the 2005–15 period. The combined emissions from sectors included in our estimation amount to 75 percent of all production-related domestic emissions on average

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[4] There is a growing literature that documents large discrepancies between carbon emissions and carbon embodied in final consumption, sometimes referred to as carbon footprint; see Sato (2014) for a recent survey. Davis et al. (2011) criticize production-based carbon accounts (i.e., the attribution of emissions to the country where they are produced) as the place of fuel extraction, production of emissions and consumption of goods and services may all differ. Peters et al. (2011) find evidence suggesting that the stabilization of emissions in developed countries in recent decades can at least partially be attributed to growing imports of embedded carbon from developing countries.

[5] OECD, Trade in Embodied CO2 Database (TECO2), compiled by Wiebe and Yamano (2016).

[6] We complement missing data in the Sato et al. (2019) dataset with data from national sources in Russia, China and India. We also use average user-price for electricity and natural gas as an additional sector in the regressions.

across covered countries.[7] We provide a list of all sectors included and carbon flows as well emissions by sector in the Appendix.

III. Empirical Results

A. Effects on Carbon Emissions and Carbon Embodied in Trade Flows

We first estimate a standard elasticity regression for carbon-in-trade and production flows:

$$ln(Q_{i,s,t}) = \beta^Q ln(p_{i,s,t}) + \gamma_{i,s}^Q + \theta_{i,t}^Q + \delta_{s,t}^Q + \varepsilon_{i,s,t}^Q,$$

where the dependent variable $Q_{i,s,t}$ refers to year t and denotes either: i) carbon embodied in exports from sector s in country i to the rest of the world; ii) carbon embodied in imports of country i originating from sector s in the rest of the world; iii) carbon embodied in domestic final demand of country i originating from sector s (irrespective of country of origin); or iv) domestic carbon emissions of sector s and country i. All regressions control for county-sector, country-year and sector-year fixed effects.[8]

Table 1 presents our main results. They suggest that energy prices have a strong effect on carbon embodied in exports, production and domestic consumption. The point estimate in column (2) suggests that higher energy prices significantly reduce carbon embodied in exports, with an elasticity estimate of -0.3. This number is very large. Consider that there is significant variation in average energy prices across countries. For instance, Sweden had an average energy price level of 677 USD per ton of oil equivalent (toe) in 2015 (in real 2010 USD). In contrast, the United States had an average energy price of 275 USD per toe. Our results imply that if the US were to implement Sweden's energy pricing policy, its exports of carbon would decline by more than 30 percent.

Column (3) confirms that domestic energy prices are a strong determinant of domestic emissions. Finally, we find that increases in energy prices also significantly reduces carbon consumption in column (4), but the magnitude is smaller which is plausible since part of carbon embodied in domestic demand comes from imports, which are not directly affected by domestic energy prices.

We find no effect of energy prices on carbon embodied in imports (the point estimate in column (1) is small and not statistically significant), consistent with the smaller effect on

[7] This amounts to a 60 percent coverage of global emissions from production. Note that around 15 percent of global carbon emissions are from households' electricity and fuel consumption. These are not included in the analysis.

[8] Our results are confirmed when using a gravity estimation framework with bilateral trade flows and prices such as the one used in Aichele and Felbermayr (2015). However, we do not use a gravity estimation framework because we aim at capturing the effects of changes in energy prices on global market share of domestic producers. For instance, differences in energy prices between two given countries could lead to changes in trade flows to third countries where both countries are competing. Such effects are difficult to capture through reduced-form gravity estimation frameworks that focus on bilateral trade flows.

domestic carbon consumption.[9] This could suggest that demand shifts in favor of foreign producers occur more easily in foreign countries than domestically when domestic energy prices increase, not least because of differences in consumption bundles between domestic and foreign consumers and home bias in consumption.

Table 1. Impact of Energy Prices on Carbon Flows

	(1) Imports	(2) Exports	(3) Emissions	(4) Consumption
Sectoral energy price	0.0158	-0.321**	-0.523***	-0.198*
	(0.0491)	(0.155)	(0.151)	(0.103)
Observations	8,247	8,124	8,168	8,235
R-squared	0.997	0.983	0.986	0.993

Notes: The dependent variables are carbon embodied in trade (imports and exports) and domestic sectoral flows (emissions and consumption). All variables are expressed in logs. Prices and values are in 2010 USD. All regressions include country-year, country-sector and sector-year fixed effects. Standard errors clustered at the country-sector level in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

B. Heterogeneity Across Sectors and Countries

We do not have sufficient degrees of freedom to estimate country-specific or sector-specific elasticities. We can, however, divide sectors and countries into separate groups and examine group-level differences in the coefficient estimates. In Table 2 , we examine whether there are any differences in the coefficient estimates between EU14+UK (referred to as EU15 for simplicity) and non-EU14+UK countries.[10] The interaction between the energy price and the EU country dummy is mostly insignificant, suggesting that there are no statistically significant differences between the energy price elasticity in EU15 and non-EU15 countries. One exception is that imports increase in EU15 countries following energy price increases.

[9] This result could potentially explain why previous papers claim to find small carbon leakage. See for example Sato and Dechezleprêtre (2015); Naegele and Zaklan (2019).

[10] EU14+UK countries include Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and United Kingdom.

Table 2. Impact of Energy Prices on Carbon Flows: Country Heterogeneity				
	(1) Imports	(2) Exports	(3) Emissions	(4) Consumption
Sectoral energy price	-0.0394	-0.260	-0.451**	-0.250**
	(0.0598)	(0.183)	(0.182)	(0.126)
Sectoral energy price × EU14+UK	0.168*	-0.187	-0.222	0.157
	(0.0954)	(0.311)	(0.297)	(0.181)
Observations	8247	8124	8168	8235
R-squared	0.997	0.983	0.986	0.993

Notes: The dependent variables are carbon embodied in trade and domestic flows. Sectoral energy price × EU14+UK is the interaction term between sectoral energy prices and a dummy for EU14 countries and the UK. All variables are expressed in logs. Prices and values are in 2010 USD. All regressions include country-year, country-sector and sector-year fixed effects. Standard errors clustered at the country-sector level in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

We also divide up the sectors based on whether they are deemed energy-intensive and exposed trade and those that are not, using the sectoral classification of the EU. **T** provides the results. Interestingly, the coefficient on the interaction term is insignificant throughout except for domestic emissions, suggesting that there are no statistically significant differences in the energy price elasticity of carbon imports, exports and consumption between EITE and non-EITE sectors. By contrast, domestic emissions in EITE sectors appear to be more inelastic with respect to changes in energy prices, potentially because substituting energy usage in these industries could be difficult.

Table 3. Impact of Energy Prices on Carbon Flow: Industry Heterogeneity				
	(1) Imports	(2) Exports	(3) Emissions	(4) Consumption
Sectoral energy price	0.001	-0.356**	-0.611***	-0.203*
	-0.054	(0.168)	(0.167)	(0.104)
Sectoral energy price × EITE	0.0432	0.099	0.247*	0.013
	-0.043	(0.141)	(0.141)	(0.131)
Observations	8247	8124	8168	8235
R-squared	0.997	0.983	0.986	0.993

Notes: The dependent variables are carbon embodied in trade and domestic flows. Sectoral energy price × EITE is the interaction term between sectoral energy prices and a dummy for energy-intensive and trade exposed (EITE) sectors. These include Mining energy, Mining non-energy, Paper products, Refined oil products, Chemicals, Basic metals and Electricity and gas. All variables are expressed in logs. Prices and values are in 2010 USD. All regressions include country-year, country-sector and sector-year fixed effects. Standard errors clustered at the country-sector level in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

C. Other Effects of Changes in Energy Prices

So far, we have only assessed the effects of energy prices on emission and trade flows in embodied carbon. However, changes in energy prices can in principle induce a number of other changes in firm behavior which our industry-level data could reflect. These include changes in (i) energy usage and efficiency; (ii) the fuel mix, and (iii) production levels. In this subsection, we explore these effects in greater detail. While these estimates are not strictly needed for the subsequent derivation of carbon leakage rates, findings that support our previous results in a broader sense would lend credibility to our estimates of the elasticities of carbon flows above and show that our energy price data contain relevant information for private sector choices. We again control for country-year, country-sector and sector-year fixed effects.

First, in **Table 4**, we examine the effects of energy price changes on energy usage. The results suggest that increases in energy prices lower energy use and the CO2 intensity, while they increase the share of biofuels used, in line with expectations. This implies that domestic firms also adjust energy usage which would mitigate leakage of emissions to foreign countries.

Second, in **Table 5**, we examine the effects of sectoral energy prices on sectoral value added, wages and employment, which can broadly be seen as reflecting changes in competitiveness and production of a given sector. Here, the evidence is more mixed. While the sign is negative throughout in line with priors, the coefficients lack statistical significance in the case of value added and employment.[12] From the evidence, we still broadly conclude that our econometric framework produces sensible estimates, and that our measure of sectoral energy prices affects a range of relevant sectoral indicators.

Table 4. Energy Prices and Energy Use, CO2 Intensity and Energy Mix

	(1) Energy use	(2) CO2 intensity	(3) Share biofuel
Sectoral energy price	-0.347***	-2.246*	0.0261***
	(0.0600)	(1.266)	(0.00655)
Observations	8024	8246	7848
R-squared	0.993	0.676	0.974

Notes: The dependent variables are total energy consumption by sector in log(KTOE) in column (1), the ratio of CO2 produced to value added in column (2), and the share of biofuel in total energy consumption in column (3). Prices and values are in 2010 USD. All regressions include country-year, country-sector and sector-year fixed effects. Standard errors clustered at the country-sector level in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

[12] For these indicators, we can also extend our panel data to 1995. When we increase the time span of the sample, all coefficients in Table 5 become significant. Carbon flows and emissions could be more responsive to energy price changes than sales or employment because firms have several margins of adjustment, including changing the energy mix and intensity. There could be also unobserved heterogeneity across firms in terms of contributions to emissions and value added that aggregate data mask.

Table 5. Energy Prices and Indicators of Competitiveness

	(1) Value added	(2) Wages	(3) Employment
Sectoral energy price	-0.219	-0.198*	-0.154
	(0.176)	(0.113)	(0.140)
Observations	8247	8247	8247
R-squared	0.975	0.988	0.990

Notes: The dependent variables are sectoral shares of value-added, wages and employment, respectively. Prices and values are in 2010 USD. All regressions include country-year, country-sector and sector-year fixed effects. Standard errors clustered at the country-sector level in parentheses. * p<0.1, ** p<0.05, *** p<0.01.

IV. Carbon Leakage Rates

A. Conceptual Framework

We use a simple reduced-form accounting framework to derive a definition of carbon leakage that makes use of the estimated coefficients from Table 1. We focus on the case of changes in unilateral, economy-wide (i.e., uniform across sectors) carbon pricing. With international trade, the carbon embodied in domestic consumption does not need to equal territorial emissions. As a result, the production, consumption and trade of carbon in country i satisfies the following identity:

$$D_i + X_{i,RW} = Y_i + M_{i,RW}, \tag{1}$$

where D_i represents carbon embodied in final domestic demand of country i, $X_{i,RW}$ and $M_{i,RW}$ represent carbon embodied in exports and imports between country i and the rest of the world (RW), respectively, and where Y_i where represents carbon emissions of country i. Governments can change the price of carbon in production, either through regulation, cap and trade mechanisms or taxation. A unilateral carbon policy change $\hat{p}_i$ that affects the domestic price of emitting carbon in country i results in the following changes in carbon consumption, production and trade both domestically and abroad:[13]

$$\frac{\partial D_i}{\partial p_i}\hat{p}_i + \frac{\partial X_{i,RW}}{\partial p_i}\hat{p}_i = \frac{\partial Y_i}{\partial p_i}\hat{p}_i + \frac{\partial M_{i,RW}}{\partial p_i}\hat{p}_i, \tag{2}$$

and

$$\frac{\partial D_{RW}}{\partial p_i}\hat{p}_i + \frac{\partial X_{RW,i}}{\partial p_i}\hat{p}_i = \frac{\partial Y_{RW}}{\partial p_i}\hat{p}_i + \frac{\partial M_{RW,i}}{\partial p_i}\hat{p}_i. \tag{3}$$

[13] Larch and Wanner (2017) provide similar equations derived from a multi-sector, multi-factor structural gravity model when p_i represents energy price.

Carbon leakage arises if carbon emission reductions from policy $\hat{p}_i$ in country i are offset by changes in carbon emissions abroad. If leakage is positive, domestic emissions are (partially) displaced through direct firm relocation or changes in net exports. Leakage could also be negative, if clean technology is also adopted abroad.

We define carbon leakage as a measure of the extent to which domestic carbon emissions reductions are offset by higher emission abroad; it equals one when domestic reductions of emissions are fully offset by emissions abroad, leaving global emissions unchanged. This definition is captured by the following equation:

$$L(\hat{p}_i) \equiv 1 - \frac{\partial Y_{RW}/\partial p_i}{\partial Y_i/\partial p_i} = -\frac{\partial Y_{RW}/\partial p_i}{\partial Y_i/\partial p_i}, \tag{4}$$

with $Y_G = Y_i + Y_{RW}$ denoting global carbon emissions. With non-infinitesimal changes in the price of carbon, the leakage rate becomes

$$L(\hat{p}_i) \equiv -\frac{\Delta Y_{RW}}{\Delta Y_i}, \tag{5}$$

which is identical to the standard definition in the literature (Branger and Quirion, 2014). Using Eq. (3) to substitute for $\partial Y_{RW}/\partial p_i$ (and assuming that $\partial D_{RW}/\partial p_i$ is approximately zero for simplicity which means that we ignore foreign consumption responses to domestic carbon price changes which we discuss in detail below) [14], the carbon leakage rate $L(\hat{p}_i)$ can be calculated as

$$L(\hat{p}_i) = \frac{\hat{\beta}^X X_{i,RW} - \hat{\beta}^M M_{i,RW}}{\hat{\beta}^Y Y_i}, \tag{5}$$

where $\hat{\beta}^X$, $\hat{\beta}^M$ and $\hat{\beta}^Y$ are the carbon exports, imports and production elasticities from **Table 1**. The values $X_{i,RW}$, $M_{i,RW}$ and Y_i denote aggregate quantities of carbon exports, imports and emissions in country i. Leakage will therefore be larger the more sensitive trade in carbon is to unilateral price and policy changes and the more open countries are to trading in (embedded) carbon. Trade effects from domestic carbon policies are necessary to test for carbon leakage. However, these effects are not *sufficient* as carbon production also enters the equation which tends to be ignored in empirical papers.

To illustrate this point, assume that an empirical analysis finds a small (but non-zero) effect of carbon pricing policies on carbon embodied in exports and imports. Taken in isolation, these findings do not allow drawing conclusions about whether or not the carbon leakage rate

[14] In particular, we ignore changes in foreign demand as a result of unilateral changes in energy prices. Depending on the size of the country, they could also dampen foreign final demand for carbon, although we expect them to be relatively small. We also ignore cross-sectoral substitution effects which could likewise trigger carbon leakage.

is small or large. If, for instance, there are no effects on domestic emissions, the confidence interval of the ratio in Eq. (5) could take any value between $-\infty$ and ∞, since the denominator could be arbitrarily close to zero. To our knowledge, this study is the first to empirically estimated these two effects jointly.[15]

Of course, this accounting framework and our derivation come with important caveats. We are agnostic as to how exactly price changes affect domestic emissions, carbon imports, exports and consumption and refrain from modelling complex linkages across sectors. Our focus is also on the aggregate net effects only, and our reduced-form approach is not well suited to conduct more involved policy counterfactuals, including for instance about the effects of sectoral variation in carbon prices or border carbon adjustment mechanisms.

Finally, Eq. (5) also ignores the foreign carbon consumption response to changes in the domestic price of carbon, $\hat{p}_i$, that could take place because of changes in global oil prices for example. The reason is that this would be difficult or impossible to estimate empirically in the absence of using a structural trade model as for instance presented in Larch and Wanner (2017) which we leave for future research. However, we expect that in many instances, it is safe to assume that the elasticity of carbon consumption in the rest of the world is small relative to elasticities of exports and imports of the country in question, at least if the country is sufficiently small vis-à-vis the rest of the world. This would imply that allowing for a foreign consumption response does not alter our estimated carbon leakage rates in a qualitatively meaningful way.

B. Country-Specific Carbon Leakage Rates

We can now use the coefficient estimates from **Table 1** to obtain measures of country-specific leakage rates using Eq. (5). The (unweighted) average leakage rate across all countries in our sample is 0.25. This implies that a *reduction* of 100 tons of carbon emissions domestically would be accompanied by an *increase* of 25 tons abroad. We also compute the carbon leakage rate for the EU14+UK aggregate, using the elasticities from Table 1 in combination with consolidated flows on carbon exports, imports, emissions and consumption.

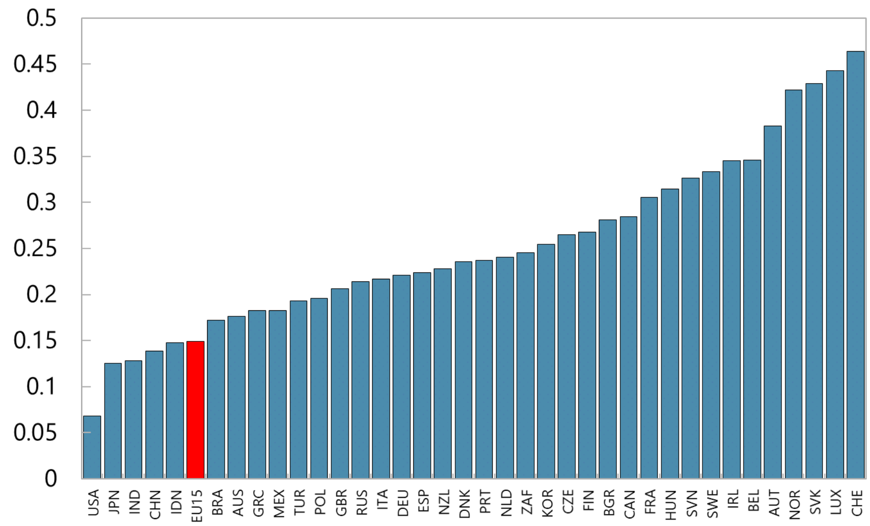
Figure 1 and **Error! Reference source not found.** present the results. Countries vary widely in terms of carbon leakage rates based on the trade intensity and carbon emissions. Overall, leakage rates are larger for small open economies compared to larger economies. EU countries tend to have higher leakage rates because they are smaller and more open on average and they tend to produce much less carbon, relying instead on large imports.[16] The

[15] Aichele and Felbermayr (2015) combine estimates of increased carbon imports from countries' Kyoto Protocol commitments with results from a previous paper on emissions reductions to calculate a carbon leakage rate of around 40 percent.

[16] All countries have statistically significant leakage rates at the 90 percent confidence level, except for Switzerland. Switzerland is an outlier in terms of how much embedded carbon it exports compared to how much it imports. The small (and not statistically significant) changes in the coefficients for imports and exports when including an interaction term with EU14+UK countries are sufficient to flip the sign of the leakage rate given levels of imports and exports for the country. However, both estimates have very wide and largely overlapping confidence intervals.

EU14+UK aggregate by contrast has a relatively low leakage rate, owing to its size, much like other large economies. While data limitations imply that we cannot compute a EU-wide leakage rate (as many countries are not in our sample), the EU-wide leakage rate could be lower than that of the EU14+UK aggregate given that the whole EU is larger than EU14+UK aggregate. Using the estimates from results in an average leakage rate of 0.15, which is somewhat lower than our baseline average of 0.25 reported above. When we exclude Switzerland, which displays a large negative but not statistically significant leakage rate, the correlation between the two sets of estimates is 0.83.

Figure 1. Leakage Rates
(2005–15 average)



Sources: OECD TECO2 database; Sato, Singer, Dussaux and Lovo 2019; and IMF staff calculations.

Our results come with some caveats which need to be taken into account when interpreting the results. Our leakage rates reflect constant marginal effects, but in practice they may be non-linear because large price increases may trigger different responses compared to small price changes, and because no carbon spillovers can arise in sectors that have zero emissions. In the econometric estimation, we consider EU countries separately to retain a sufficient number of countries and a sufficiently large sample. However, to the extent that the EU increasingly implements uniform climate policies, spillover between EU countries will not occur.

Table 6. Country-Specific Leakage Rates

Country	CO2 imports	CO2 exports	CO2 product	leakage est.
AUS	100.985	74.432	275.888	0.177
AUT	33.051	18.735	32.600	0.383
BEL	39.255	23.823	45.688	0.346
BGR	7.552	15.255	34.135	0.281
BRA	85.333	65.005	246.737	0.172
CAN	131.160	131.181	296.797	0.284
CHE	46.112	4.230	8.589	0.464
CHN	488.635	1775.187	7949.845	0.139
CZE	24.313	29.495	71.119	0.265
DEU	216.854	153.780	455.922	0.221
DNK	19.762	5.353	16.480	0.235
ESP	79.380	45.345	135.192	0.223
EU15	789.657	298.318	1384.193	0.149
FIN	17.391	11.626	28.585	0.268
FRA	153.702	41.761	99.029	0.305
GBR	176.561	58.488	200.012	0.206
GRC	16.038	11.685	41.964	0.182
HUN	13.849	9.508	19.888	0.314
IDN	79.967	76.465	333.318	0.148
IND	213.841	339.634	1674.379	0.128
IRL	14.645	8.834	16.963	0.345
ITA	120.244	52.682	165.587	0.217
JPN	287.074	157.272	839.268	0.125
KOR	142.265	178.500	447.229	0.254
LUX	2.211	0.921	1.426	0.443
MEX	104.157	76.042	272.955	0.182
NLD	46.727	36.249	98.266	0.241
NOR	24.615	13.665	21.618	0.422
NZL	14.667	5.304	16.190	0.228
POL	51.546	58.241	190.201	0.196
PRT	14.009	9.998	27.647	0.237
RUS	82.637	356.962	1035.659	0.214
SVK	14.073	13.029	19.617	0.429
SVN	4.476	3.115	6.275	0.326
SWE	29.585	8.780	18.827	0.333
TUR	96.310	56.198	193.572	0.193
USA	998.644	258.673	2766.607	0.068
ZAF	34.028	132.687	336.002	0.245

V. Conclusions

Understanding and quantifying carbon leakage is of paramount importance from a policy perspective: Robust estimates of carbon leakage can help inform the international climate policy debate, including on carbon border adjustment mechanism and unilateral climate policies. Yet, carbon leakage remains subject to significant uncertainty.

In this paper, we have shown that carbon leakage differs across countries and can be sizeable in some but not all cases, in particular in small open economies. Contrary to earlier papers, our estimates are guided by a simple and transparent emissions accounting framework, and we exploit policy-induced changes of energy prices. The latter avoids a narrow focus on carbon prices which can be argued to have downward biased past estimates of leakage, given their low levels and often narrow coverage in practice.

Carbon leakage is a necessary but not sufficient condition to implement border carbon adjustment schemes, given that their design is complex and subject to legal, administrative and other constraints. In light of limited existing empirical evidence on carbon leakage, some observers are arguing against carbon border adjustment schemes (e.g., Zachmann and McWilliams, 2020). Our results suggest that this type of reasoning could be revisited. In addition, given that we estimate relatively high leakage rates for many European countries, our results suggest that common European climate policies can be advantageous from this perspective as well.

Our estimates of carbon leakage could be subject to upward and downward biases. First, we cannot rule out that endogenous technological change could lower the amount of carbon leakage over longer time periods. For instance, Di Maria and van der Werf (2008) develop a stylized theoretical model and argue that the extent of carbon leakage can be overestimated when not accounting for incentives to innovate in other sectors that are not energy intensive. Gerlagh and Kuik (2014) argue that there could also be smaller carbon leakage if carbon mitigation policy induces energy-saving technological innovation in the abating region, and if this innovation can freely spill-over to energy users abroad. While these effects are notoriously difficult to capture empirically, it is unclear whether policy makers embarking on unilateral emission reductions can and should hope for them. Second, our framework does not adequately capture that emission constraints in larger open economies may depress the demand for fossil fuels and thus induce a significant drop in world energy prices if energy supply (including oil production) remains unchanged, which in turn could lead to an increase in the level of energy demand in other regions (Fischer and Fox, 2012; Keen et al., 2021). This channel would imply that our estimates are downward biased.

Future research could explore sectoral difference in leakage rates in greater detail. In principle, our conceptual framework could also be used to calculate sectoral leakage rates, but ideally, a richer model would be used for this purpose. The latter could also be used to explore intersectoral leakage whereby carbon price increases in some sectors will increase emission in other sectors of the same country, thereby contributing to ‘total’ leakage. The theoretical literature suggests that intersectoral leakage as a result of partial carbon taxation can be positive or negative (King et al., 2019). Whether or not sectoral differentiation in carbon prices, in line with the prevailing climate policy practice, is less effective in lowering aggregate emissions is therefore an interesting but empirically largely unexplored matter.

Appendix I. Summary of the Literature

A. Theoretical Literature

Cross-border leakage

The earlier theoretical literature has quantified cross-border leakage rates mostly using computable general equilibrium (CGE) frameworks and generally finds positive carbon leakage rates of widely differing magnitudes. For instance, Babiker (2005) considers an economy-wide CO2 constraint and finds that depending on assumptions with respect to market structure and the substitutability among trade energy-intensive products, leakage rates can range from 25 percent to 130 percent where a leakage rate of above 100 percent would imply higher global emissions as a result of domestic reductions. Branger and Quirion (2014b) survey a subset of theoretical papers and find that leakage rate estimates are more moderate and range from 2 percent to 41 percent.[1] In a related paper, Branger and Quirion (2014a) discuss in detail the factors that underlie the heterogeneity of the estimates. They note that first, the results depend on scenario hypotheses (the bigger the abating coalition, the smaller the leakage rate while the more ambitious the target, the higher the leakage rate). Second, the results are driven by fossil fuel supply and Armington elasticities (the former reflect the extent to which a decrease in fossil fuel demand drives the reduction in the fuel price, while the latter determines the substitutability between domestic and foreign products).

More recent theoretical papers identify a number of channels that could lead to negative carbon leakage, i.e., that emissions abroad decrease as a result of unilateral policies using analytically tractable trade models.[2] Schenker et al. (2018) argue that with trade in intermediate goods in a multi-stage production setting, the effects of unilateral emission abatement become more complex: While they show that leakage rates are always positive, they nevertheless identify a channel of negative leakage whereby less emission-intensive industries relocate to the more stringent regulated region. This is triggered by a reduction of relative factor prices due to the relocation of more emission-intensive upstream producers to the less regulated region. Bogmans (2015) show that by reducing the net supply of intermediate goods to world markets, stricter unilateral environmental policy can have negative global supply effects, thereby reducing emissions abroad. Perino et al. (2019) examine unilateral abatement policies within a group of countries that has a carbon-pricing system (such as the EU ETS). They find that the magnitude and the sign of internal carbon leakage, i.e., carbon leakage to other countries covered by the common carbon-pricing system, depend on the design of the unilateral policy. Ferguson and Sanctuary (2019) develop a tractable model that illustrates that carbon leakage could be negative if as a result of difficulties to substitute between domestic- and foreign-sourced inputs domestic firms reduce the level of output, leading to a fall in foreign sourced inputs. Using a two-sector model with three factors of production, Karp (2013) shows that unilateral regulation lowers

[1] For instance, Burniaux and Oliveira-Martins, 2000 and Light et al. 2000 find moderate leakage rates, whereas Mattoo (2009) finds very small leakage rates. Bednar-Friedl et al. (2012) argue that leakage rates are significantly larger once industrial processes which physically or chemically transform materials (in addition to emissions from fuel combustion only) are accounted for.

[2] Earlier papers have also found evidence of negative carbon leakage, but mostly only in scenarios with a border carbon adjustment; see Branger and Quirion (2014) for a discussion.

national income, reduces demand for both clean and dirty goods and shifts domestic production factors into home's dirty goods sector. This factor mobility effect undermines the need for dirty goods supply abroad, thereby promoting negative leakage. Using a two-country model, Baccianti and Schenker (2021) show that firms in the non-regulating country increase markups rather than output under some conditions, resulting in a fall of emissions.

Inter-sectoral leakage

Another, albeit small, strand of the theoretical literature analyzes inter-sectoral leakages, i.e., leakage from one sector to another within countries, as a result of partial carbon price increases, often within closed economy settings.[3] These papers can be seen as part of a more general literature that considers the aggregate effects of sectoral distortions in models that reflect production networks; see for instance Bigio and La'O (2020). The theoretical evidence on inter-sectoral carbon leakage remains inconclusive. Using a simple two-sector closed-economy model with factor mobility, Baylis et al. (2014) show that the effects of an increase in the price of carbon in one sector on economy-wide emissions is ambiguous. The reason is that there are two opposing effects: First, higher prices of the taxed sector induce consumer substitution towards the output of the other sector which results in positive leakage. Second, as firms in the taxed sector substitute away from energy, they bid up the price of the mobile factor, resulting in negative leakage (i.e., lower production and lower emissions in the untaxed sector). Their model can also be interpreted as a two-country model with one sector.

King et al. (2019) consider more sophisticated intersectoral linkages and argue that the effects on aggregate emissions of partial carbon taxation depend on three factors, including the sector's level of emissions relative to aggregate emissions, the sector's intersectoral influence on emissions via upstream and downstream linkages, and the aggregate demand effects of rebating the tax revenue. They predict that carbon taxation in sectors with sufficiently high emissions will always translate in reductions of aggregate emissions. By contrast, if the sector's emissions are low, then the tax rebate effect can exceed the other effects depending on the intersectoral influence on emissions, resulting in an increase in aggregate emissions.

B. Empirical Literature

Overview

Compared to the literature that uses ex ante modeling to assess carbon leakage, the empirical literature on carbon leakage remains relatively small but is growing (Dechezleprêtre and Sato, 2017). Ellis et al. (2019) review the relevant literature and argue that there is little evidence in support of carbon leakage, similarly to earlier conclusions by Branger and

[3] In a related theoretical paper, Perry (2020) finds that the welfare benefits of equating emissions prices across ETS and non-ETS sectors are small.

Quirion (2014).[4] In addition, existing papers—with one exception—do not quantify the rate of carbon leakage and only provide indirect evidence. A related literature examines whether an increase in carbon and energy prices results in a loss of international competitiveness which can be considered as the flipside of carbon leakage. Broadly, the existing papers can be differentiated by the policy variable they consider and whether they test the effects on trade flows (both, in terms of goods and services as well as embodied carbon) or on firm location and investment decisions.

Effects of changes in sector-level prices

Similar to our analysis, Sato and Dechezleprêtre (2015) also use variation in industry-level energy prices to examine the potential of carbon leakage (without attempting to quantify carbon leakage rates). They find relatively small effects of changes in energy price differentials on bilateral goods and services imports, but they do not examine the effects on trade flows of embodied carbon exports and domestic emissions. Tian and Yang (2020) find that increases in industry-level energy prices have dampened domestic emissions in China.

Effects of ratifying the Kyoto Protocol

Another group of papers examines the effects of ratifying the Kyoto Protocol on carbon embodied in trade flow; interestingly, these papers are almost the only ones that find evidence in support of carbon leakage. Aichele and Felbermayr (2012) employ an instrumental variable strategy to show that ratification of the Kyoto Protocol has reduced domestic emissions, but not the overall carbon footprint of countries which includes carbon embodied in imports, thereby failing to reduce global emissions. Aichele and Felbermayr (2015) estimate a gravity-type of equation using bilateral sector-level flows of carbon embodied in trade. Their policy variable of interest is the differential Kyoto commitment between importing and exporting countries, allowing them to control for unobserved country-sector and country-year effects. They show that embodied carbon imports in committed countries from noncommitted ones have increased significantly, suggesting that the Kyoto Protocol has indeed led to leakage. Hartl (2019) expands upon Aichele and Felbermayr (2015) methodologically. He also finds evidence of carbon leakage, as shown by the deterioration of the carbon trade balance of Kyoto ratifiers vis-à-vis non-ratifiers.[5]

Aichele and Felbermayr (2015) appears to be the only paper that argues that coefficient estimates from regressions based on bilateral trade flow data cannot directly be used to infer carbon leakage *rates*. Combining their results with the effects of Kyoto Protocol on domestic

[4] These findings mirror, at least to some extent, the broad conclusions of the literature that tests the ‘pollution haven hypothesis’ by examining whether environmental regulation, more broadly defined, undermines economic competitiveness. An early review of the literature by Jaffe et al. (1995) finds that the effects on competitiveness are generally estimated to be small, statistically insignificant, or not robust; some later studies also confirm these findings, see Eskelanda and Harrison (2003) and Javorcik and Wei (2003) for examples. Dechezleprêtre and Sato (2017) survey the more recent literature and argue that there is much evidence that environmental regulations can lead to statistically significant adverse effects on competitiveness, but that these impacts are relatively small; see Kellenberg (2009) as an example.

[5] Kumar and Prabhakar (2016) have taken a similar approach but use export data from a few Asian countries only; they do not find overall no robust evidence of carbon leakage from ratifying the Kyoto Protocol.

emissions obtained from Aichele and Felbermayr (2012), they argue that their coefficient estimates would amount to a leakage rate of 40 percent, well in line with some of the earlier theoretical literature. However, the findings by Aichele and Felbermayr (2015) remain controversial. For instance Naegele and Zaklan (2019) suggest that the channel through which the Kyoto protocol has induced carbon leakage is unclear, and Branger and Quirion (2014) and Sato and Dechezleprêtre (2015) suggest that the absence of sectoral variation in the policy variable makes it difficult to control for other confounding macroeconomic shocks.

Effects of the EU ETS and other country-specific policies

A growing literature examines the effects of the EU ETS on carbon leakage and various indicators of competitiveness; see Verde (2020) for a comprehensive survey. He concludes that so far, there is no evidence of the EU ETS having resulted in a loss of competitiveness or in carbon leakage. He attributes this conclusion mainly to the low carbon prices under the EU ETS during the period which existing papers study and the fact that most studies ignore longer-term impacts. Joltreau and Sommerfeld (2019) examine why the empirical literature finds no effects of the EU ETS on competitiveness and identify similar reasons. Ellis et al. (2019) attribute these findings to low carbon price levels, exemptions to carbon taxes for industry, generous free allowances under emission trading schemes or other compensation mechanisms.

Naegele and Zaklan (2019) is one of the most relevant papers for our analysis. They examine the possibility of carbon leakage under the ETS using data on trade and embodied carbon to and from the EU, differentiated by source country and industry. They use several alternative EU-ETS related policy variables. While they control for unobserved industry-country effects, they do not find any significant effects of their policy variables on net imports of goods and services and embodied carbon. They attribute these findings to the possibility that barriers preventing leakage are greater than the costs imposed by the ETS during the period they study.[6]

Similarly, Garnadt et al. (2020) empirically search for indications of carbon leakage in a gravity-type of setting, using a dummy variable to indicate whether there are differences in adherence to the EU ETS between the importer and exporter. Among other results, they show that the CO2 footprint of final demand in a country with ETS originating from production of a country without ETS increases by around 3 percent, but they do not find clear aggregate effects when examining the effects on import-related indicators.

[6] Other papers use less sophisticated methods and data to study the effects of the EU ETS. Some papers use time series data, implying that their specifications do not allow to control for unobserved effects. Sartor (2013) uses quarterly time series data of EU net aluminum imports and finds no evidence of carbon leakage. Branger et al. (2016) examine the effects of carbon prices on net imports in the steel and cement sectors, using monthly time series data. They do not find any significant effects, but their specifications do not allow controlling for sector- or country-fixed effects. In addition to econometric studies, there are also studies that simply examine the level and composition of costs faced by firms in different sectors to assess carbon leakage. For instance, Bolscher et al. (2013) argue that the contribution of ETS-related costs to overall input costs in various industries in Europe is too small for carbon leakage to plausibly occur. A related strand of the literature examines the extent to which ETS-related carbon costs have been passed through to product prices. Cludius et al. (2020) find evidence that there was significant pass-through of ETS-related costs which could be interpreted as evidence that carbon leakage was limited subject to some caveats.

The results of our analyses are well within the range of conclusions of other analyses in the literature. Zachmann and McWilliams (2020) and Felbermayr and Peterson (2020) review the literature of ex-ante simulation studies and of econometric studies analyzing ex-post data; they document evidence in support of carbon leakage in some industries but overall mixed evidence of carbon leakage in response to environmental policies at the aggregate level. There are also several papers that examine carbon leakage as a result of policies in other jurisdictions. Ferguson and Sanctuary (2019) show empirically that the imports of intermediate inputs by Swedish manufacturers rise in response to a sudden and unexpected increase in electricity prices, suggesting that carbon leakage is negative. The attribute this effect to the possibility that higher production leads to a fall in the firms' output and demand for inputs. Based on a decomposition analysis, Levinson (2009) finds that the pollution reduction in U.S. manufacturing can largely be attributed to improvements in production technology, rather than to a relocation of dirty production abroad, suggesting that carbon leakage has been small.

Effects of carbon prices on firm-leavel investment and location decisions

A separate strand of the literature examines the effects of carbon emission abatement policies firm-level investment and relocation which is another possible channel of carbon leakage in addition to changes in trade flows, although one that probably takes more time to materialize. Dechezleprêtre et al. (2019) use survey data and find no evidence that there has been relocation of economic activity within multinational firms in response of the EU ETS, using survey data. Koch and Basse Mama (2019) use administrative data and find evidence in support of carbon leakage as a result of the EU ETS through increased outward foreign direct investment (FDI) of German multinational firms. Based on firm-level survey data covering the manufacturing sector, Martin et al. (2014) find that the propensity to downsize or relocate in response to higher carbon prices is relatively small but heterogenous across sectors and firms. Calel and Dechezleprêtre (2016) find that the EU ETS has significantly increased low-carbon innovation among regulated firms.

Appendix II. Stylized Facts At the Sector Level

Carbon Flows and Emissions by Sector (average)				
	Exported emissions (percent total emissions)	Imported emissions (percent sector emissions)	Exported emissions (percent sector emissions)	Emissions (percent total emissions)
Basic metals	0.7	15.7	14.7	6.5
Chemicals	0.6	5.5	5	2.5
Construction	0.0	0.1	0.2	1.6
Electrical equipment	0.6	0.2	0.2	0.1
Electricity and gas	0.2	31.7	24.2	29.9
Electronics	0.6	0.4	0.3	0.1
Food	0.3	0.9	1.7	1.3
Machinery	0.6	0.4	0.5	0.2
Metal products	0.5	0.3	0.4	0.2
Mining energy	0.5	6.3	4.7	2.2
Mining non-energy	0.6	1	1.2	0.5
Mining non-metals	0.3	3.6	3.7	3
Mining support activities	0.5	0.2	0.2	0.1
Motor vehicles	0.6	0.2	0.4	0.2
Other manufacturing	0.4	2.4	1.3	0.7
Other transport equipment	0.5	0.2	0.1	0.1
Paper products	0.4	0.7	1.4	0.8
Plastics	0.6	2.8	1.4	0.8
Refined oil products	0.4	4.8	5.3	3.7
Textiles and clothing	0.5	0.7	0.5	0.3
Wood products	0.4	0.2	0.2	0.1
Total	*9.6*	*n/a*	*n/a*	*54.8*
Average	*0.5*	*3.7*	*3.2*	*2.7*

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